Gassing Station and Anaerobic Batch Reactor for Methane Production

Final Paper

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EXECUTIVE SUMMARY

With concerns of global warming due to burning of fossil fuels there has been much focus on research for alternative energy sources. One option is to produce methane from biomass by anaerobic biodegradation using microbial communities. Methane production by anaerobic processes depends on the environment of microbial communities; therefore, more research is needed to optimize conditions for maximum methane production. For this research, labs need to have the capability of mixing gases in reactor bottles containing microbial communities and running short anaerobic batch experiments in a controlled temperature environment. Our project is to design and fabricate this equipment for the Department of Civil and Environmental Engineering at the University of Michigan.

Gas mixtures for reactor bottles are created using a gassing station. Customer requirements for the station are safety, equal gas flow to eight bottles, preservation of anaerobic conditions and convenience. For the gassing station to be safe, it needs to be located near the fume hood, have pressure regulators and relief valves. To achieve equal gas flow, the gas mixture will be directed in a closed loop to both ends of the outlet valve connection setup. Anaerobic conditions are preserved by using a heated copper column as an oxygen scrubber. Convenience is determined by the availability of three taps for inlet gases of hydrogen, carbon dioxide, and nitrogen, which will be used to create gas mixtures for testing in the reactor bottles. Also for convenience, bottles need to be secured in a bottle holder that prevents tipping and release of water and microbial communities through a purging syringe. To design the bottle holder we brainstormed ideas, created a selection criteria matrix and chose materials using Granta CES® program. After material selection we had to redesign the chosen concept due to machining and adhesive limitations. The final concept is a Plexiglas box with holes over which polyethylene foam is placed in one piece with cut out slits.

The second piece of equipment we designed is an anaerobic batch reactor that provides a temperature controlled environment for reactor bottles and measures the production rate of methane. Customer requirements for the temperature regulator are accurate temperature control in a 5 to 65°C temperature range and stirring capabilities within the bottles. After researching and brainstorming concepts we created a selection criteria matrix and determined that purchasing a Barnstead International 1286 Water Bath Magnetic Stirrer is the best option. The cover lid of the water bath will need to be redesigned to accommodate tubing for the methane meter without causing a significant heat loss. Currently the purchase of the water bath has been postponed until a methane meter prototype can be tested. Main customer requirements for the methane meter are continuous and automated measurements of methane production from each bottle. After brainstorming several concepts and compiling selection criteria matrices we determined that the methane meter should use potassium hydroxide pellets placed in line with a syringe to remove carbon dioxide from the biogas and pressure transducers, and a solenoid valve, pressure transducer and a data acquisition card connected to a computer with LabVIEW® for automated data collection. The time constraint of the ending semester did not allow us to assemble this design, thus we will be providing a prototype design for the methane meter. We recommend that two prototypes are built which can be used to test two recommended pressure transducers to determine which one is better for the final design.

Our final deliverables are the completed gassing station, to be installed in Dr. Raskin's lab, a recommendation for a temperature controller for the batch reactor, and a prototype design for a methane metering system.

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ABSTRACT

Methane gas can be produced by biological treatment of organic waste and wastewater by microbial communities. This is done by converting chemical energy in the waste into chemical energy in the form of methane. Unfortunately, methane-producing communities are complex and the biological processes are largely undefined. Specific methanogenic activity (SMA) tests are used to evaluate the viability of methane-producing microbial communities. However, more research is necessary in understanding how to optimize productivity of the communities that carry out methanogenesis. One of the primary factors affecting methane production is the ratio of gases in the bottles containing these microbial communities. In this project, our team designed a robust SMA system capable of high accuracy and high throughput.

INTRODUCTION

The aim of this project is to design 1) a gassing station for preparation of gas mixtures in test bottles, 2) an anaerobic batch reactor with a temperature regulator and 3) a measurement system for determining production of methane in the anaerobic batch reactor. Using this system, our sponsors will be able to determine performance of anaerobic digestion systems based on yield of methane. Methane has been named one of the energy sources of the future due to its cleaner burning capabilities, but more research needs to be done in order to optimize temperature conditions and nutrient ratios of nitrogen, hydrogen and carbon dioxide gas mixtures for microbial communities. The gassing station will be an improvement of the current system in the lab because it will be able to accurately prepare mixed gases for multiple bottles at the same time. The lab currently does not have an anaerobic batch reactor or the means for measuring methane; therefore, success of our project will add invaluable resources to the lab. Dr. Lutgarde Raskin, a professor in Environmental Engineering at The University of Michigan, and graduate students Tanna Alford, Roya Gitiafroz and Jeremy Guest, are sponsoring this project.

INFORMATION SOURCES

Methane Production Methane is the primary component of natural gas, which is the cleanest most nonpolluting fuel that is currently used. Due to its environmental impacts natural gas is becoming the preferred fuel for more than 80% of new electric generating capacity in the U.S.; however, the newly discovered domestic natural gas fields are smaller in production [1]. Therefore, production of methane from biomass will provide relief on the demand of natural gas and at the same time reduce municipal waste.

Anaerobic decomposition of organic material by fermentative, acetogenic and methanogenic bacteria results in production of biogas consisting of 50 to 70% methane, 25 to 45% carbon dioxide and small amounts of hydrogen, nitrogen and hydrogen sulfide [2]. This is a chemically complicated process that can involve various intermediate compounds and reactions [3].

There are multiple factors that affect the anaerobic processes. One of these factors is the temperature at which the bacteria are held during the production stages. It has been determined that small fluctuations from the ideal temperature could result in a process upset. Another factor that determines the production rate of methane is thermal pretreatment of anaerobic cultures. Methanogenic bacteria are also sensitive to fluctuations in acidity levels of their environment. The pH level should be at neutral for the greatest production of methane. Moisture levels, physical characteristics of substrates and the nutrients are some of the other factors that determine the amount of methane produced during the anaerobic process [3]. Current research focuses on optimizing these conditions for various methanogenic bacteria. The equipment that we are designing for the lab in Department of Civil and Environmental Engineering at the University of Michigan will aid in furthering this research.

Gassing Station One of the goals of this project is to redesign the existing gassing station. Microbial communities require the use of a gassing station to prepare nutrients in the form of gas mixtures. The current setup does not meet several expectations. One complaint with the system has been the amount of time spent manually preparing the gas mixtures bottle by bottle and the human error associated with the process. Users are unable to measure if the gas mixture in the bottles is accurate, thus standards cannot be made. Without standards, it is difficult to decide the proportions of gases that optimize methane productivity. Another complaint about the system is that inlet gas tanks can be connected only one at a time. This also increases the time required for preparation of gas mixtures. One of the challenges that our team faces is providing a uniform flow of gases concurrently to multiple bottles. Another challenge is to prevent leakage of gases. Finally, Ms. Gitiafroz requested the implementation of an automatic pressure relief system for the glass bottles to ensure a safe working environment. Besides the current lab setup our team was provided by Dr. Raskin with the flow diagram of a gassing station at the University of Illinois. We used this setup as a benchmark for our system. The flow of the gassing station will be very similar to the one at University of Illinois, but it will incorporate our sponsors' requirements.

Temperature Regulator Another component of the project is to develop a temperature regulator within the anaerobic batch reactor. The productivity of the microbial communities is measured as the rate of growth, yield of biogas, and substrate degradation performance [4]. Chae's paper concludes the efficiency is dependent on a variety of critical factors, one of which is digester temperature setting [5]. Bacteria are most productive within a certain range of temperatures and the different bacteria involved in this project for anaerobic digestion have different temperature optimums.

The current system has no temperature regulator. After researching similar projects, our team has an understanding of how other labs have fulfilled this requirement. Several papers suggested the bioreactor to be equipped with a water jacket and a water heating system for temperature control [5, 6]. The Plexiglas tube surrounds the sample tube in a water jacket, which can circulate water through the jacket. Using an external water circulator, the temperature of the bottles can be controlled. There were three fluids that were suggested for the heating and cooling of the batch reactors: steam, water, and a mixture of water and monopropylene glycol [7].

Methane Separation from Carbon Dioxide Possible separation technologies include cryogenic distillation, adsorption, polymeric membranes, or chemical scrubbing. Based on our research we selected chemical scrubbing as the technology we would implement.

Cryogenic Distillation Carbon dioxide can be separated from methane by using a cryogenic distillation column. Off-gases from anaerobic reactions would be channeled through a region of cryogenic temperatures cold enough to solidify any carbon dioxide present, thus leaving solely methane [8]. However, achieving cryogenic temperatures requires a significant amount of energy relative to the amount of gases produced by the communities. Therefore, we will not consider cryogenic distillation as a concept for separating the off-gas stream.

Adsorption In this process a bed packed with carbon dioxide absorbents is pressurized to the pressure of the supplied off-gas stream. Following this, the off-gas stream is passed through the bed releasing pure methane. Adsorption is very effective for removing carbon dioxide; however, the high pressures required for the process use excessive energy and equipment for our simple setup. High pressures can also disturb the chemical equilibrium of the reaction culture producing invalid results.

Polymeric Membrane Polymeric membrane separation offers some advantages over cryogenic distillation and adsorption. These include lower cost and simplicity of operation. Glassy, amorphous polymers are the best materials that can be used for this process because of their high load bearing properties, temperature properties and composition. In addition, some membranes can also minimize the amount of hydrogen sulfide in the mixture.

Although membrane separation would be economically feasible with more research we discovered several challenges. The first challenge is that we were not able to find a commercial distributor of the PTMSP membranes. The second challenge is that we would need a pressure ratio of 2.01 to diffuse methane faster through the membrane than carbon dioxide. This property is called the permselectivity of the membrane and is defined as $\alpha_{ij} = P_i/P_j$ [9]. As the pressure of the reactor system increases, larger pressures would be needed to effectively diffuse methane through the membrane. However, any pressure above atmospheric increases the liquid-phase solubility of the gas in the bottle with microbial communities. This is due to the increase of the partial pressures of the head space gases, affecting the reaction equilibrium [10]. The higher pressure could also pose a safety hazard because of the pressure rating for glass bottles.

Chemical Scrubber Another method of separating carbon dioxide from methane is to use a chemical, such as potassium hydroxide or sodium hydroxide, which would react with carbon dioxide leaving only methane. There is also a commercially available chemical, Decarbite, by Perkins Intl. designed for removing carbon dioxide. The chemical scrubber is very cost effective and mechanically simple option in comparison to other separation technologies. Potassium hydroxide is a widely available chemical, costing about $60 for 500 grams of pellets or $38 for 1L of potassium hydroxide in solution [11]. The cost of housing for this chemical is also relatively low and is discussed further in the carbon dioxide scrubber concept generation on page 13.

Methane Measurements Various technologies exist for measuring methane after carbon dioxide removal; however, few of them are feasible for our project due to size and money limitations. The technologies involve measuring the accumulated mass, volume, or pressure of the produced gas over time.

Gas Flow Meters Gas flow meters are abundant in commercial applications; however, they operate on a much larger scale than our system. The challenge with our application is measuring very low methane flow rates from the reactor bottles. These flow rates are approximately 5 standard cubic centimeters per minute (sccm). Small digital flow meters available from general suppliers such as McMaster-Carr only measure flow rates on the order of 47 sccm. Specialty flow meters are available for measuring flows at low rates; however, the accuracy of their measurements will be compromised by the lack of steady state flow in our system. These flow meters also cost $1,095 a piece plus an additional $95 for electrical accessories as quoted from DigiFlow Systems.

Pressure Measurements Gas production can be measured at regular time intervals by capturing methane and recording pressure inside a fixed volume container. Using ideal gas relations and assuming an isothermal process, the amount of produced methane can be calculated.

PROJECT REQUIREMENTS AND ENGINEERING SPECIFICATIONS

After meeting with Dr. Raskin, Ms. Gitiafroz and Mr. Guest, we proceeded by outlining their specifications and forming tables. Since many of the requirements mentioned during the meeting were related to each other, we grouped them under the same category. For example, the location of the gassing station near the fume hood is directly related to safety in the lab; therefore, we placed this requirement under safety. In addition, we decided to separate the project into two distinct parts: gassing station and anaerobic batch reactor. The temperature regulator and the measuring instrument for methane are grouped with the design for the anaerobic batch reactor. We created engineering specifications by taking into consideration sponsor requirements. Finally, we assigned values to sponsor requirements to prioritize and to determine the relationship between these and engineering specifications. In the process of organizing requirements and speicifications, we determined that tables would be more efficient and useful than a Quality Function Deployment (QFD). Even though creating a QFD helped us prioritize needs and relate sponsor requirements to technical specifications, there were several sections that did not have relevance to our project.

Gassing Station The customer requirements for the gassing station are listed in Table 1 on page 5. Using these requirements we developed engineering specifications listed in Table 2 on page 5.

	Gassing Station Customer Requirements	Rank
1	Safe	1
2	Sterile	2
3	Number of taps	3
4	Pressure measuring device	4
5	Accommodation of various bottle sizes	5
6	Overall size of station	5
7	Bottle capacity	6

Table 1: Gassing station sponsor requirements

Gassing Station Engineering Specifications	Units	Related to:
Venting gases	ppm	1,6
Equal flow of gases to bottles	cm^3/s	1,3,4,7
Gases per experiment	gases	3
Accommodate volume range	mL	1,3,4,5
Table space available	m^2	1,3,5,6
Range of pressure measurements	psi	1,3,4,7
Minimum amount of oxygen in bottles	ppm	2
Bottle dimensions	cm	1,3,4,5,6
Capacity of pressure relief device	sccm	1,5,7
Resolution of pressure measurements	psi	1,4,7
Bottles per experiment	bottles	3,4,5,6

Table 2: Gassing station engineering specifications

The most important customer requirement is safety of the gassing station. We determined its safety by several engineering specifications shown in Table 2. The first engineering specification is ensuring that any released gas can be vented into the fume hood. This engineering specification is measured in parts per million (ppm) over eight hours according to OSHA standards. The allowable limit of carbon dioxide is 5000ppm. Hydrogen, nitrogen and methane are asphyxiants and the allowable parts per million of these gases are limited by the amount of oxygen present in the room. The amount of oxygen has to be at least 18% [12]. The second engineering specification that relates to safety is equal flow of gas mixture to eight bottles, measured in cm^3/s. This target specification depends on the desired concentration of gases and will change accordingly. To be safe the gassing station also needs to accommodate bottle sizes ranging from 0.06 to 1L. These bottles need to be secured to ensure that they do not tip over when they are being filled with gas mixture. If the bottles get tipped over the water with the microbial communities will spurt out of the purging syringes. Another engineering specification that ensures the safety of the user is the available work space area. Our target is $10ft^2$ of work space given the room dimensions in Figure 1 on page 6. Range and resolution of gauge pressure measurements are also important to safety as these measurements will be used to determine if the bottles are over pressured. The target range for this specification is 340psi. The resolution of the gauges needs to be 0.5psi, which is sufficient because the bottles should not contain pressure that close to their rating. The final specification for safety is to ensure that there is a pressure relief device for each of the bottles. This specification depends on the pressure settings for the gas mixture and is measured in cm^3/s.

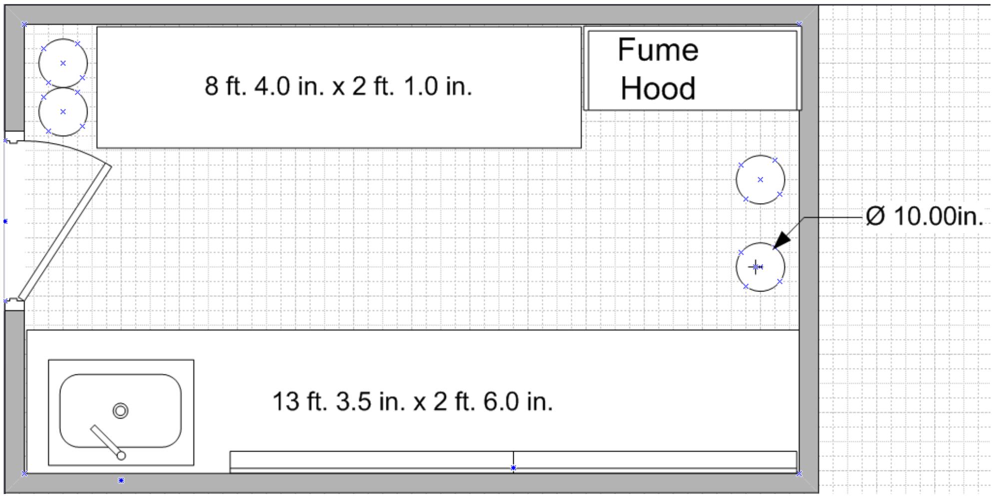


Figure 1: Room Layout for Lab 18 in EWRE

The customer requirement for sterile bottles is predominantly determined by the engineering specification of no oxygen in the bottles. We rated this second highest sponsor requirement because the production of methane is significantly affected by any presence of oxygen.

Our sponsor requires the gassing station to have the ability to simultaneously fill eight bottles with gas mixture. The current gassing station does not have the capability of filling multiple bottles; therefore, taking large amounts of time. This requirement relates directly to the engineering specification of equal flow of gases to bottles and the number of gases per experiment. Each inlet gas needs to be reaching the bottles in the ratios specified by the user. The availability of work space area is also related to the number of taps as a lot of room might be taken up by the bottle holder setup. Also available work space area can be affected by the routing of the tubing, which is determined by how far the gas cylinders are located from the fume hood. As previously mentioned pressure gauges will be used at each tubing outlet to determine how much gas flows into the bottles. Finally the number of taps of the gassing station relates to the bottle dimensions and the number of bottles per experiment. It will be important for us to space the taps according to the bottle size that is most commonly used.

The forth ranked customer requirement is having a pressure gauge at each outlet tap. These gauges ensure that engineering specifications such as equal flow of gases to all eight bottles and accommodating various volume ranges of the bottles are met. Our sponsors will be able to control the gas flow individually at each outlet. At the same time this customer requirement relates to the engineering specifications such as pressure gauge readout range and resolution.

Accommodation of a range of bottle sizes and the overall size of the gassing station are two customer requirements that were not highly rated. The customer specified that majority of the time 250mL bottles are used for specific methanogenic activity (SMA) tests. Therefore, we decided that accommodating 1L bottles is not the most important customer requirement. Our target for accommodation of bottle sizes is to provide our sponsor with an option of eight 1L bottle set up. The overall size of the gassing station is not rated highly because there is sufficient counter space to allow the gassing station setup to extend length wise along the counter. One of our engineering specifications that relates to the size of the gassing station is to create a safe working environment by venting gases to the fume hood. Therefore, the setup of outlet tubes and bottles needs to be close to the fume hood in order to minimize gassing station size by minimizing tubing lengths.

The last customer requirement is to guarantee that the bottles can withstand pressures of incoming gas mixture. As previously mentioned this is closely related to the regulation of flow to the bottles by pressure gauges and valves. A pressure relief device also needs to be implemented in the gassing station as another safety precaution.

Anaerobic Batch Reactor The anaerobic reactor system consists of a temperature regulator and a methane meter for bottles filled with microbial communities and gas mixture. Tables 3 and 4 show how we related sponsor requirements to the engineering specifications for the batch reactor.

	Anaerobic Batch Reactor Requirements	Rank
1	Measure methane	1
2	Sterile	2
3	Temperature range	3
4	Remove carbon dioxide	3
5	Continual measurements	4
6	Discontinuous flow	5
7	Bottle capacity	6

Table 3: Anaerobic batch reactor sponsor requirements

Anaerobic Batch Reactor Engineering Specifications	Units	Related to:
Number of bottles	bottles	1,3,4,5,6,7
Temperature range	°C	5
Length of experiment	hours	2,3,4,5,6
Number of experiments per day	experiments	1,2,3,4,5,6,7
Amount of carbon dioxide per bottle	sccm	1,3,4,5,6
Amount of methane per bottle	sccm	1,3,5,6,7
Amount of oxygen	ppm	1,4,5,7
Temperature resolution	°C	1

Table 4: Anaerobic batch reactor engineering specifications

The most important sponsor requirement for the methane meter is that it must accurately measure methane produced in each of 16 reactor bottles. Methane production is measured as a rate in units of liters per day. The methane meter must be able to measure flow rates as small as 5 standard cubic centimeters per minute for 125mL reactor bottles and accommodate or vent methane volume of up to 7L per day per 125mL bottle [13]. This customer requirement relates to the engineering specification of number of bottles, as there must be a way to meter each of the 16 bottles individually. Finally, measuring methane relates to the amount of carbon dioxide and oxygen per bottle. The carbon dioxide is produced with the methane, so it needs to be completely removed in order to measure only the volume of methane. Also if any oxygen gets inside the reactor bottles, the methane meter will show a significant decrease in methane production from the microbial communities. Therefore, we need to ensure the environment in the glass bottles remains anaerobic and the rubber stopper is secure. The resolution of the temperature regulator will also have an effect on the amount of methane produced in each bottle. Microbial communities are very sensitive to temperature variations; therefore, we need to minimize the temperature gradient within the temperature regulator.

The second ranked requirement of the anaerobic batch reactor is keeping reactor bottles sterile, which means there is no oxygen present. As the experiments involve microbial communities it is imperative that the crimped seal is maintained on the bottle and we are aware of any design features that might disturb the seal.

The third batch reactor requirement is maintaining the cultures at various temperatures within a range of 10 to 65°C. This relates to the engineering specification of number of bottles, as the temperature regulator must accommodate and control all 16 bottles equally. Also, the temperature must be maintained constant during any time duration of the experiment. Experiments can range anywhere from less than 24 hours to several weeks. Depending on the temperature stability during the experiment, the amount of produced carbon dioxide and methane gases per bottle will vary.

The fourth requirement of the methane meter is to remove carbon dioxide. In Table 3 on page 7 removing carbon dioxide from biogas is ranked the same importance as maintaining bottles at a specified temperature. The biogas produced in the reactor bottles is assumed to be composed of only methane and carbon dioxide; therefore, the carbon dioxide must first be removed before the amount of produced methane can be measured. The methane meter must be able to remove carbon dioxide from all 16 bottles for the entire duration of an experiment. The carbon dioxide removal also relates to the amount of oxygen in the bottles. In case of the reactor bottles becoming contaminated there will not be as much carbon dioxide produced by the microbes.

Another reactor requirement is that the methane measurement is continuous and able to produce accurate production curves. The carbon dioxide must be removed continuously and the methane must be measured for the entire duration of the experiment. Also, by having continuous methane measurements, any unusual outputs for the methane measurements might indicate a presence of oxygen in the reactor bottle. The final requirement for the anaerobic batch reactor is that the setup can be used for bottle capacity ranging from 50mL to 1L. The bottle capacity needed will be dependent upon the duration of the experiment.

ENGINEERING ANALYSIS

Gassing Station One of the engineering fundamentals that we will use for the gassing station is fluid dynamics in order to verify our design hypothesis for equal flow distribution of gas mixture. Equal flow of gas mixture is necessary when preparing gas mixture in multiple glass bottles. Manufacturing skills will also be necessary when we start working in the shop. Finally, basic knowledge of chemistry and thermodynamics will help in understanding the partial pressures of gases.

Temperature Regulator The engineering fundamentals of heat transfer will be most relevant to the design of the temperature regulator. The selected concept will be modified to accommodate the tubing of the methane meter in order to minimize heat loss in the regulator. Behavior of materials will also be important in identifying which material is best for insulation.

Methane Meter The methane meter requires use of engineering fundamentals such as chemistry, fluid dynamics, thermodynamics and circuits. Chemistry is very important in understanding the separation process of carbon dioxide and methane. Fundamentals of fluid dynamics help to understand the flow of gases through the tubing. We used thermodynamics concepts to introduce the ideal gas relation that is used to determine the amount of produced methane from pressure measurements.

Finally, knowledge of circuitry will be used to build the computer interface with the pressure transducers.

CONCEPT GENERATION

Gassing Station To generate concepts for design of a gassing station we first developed a functional decomposition by operation shown in Figure 2. The main output operation is to safely and equally fill eight glass bottles of various sizes with a gas mixture. Before beginning to brainstorm ideas for the gassing station we researched literature for similar equipment that can be used for benchmarking purposes. Due to this equipment not being commercially available we only used the gassing station built at the University of Illinois Urbana Champaign and the one currently in the lab for benchmarking. After reviewing these setups and analyzing the functional decomposition we determined that there are two parts that need to be improved to satisfy sponsor requirements. These are: neat appearance of the outlet tubing and a bottle holder. Once we determined the parts that need to be designed we began brainstorming.

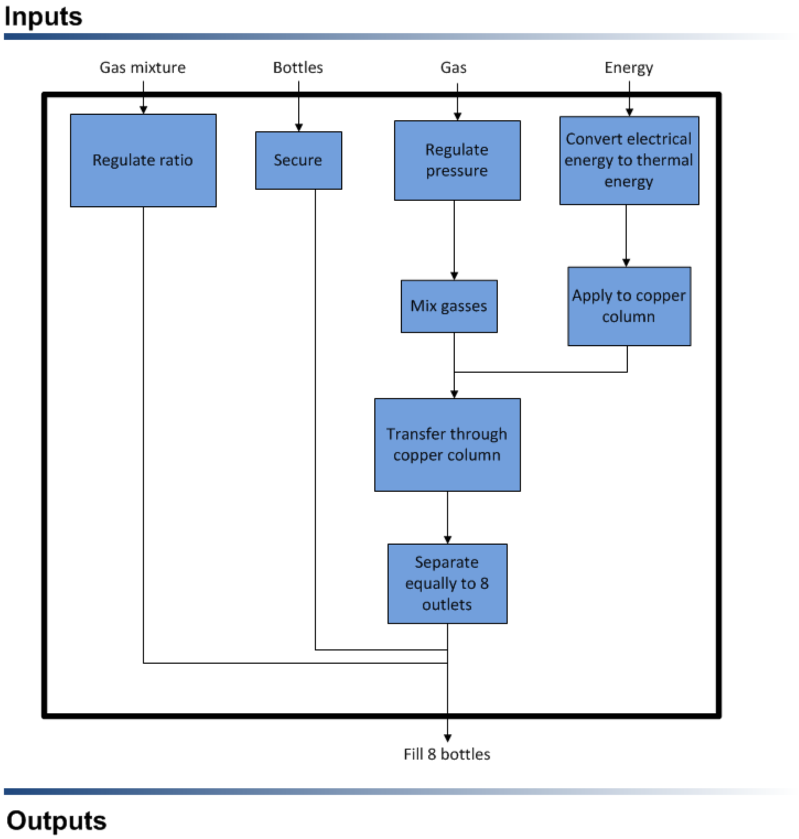


Figure 2: Functional decomposition for the gassing station

Outlet Tubing One of the main challenges with the benchmarked gassing station setups is that the outlet tubing is not aesthetically appealing, nor simple to operate. Therefore, we developed the following six concepts, with diagrams found in Appendix A, to organize the arrangement of the tubing, making the station more user-friendly.

Figure A.1 has the tubing arranged in a line and attached to a plate with a built-in filter and syringe. The plate rests on ledges attached to two stands. The stands have multiple ledges to accommodate various bottle heights. The second concept, Figure A.2, has a similar design to a Lazy Susan. It has the tubing arranged and attached in a circular pattern to a rotating circular plate that has built-in filters and syringes. The plate is attached to a shaft with holes. To adjust the height the user must adjust the circular plate up or down the shaft and then slide a pin through a hole at the desired height for the syringes. The third concept shows the tubes arranged in grooves on a fixture that resembles a Menorah, see Figure A.3. The height is adjusted by moving the top half of the Menorah like fixture up or down and then inserting a holding pin through a hole in the base. The fourth concept shown in Figure A.4 has the tubing arranged on a support plate that is in a shape of a quarter of a circle. The plate is attached to the backboard of the gassing station at the height for 1L bottles. The hole through which each tube is passed has enough tolerance so that the user can pull and push through the extra tubing that is necessary for shorter bottles. The fifth concept, Figure A.5, shows part of a backboard of a gassing station with large holes with notches at various heights. The support shown on the side of the part of the backboard is attached on to the tubes and holds the tubes on notches at necessary heights.

Bottle Holder Specifications for the bottle holder are: have the ability to secure bottles of varying diameters, provide easy method for securing bottles and be large enough to hold eight bottles for filling at a time. Our team generated 5 concepts for this design, which are listed in Appendix B.

Our team began researching by going to Home Depot where employees showed us hose clamps. This helped us generate the first concept. As an inexpensive option, each clamp is $1.39, and would have to be tightened individually. The hose clamps could be easily attached to the backboard of the gassing station. This hose clamp concept is illustrated in Appendix B Figure B.1. Figure B.2 shows the second design that emulates the function of a cup holder in a car. The relevant features of this design are the four “flanges” that adjust to the required range of bottle diameters by deflecting as the bottles are inserted into the holder. Figure B.3 was proposed as a more efficient method to hose clamps for securing the bottles. All bottles could be secured by tightening only two bolts, located at each end of the device. A thin C-shaped rubber piece is fixed to each bottle holder which helps secure the bottles without damaging the glass. This system holds the bottles securely in place because the rubber has a large friction coefficient. Figure B.4 is our simplest design, where the bottles are secured by a large rubber band that straps around the bottles in a figure-eight shape. In addition, the bottles will need to be placed in a box to prevent them from tipping over. The last design, seen in Figure B.5, includes a range of dividers which fit in small grooves in the side of the box. The dividers act as separators that prevent the bottles from tipping over. We would also use a divider placed along the length of the box for bottles with smaller diameters.

Temperature Regulator Our team generated several solutions to meet Dr. Raskin’s requirements for a temperature regulator. Adjustable temperature control is necessary for the anaerobic batch reactor because the microbial communities are very sensitive to their environment temperature. The temperature regulator had to be of large dimensions in order to accommodate 16 1L bottles for testing. The bottles also require a magnetic stir bar (used in conjunction with a stir motor) to stir the solution. These requirements had to be taken into consideration when generating concepts.

To begin concept generation, our team developed a functional decomposition, Figure 3, to explore diverse solutions to achieve the necessary functions. The functional decomposition was done by operation, so as to provide a better definition using sub-functions and identifying system requirements. We began researching methods of converting electrical energy into thermal energy. For the temperature range of 10 to 65°C all research pointed in one direction: heating a coil which in turn heats a fluid or a gas. Figure 4 on page 12 shows a simple circuit diagram that achieves this goal. This could work for an incubator, heating pad or water bath with a heat exchanger. All concepts generated in this section can be found in Appendix C.

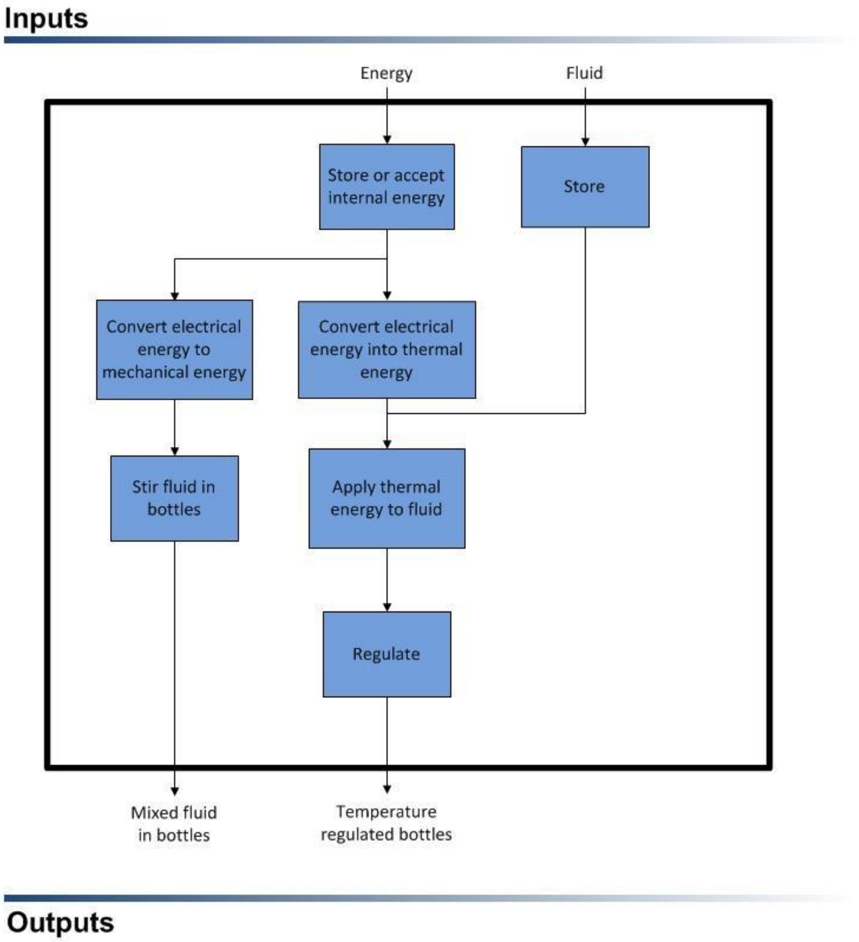


Figure 3: Functional decomposition for temperature regulator

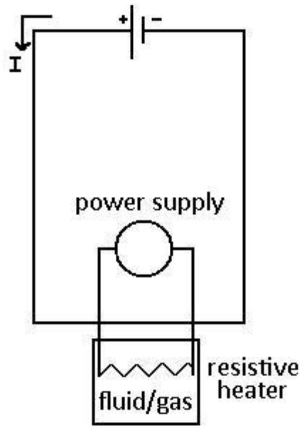


Figure 4: Circuit diagram for temperature regulator

The first concept we researched in detail was the incubator. The most important specification for laboratory incubator is temperature range. An incubator is comprised of a transparent chamber and equipment that regulates its temperature, humidity, and ventilation. Laboratory incubators are used in most cell culture laboratories because they are accurate, reliable and convenient. There are two primary heating options in small to mid-sized incubators: water-jacketed incubators and radiant-walled incubators. Although both heating systems are accurate and reliable, they each have their advantages and disadvantages. Water-jacketed incubators maintain temperature by surrounding the interior cavity with heated water. The heated water circulates by natural convection inside the inner chamber and the heat radiates towards the interior cavity and maintains a constant temperature within the chamber. Water is a particularly effective insulator and the water-jacket system is considered a more reliable method of heating in case of a power outage. Radiant-walled incubators heat the interior chamber using heaters fixed within the outer cavity. These heaters radiate heat towards the inside chamber. A radiant-walled heating system recovers more quickly than a water-jacketed incubator when the chamber is opened. Radiant-walled heating systems are also more user-friendly and do not require filling and emptying water in the jacket [14]. The model our team considered was the Cole Parmer StableTemp ® BOD Incubator; see Appendix C Figure C.1, because of its low price and size which is large enough to accommodate the magnetic stir plates [15]. However, a radiant-walled incubator does not provide an outlet for the biogas tubing.

The next concept we generated was the heating pad. Similar to a sodium acetate heating pad that immediately warms up, our team researched particular fluids that were suggested in the readings for the heating and cooling of the reactor bottles: steam, water and a mixture of water and monopropylene glycol. Heating pads equipped with a rheostat, similar to those used in reptile tanks, are inexpensive, safe and have multiple heat settings. Shown in Figure C.2, the Kane Heat Mat with Rheostat was the particular model we were interested in emulating [16]. Several heating coils produce an even heat distribution inside of the polyethylene glove. Our team was unsure if the magnetic stir bar would still function if the heating pads were used between the bottles and the stir plates. The flexibility of the mat means that it can be easily wrapped around the bottles, thereby eliminating previously mentioned issue. The number of mats required to meet the project specifications set the price near the same price level of the considered incubator.

The final concept generated was a water bath similar to those used in laboratories. This option is attractive because of the vacant water bath shaker available in the lab. We considered three options: using the water bath shaker, modifying the existing design to accommodate stirring of the bottles by using magnetic stirring plates, or purchasing a water bath with built-in stirring capabilities. The water shaker eliminates use of a stir bar because the shaking is adjustable under a precisely controlled and reproducible temperature environment, but the shaking could potentially cause methane meter tubing to loosen. The temperature of the water in the bath depends on an external heating and cooling device, which allows for precise temperature control. Our team considered using various fluids suggested in the literature for implementation inside the bath. The second available option was to design a bath with stir plates attached to the bottom of it. A layer of glass would separate the magnetic stir plate from the water and be thin enough not to interfere with the magnetic stirring. The third option is to invest in a water bath with stirring capabilities [17]. The model we were looking at in particular is the Barnstead International 1286 Water Bath Magnetic Stirrer. This bath can accommodate only six 1L bottles; therefore, our team recommends for using the temperature control room for larger batches. For all three water bath concepts, our team will need to redesign the water bath covers to accommodate the tubing and minimize heat loss.

The last concept our team created was to design and build a homemade water bath, made of an environmentally-friendly insulative material, large enough to hold the bottles. Separating the water from the stir plate would be a thin sheet of glass. The water would be heated and circulated using the unoccupied heat pump available in the lab. A thermocouple would be kept inside the bath sending feed back to the proportional integral derivative (PID) temperature control attached to the lid. This control would maintain and regulate the temperature of the compartment using sensors. Although cost is minimal with this concept, heat loss due to tubing and water flow is our biggest concern.

Methane Meter After finishing functional decomposition our team began developing concepts for carbon dioxide scrubber and metering device. The functional decomposition is shown in Figure 5 on page 14. All generated concepts can be found in Appendix D for carbon dioxide scrubber and Appendix E for the metering device.

The carbon dioxide scrubber is used to remove any carbon dioxide from the produced biogas, leaving only methane. All of our generated concepts for a carbon dioxide scrubber use chemical reaction principles, where a base chemical such as potassium hydroxide is used to react with the acidic carbon dioxide and remove it from the biogas. The metering device needs to measure methane which remains after scrubbing. We developed concepts for the methane meter by brainstorming how we could capture the produced methane and use ideal gas relations to determine the volume of methane produced. Major requirement for the carbon dioxide scrubber is simplicity of the design and assembly and for the methane meter automated data acquisition.

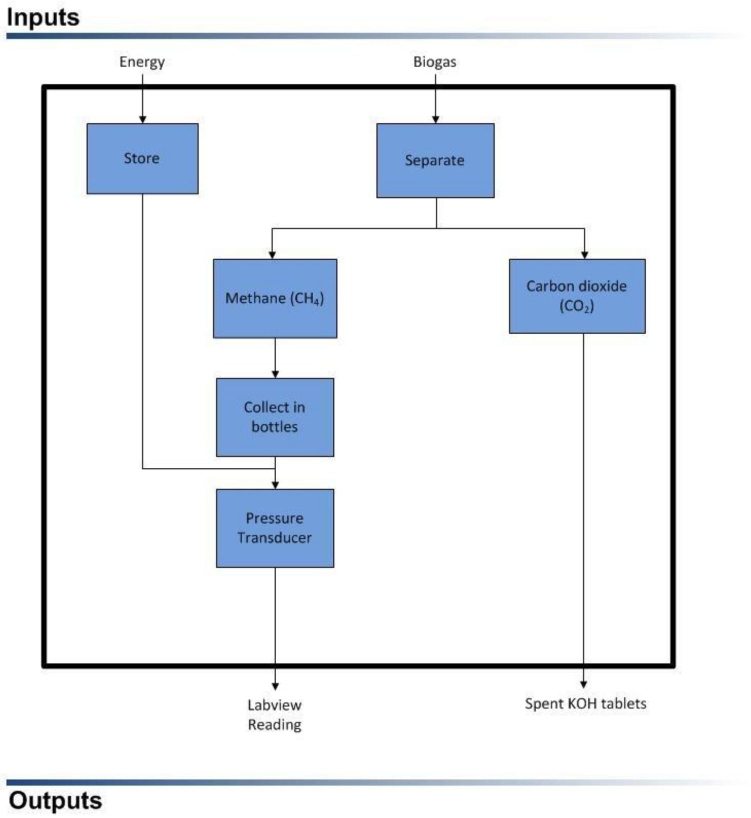


Figure 5: Functional decomposition for the methane meter

Carbon Dioxide Scrubber We generated five concepts for the carbon dioxide scrubber. The first concept is the inline syringe design, which consists of 60mL disposable plastic syringes, filled to 50mL with potassium hydroxide pellets which react with the carbon dioxide in the biogas [13]. The syringe would then be inserted into the stopper of the reactor bottle, and would be connected to the tube going to the methane metering device, as shown in Appendix D, Figure D.1. The inline bottle design, our second concept, is similar to the inline syringe scrubber, as seen in Figure D.2. The inline bottle scrubber would be connected to the line heading from the reactor bottle to the methane meter and would contain a liquid salt, such as potassium hydroxide, for adsorbing the carbon dioxide in the produced biogas.

The company which supplies commercial batch reactor setups, Challenge Environmental Systems™, uses a small vial that is suspended from the lip of standard reactor bottles. This vial holds a liquid salt for scrubbing carbon dioxide out of the produced biogas. For this concept we would look into an aftermarket part line at the company to see if we could purchase only the suspended vials. For our fourth concept, we followed the same approach as Challenge and developed the idea of suspending a net from the underside of the rubber stopper to hold a potassium hydroxide pellet in the head space of the reactor bottle. The fifth concept, shown in Figure D.3, places the pellet within the head space of the reactor bottle by creating a pedestal which would fit inside the reactor bottle.

Methane Meter We have generated concepts for the methane measuring device by brainstorming ideas for how we could measure the volume, pressure, or mass of produced methane.

The first concept we generated was to capture methane in a bladder, which could rest on a scale that would be connected to a data interface. The bladder would collect methane and the mass of produced methane could be measured over time by the scale. We found that Tedlar bags, which are made out of Polyvinyl Fluoride (PVF), could be used to capture gas, which would also allow the user to analyze the gas using gas chromatography. The second concept we generated was a piston-cylinder device. Ideal gas relation could then be used to determine the mass or volume of methane. We could also build a circuit that would record the height of the piston by using a computer.

The third concept we considered, which is also the most common and reliable method for measuring produced gases involves accumulating methane in a bottle, connected to the reactor bottle, and using pressure transducers to measure the pressure over time. By assuming the process to be isothermal, the ideal gas relations are then used to calculate the volumetric rate of produced methane. Using the same approach as the pressure transducer measurements, our fourth concept is the low-cost option for measurement. Pressure gauges are much less expensive than pressure transducers. We would semi-automate the data acquisition by setting up a webcam to take pictures of the dial gauge readings at regular time intervals.

Finally, we could also develop a system similar to the commercially-available system made by Challenge Environmental Systems™. They use a bubbling technology where part of a container is pressurized until bubbles can be pushed through a high-density silicone. The bubbles are then counted by a laser. All of the bubbles formed in the silicone are of a known volume; therefore, the total volume of produced methane can be calculated.

CONCEPT SELECTION PROCESS

Following design development, our team's next step was concept selection. In order to analyze and evaluate the concepts generated, we prepared selection matrices to assist in this process, see Appendices F-H. The selection criteria for the matrices were generated using customer requirements, engineering specifications and the interaction functions from the functional decomposition. After listing the selection criteria we gave each criterion a weight of significance based on the ranking of customer requirements in Tables 1 and 3 on page 7, respectively, and based on the time left until completion of the project. We discussed all of the given weights and assigned ratings to each concept where 5 means that the concept exceeds specification and 1 means that specifications are not met.

Gassing Station

Outlet Tubing Setup After generating concepts for the setup of the outlet tubing we proceeded with the concept selection process by creating a selection criteria matrix, shown in Appendix F, Table F.1. There are three selection criteria that are most important. The first one is easy height adjustment of the syringes relative to the rubber stoppers in the bottles. The second one is accommodation of various bottle sizes. Both of these criteria were determined by customer specification of the gassing station being able to accommodate bottles ranges from 50mL to 1L. The third most important selection criterion is the ease of inserting syringes into the rubber stoppers in the glass bottles. This criterion was chosen based on our sponsors requesting an aesthetically pleasing and easy to use gassing station. The current setup in the lab fills just one bottle at a time and it is very difficult to manipulate.

One of the advantages of the plate concept, Figure A.1 on page, is that the height is easily adjustable for any bottle size. This concept has the syringes and filters built into a plate, making the outlet tubing very organized and easy to use. Because the syringes and filters are built into a plate, the force from the weight of the tubing which causes bottles to tip over in the current lab setup is eliminated. This setup can also be moved across the work space area, which allows the user to adjust it to the most convenient setup. One of the main disadvantages of the plate design is that the bottle on-center pattern is limited to a certain bottle size. Since this is one of the main selection criteria this disadvantage significantly brought the design down in the selection criteria matrix, as seen in Appendix F, Table F.1.

The Lazy Susan concept, Figure A.2, is similar to the plate concept in some of its advantages and disadvantages. The height of the syringes relative to the rubber stoppers in the glass bottles can be easily adjusted by the user. The Lazy Susan concept is also very compact and can be easily moved across the work space area. Although the Lazy Susan concept is compact and easily movable, the work space is inconveniently set up as the user has to reach around bottles in order to make an adjustment to some of the bottle setups. Reaching around bottles causes some potential safety concerns as it may result bottles getting tipped over. The Lazy Susan concept could be improved by making the base rotating, but this would add complexity to its manufacturing and would require the bottle holder to also be incorporated into the design. Finally this concept is designed for a limited bottle size range; therefore, it also scored low in the concept selection matrix for outlet tubing, Table F.1.

The Menorah concept has many advantages, Figure A.3. Just like the Lazy Susan concept, the Menorah concept would have an adjustable height that would satisfy one of the main selection criteria. In the selection matrix, the ease of adjusting the height did not score the highest rating because the user would have to maneuver their hand through the bottle setup to get to the center shaft where the height is adjusted. The Menorah concept satisfies the criteria of easy of insertion of syringes because the tubing is not built into a plate, but instead rests on a support that eliminates the force of the tubing weight. The main disadvantage of this concept is the design of the base. We decided that the base was not stable enough to have tubing resting on it. Another disadvantage is that there is nothing preventing the outlet tubing from getting tangled in the front. Finally, we hypothesized that the tubing would not be able to rest in the grooves without fixing it with u-bolts. Based on these criteria the Menorah concept was our third highest scoring concept.

The slotted design concept in Figure A.5, has individually adjustable height for the outlet tubes; therefore, satisfying the main selection criteria. In this concept the tubing is also not restricted to being stretched out to the sides, so it would easily accommodate various bottle sizes. Since each outlet tube is not fixed to a plate as in the plate and Lazy Susan designs, it would be easy for the user to individually insert syringes into the bottles. The support plate would also not limit the clearance height for the purging syringe. There are two main disadvantages to this concept. The first one is the number of setup steps. We decided the user would be overwhelmed by the amount of height adjustment options and would prefer not to adjust the height of the tubing. This would completely eliminate the function of this concept. The second drawback is the difficulty of manufacturing this setup. For these reasons this concept did not score the highest in the selection matrix.

The curved plate concept that we generated rated high across all of the criteria. Although it did not rate as the highest in the three main selection criteria of easily adjustable height, accommodating various bottle sizes and easily inserted syringes, it had the highest rating overall. After determining that the curved plate rated the highest, we analyzed it again for the three main criteria and decided that it was the simplest setup that satisfied our sponsor requirements.

Bottle Holder The results of the selection matrix showed that the concepts scored fairly close except cup holder concept, which met and exceeded most of our requirements for the gassing station holder (see Appendix F, Table F.2). The largest weights were given to preventing the tipping of bottles and the height adjustability. Ease of manufacturing and minimal parts was given less weight.

The cup holder design does not require extra storage place, prevents the bottle from tipping, fits bottles of varying diameters and heights, and requires minimal set up steps. This design may be difficult to manufacture, but that criterion was not given much weight in the matrix so it did not prevent us from selecting the design. The slider concept was low cost and adjusted easily to varying diameters, but it would require extra storage to hold unused separators, and smaller bottles might still be able to tip over within the compartment. The hose clamp concept scored well in diameter adjustability, but since each bottle must be secured individually, it scored low on easy setup. The clamp concept scored lowest of the concepts. Though it requires minimal set up steps, it is difficult to manufacture and the number of moving parts would make it difficult to assemble. Finally, the rubber band concept required little manufacturing, was low cost, and fit bottles of varying height and diameter, but our team worried about the durability due to the rubber stretching, and that set-up might require one person to hold the bottles while the rubber band was being strapped around it.

Temperature Regulator The method used in selecting the temperature regulator was a selection matrix which included the aforementioned concepts. The first design concept rated was the Cole Parmer StableTemp® BOD Incubator. This concept was large enough to accommodate the stirring plates and bottles. One negative aspect of this concept is the high cost associated with the product, priced around $4625. Also, its inability to accommodate tubing ruled out the possibility of overlooking cost.

The second design concept was our Kane Heat Mats with Rheostat. These mats were fantastic for maintaining even temperatures across the bottle and accommodating the magnetic stir bar, but they could not be used for bottles of smaller sizes. Also, there was plenty of heat loss escaping from the mat and the set up would be a hassle. After individually wrapping the mats around the bottles, rubber bands would be necessary to secure the mat around the bottle. Our team was not confident with the durability and lifetime of the mats. Also, the lack of digital readout for the temperature meant if there were an error it would be difficult for our sponsors be tell.

The third concept generated was to use the available water bath shaker in the lab. The low cost was our main attraction to this concept. The tank in Professor Raskin's lab is large enough to accommodate eight 1L bottles and the temperature can be controlled by rotating a dial on the outside of the tank. However, this concept scored low in stirring capabilities because the shaking does not provide a mixture as uniform as the magnetic stir bar. Also, it may loosen the tubing connected to the bottles, resulting in inaccurate readouts.

The homemade water bath was also a viable option by utilizing the available water pump in the lab. This concept would be a low cost option, and we could build the bath to accommodate as many bottles as necessary. However, the water bath would need to be very reliable, accurate, and durable, last many years, and we questioned whether a home-made bath would stand the test of time as well as a purchased bath.

The final concept is our recommended concept. We could purchase the Barnstead International 1286 Water Bath Magnetic Stirrer including the Mistral® six-place multi-stirrer. The temperature is easily adjustable and it accommodates up to six 1L bottles and requires minimal setup. Water baths are easy to service and the product comes with a lifetime warranty. This met and exceeded all of our design specifications except being low cost and being large enough to contain eight bottles. The price of one water bath with stirring capabilities is $2,454. We met with our sponsor and told her we recommended the costly concept. Our sponsor was satisfied with our recommendation and to meet the specification of size, suggested we purchase an additional bath.

Methane Meter

Carbon Dioxide Scrubber We used a selection matrix to evaluate our concepts for the carbon scrubber. Our main criteria for the carbon dioxide scrubber were the ability to change out the scrubbing chemical during the experiment, and the simplicity of its setup. Main advantages of the inline syringe concept are that the parts are all commercially available (no manufacturing required), the potassium hydroxide pellet will not come in contact with the anaerobic solution, and you can change the pellet without disturbing the reactor bottle. Disadvantages are that the potassium hydroxide pellets cannot adsorb as much carbon dioxide as a liquid base, however the pellets are much easier to contain than a liquid chemical. This concept, the inline syringe, is our recommended concept, as it scored the highest in the selection matrix and seemed to be the simplest and most straight-forward design to us.

The second concept would be to use an inline liquid base scrubber in a bottle. Although the liquid can last about 1.5 times as long before becoming spent during an experiment, having another bottle filled with liquid in the reactor setup made us decide on the simpler option of the inline syringe scrubber.

The third concept we evaluated was the suspended vial from Challenge. Although this would not require manufacturing on our part, we estimate that purchasing their parts would be relatively expensive compared to other scrubbing concepts, and that we still would not be able to change the chemical during an experiment. The fourth concept, the suspended net would be suspended from the rubber stopper inside the bottle to absorb carbon dioxide. However, this concept allows for possible contact between the culture and the pellet, does not allow the KOH to be changed during setup, would be difficult to assemble, and it would limit the space available for the outlet line syringe to be inserted. The final concept of having a type of stand or pedestal in the bottle would require us to manufacture new parts, would allow for possible contact between the culture and the base chemical, would be difficult to set up, and would limit the space for the outlet line syringe to be inserted.

Finally, we had considered using polymer membranes to separate the CO_2 and CH_4. As discussed in the information sources, the membranes require a pressure differential which causes one of the gases to diffuse more quickly through the membrane than the other. Disadvantages are that the membranes begin to degrade in a matter of weeks after first use, we would have to design an entire housing for holding the membrane, and we could not find them commercially available. As this concept did not seem very feasible from our research, we decided to not include it in the selection matrix.

Methane Meter Our main criteria for the methane device were for it to take automated measurements of the produced CH4 during experiments, and to be a simple design. After creating a design selection matrix of our concepts, we decided that capturing the CH_4in bottles and using pressure transducers to measure the pressure over time is the best design. This method is known to be very reliable, however purchasing pressure transducers rather than gauges can be expensive. The transducers allow for automated measurements of produced gas over the length of the experiment. However, without the use of any solenoid valves, the bottles will still need to be manually vented to prevent them from over pressuring.

The advantages of the Tedlar® bag concept are that it captures the methane, which could be studied after the experiment, and the design is very simple. However, purchasing scales would become expensive, they would take up excessive space, and the bags do have the potential to overpressure and release toxic methane into the lab room. The webcam concept would be low cost; however, it would only be semi-automated, as someone would need to manually input the pressure gauge readings. This would be very time consuming, and reading fine resolution off pictures of dial pressure gauges would be difficult.

Disadvantages to capturing the methane in a piston cylinder device would be that the collected would need to be manually released at some point. Also, we would have to spend much time developing the technology for automatically tracking the height increase of the piston to measure the CH_4produced. A piston-cylinder setup would also likely require a large amount of material, and would take up excessive space in the lab room. Finally, the concept of designing a bubbling system similar to Challenge's would be very time consuming for us to develop, and the lasers would be very expensive.

SELECTED CONCEPT DESCRIPTION

Gassing Station

Outlet Tubing Setup The chosen concept is concept the curved plate shown in Figure 6 on page 20. The outlet tubing is going to pass through designated holes in the backboard of the gassing station. The holes will be drilled for the highest bottles, which are the 1L bottles. They will also have enough tolerance, so that the user can easily pull out extra tubing from the back for shorter bottles. This satisfies the easily adjustable height selection criteria. Underneath the drilled holes we will attach a smooth plate that is in a shape of a quarter of a circle. The outlet tubing will be rested on this plate. This plate will provide extra support to the tubing and minimize the force of the tubing weight on the glass bottles. This setup also does not limit the sideways movement of the outlet tubing; therefore, it accommodates various bottle sizes. Having the outlet tubing arranged on a plate will make it more difficult for the tubing to get tangled around the workspace area. By having the outlet tubing overhang the glass bottles the workspace area will also be maximized as only the glass bottles in the bottle holder will be set up in front of the gassing backboard. This concept also does not require a lot of setup steps; therefore, after analyzing all of these advantages we decided that this concept best meets sponsor requirements.

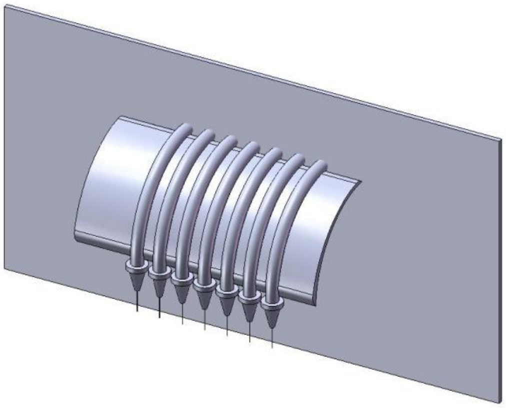


Figure 6: Selected concept for outlet tubing setup

Bottle Holder Figure 7, below, is a three-dimensional model of the chosen concept. Our team is still selecting the proper material for machining. Eight holes, with the diameter large enough to hold a 1L bottle must be drilled into the top of a rectangular box. From there thirty-six wedges must be manufactured of rubber material. For each hole drilled, four "flanges" will be affixed to the inside perimeter. The diameter of the smallest bottles will fit securely within the hole. The design resembles a cup holder in most automobiles. This holder will sit on the table and provide support for the bottles during gassing. The rubber flanges will support the sides of the bottles to prevent dislodgement and tipping. This will allow for easy insertion of the needles into the rubber stopper so that the bottles are filled simultaneously.

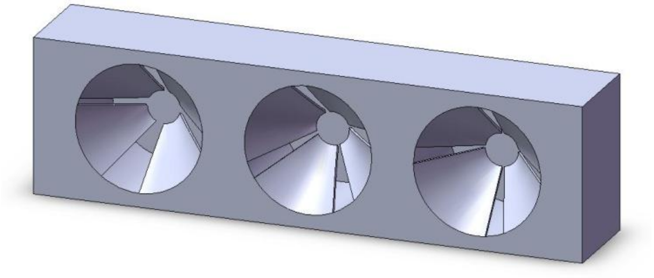


Figure 7: Selected concept for bottle holder

Temperature Regulator After meeting with our sponsor, and discussing the long term nature of the project, our team has decided to ahead with our selected concept. This concept was the temperature regulator is the Barnstead International 1286 Water Bath Magnetic Stirrer including the Mistral® six-place multi-stirrer see Figure 8 on page 21. The product is a clear acrylic water bath and analog circulator and ranges from 5°C above ambient to 70°C. It features the Mistral six-place multi-stirrer that includes six independently controlled stirring positions with adjustable speed control of varying agitation. It can accommodate the stirring of bottles of sizes up to one liter and has a bath capacity of 28.4 L. Our team will have to redesign the top of the lid to accommodate the tubing after ordering the bath. The bath has an electrical cord, which when plugged in and switched on, heats coils within the walls. The stir plate is located at the bottom of the bath and is also powered electrically. The result is bottle solutions that are temperature regulated and homogeneous. Our sponsor has requested that we by multiple baths to satisfy the specification of testing eight bottles simultaneously. She has also asked we look into contacting Barnstead International in customizing the model.

Figure 8: Selected temperature regulator for anaerobic batch reactor

Methane Meter

Carbon Dioxide Scrubber From our concept selection matrix we decided that the best design for the CO_2 scrubber would be the inline syringe scrubber with KOH pellets. We will use 60mL disposable plastic syringes, filled with KOH pellets to 50mL. The KOH pellets and syringes can be bought from a general laboratory supplier. We also recommend the use of a desiccant, such as Drierite®, in the syringe to remove any water vapor present in the biogas.

Methane Meter We have decided that recording pressure transducer measurements would be the best way to measure the methane produced from the bio reactor. We would like to use a design where the collection bottles act as ballast bottles for the system. By allowing them to only pressure up to 1kPa, we would be able to maintain near-atmospheric pressures at all times in the reactor bottles, which prevents significant changes in the equilibrium concentration of the culture liquid. When the system does reach the set pressure of 1kPa, the solenoid valve would be triggered to open for a specific amount of time, allowing a specific amount of gas to vent out of the system. LabVIEW® can then be used to track how many times the valves opens and close, tracking the amount of methane produced.

After meeting with our sponsor, we received approval of both the inline syringe scrubber and the pressure transducer method. Professor Raskin has asked for a full cost breakdown of different options for pressure transducers and solenoid valves, and a corresponding breakdown of the measurement accuracies of which each system is capable.

ENGINEERING DESIGN PARAMETER ANALYSIS

Gassing Station

Gas Cylinders and Tubing In order to satisfy OSHA safety specifications the gas cylinders with carbon dioxide, nitrogen, hydrogen and argon need to be placed in the space between the wall and the counter by the door as seen in Figure 9 on page 22.

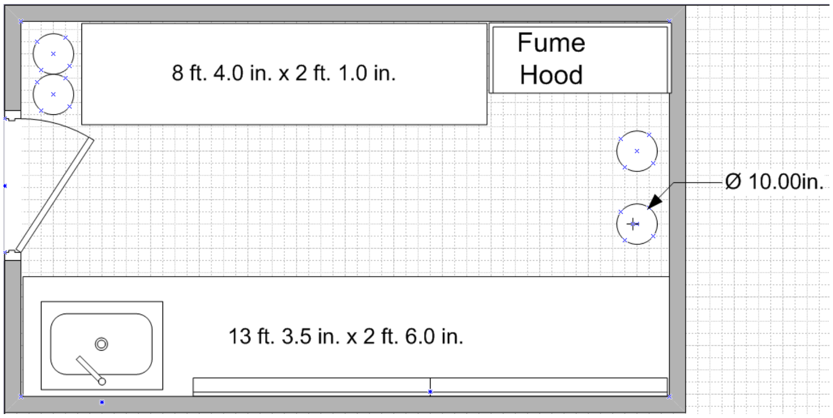


Figure 9: Placement of gas cylinders in Lab 18 in EWRE

As recommended by Texas A&M University the gas cylinders should also be stored in a restraint area 26" high [18]. All of the cylinders also need two restraints such as belts or chains that need to be anchored to the wall of the room at one third and two thirds the height of the cylinder, in order to prevent the cylinders from tipping over. The gas cylinders will need to have regulators attached to them. Before the regulators are attached the valves on the cylinders need to be cracked and closed immediately, to clear the valve of any dirt that might enter and ruin the regulator [19]. The tubing coming from the regulators will be 1/4" copper tubing. Since the gassing station will be placed directly across from the fume hood, Figure 10, and two of the gas cylinders will be placed on the other side of the room we will need the deliver the gas to the gassing station in a very efficient manner. We chose 1/4" copper tubing because the pressure loss due to gas flow is not large and copper tubing this small can be easily mounted for routing purposes.

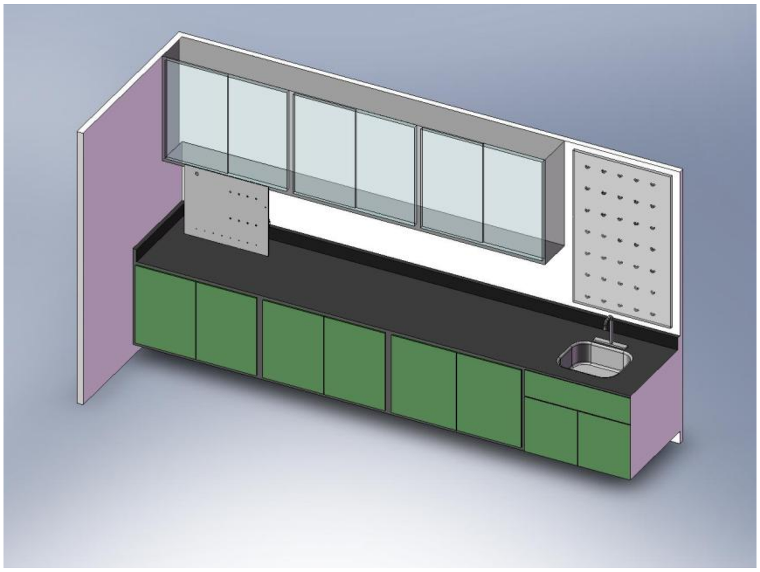


Figure 10: Placement of the gassing station in the lab setup

Backboard Tubing and instrumentation will be mounted on the backboard of the gassing station; therefore, there are a lot of holes that need to be made as seen in Figures 11 and 12 on page 23.

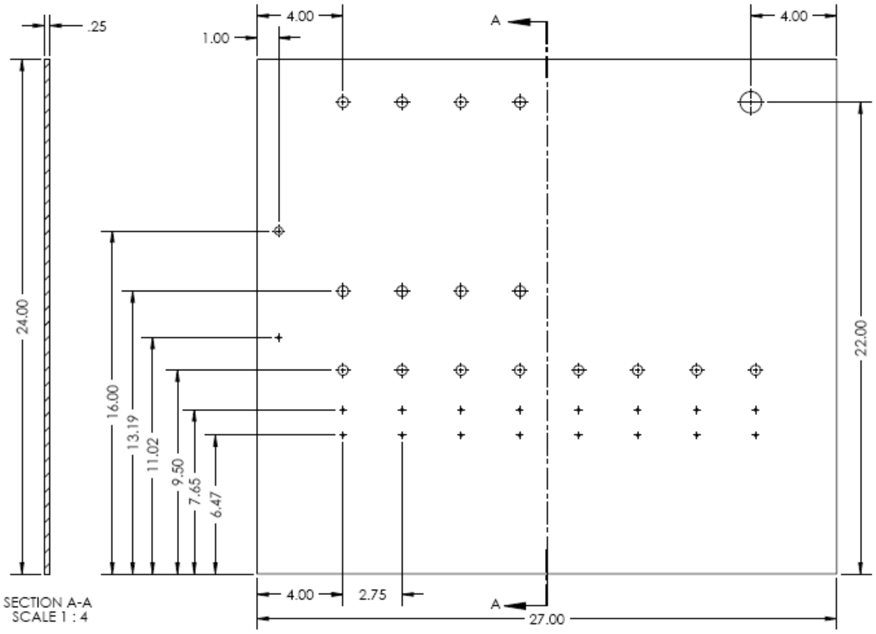


Figure 11: Spacing dimensions of the Plexiglas backboard

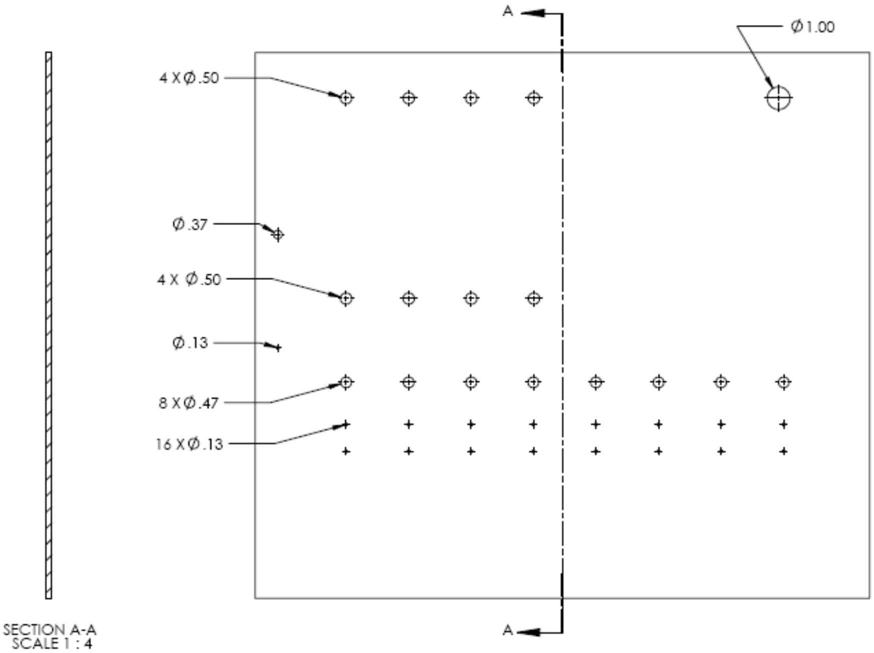


Figure 12: Diameter dimensions of the holes in Plexiglas backboard

The two main materials we considered for the backboard are plywood and Plexiglas. If the backboard is made out of plywood we would need to use the drill press to make the holes. This is a very labor intensive process and due to the large dimensions of the backboard it might not be feasible to use the drill press. Using Plexiglas for the backboard simplifies the machining. We would use a laser cutter and make a path for the laser in BobCAD. After a recent meeting with our sponsor we learned that they are keen on using a keg board for the backboard of the gassing station because all of the instrumentation can be zip tied to the keg board. Also, if the gassing station setup changes in the future our sponsors will not need to drill new holes for the equipment mounted on the backboard.

Copper Column The 0.33" diameter of copper column was chosen in order to have a tight connection with Viton tubing. We chose to purchase 3/8" diameter Viton tubing with an inner diameter of 0.31". To eliminate gas leaks the Viton tubing needs to be stretched over the glass and tightened with a hose clamp. Viton tubing was chosen based on the specifications table provided by Cole Parmer. The tubing that we connect to the copper column needs to withstand temperatures up to 150°C. The tubing also needs to have low permeability to gases, so as to keep the original gas mixture concentration. The most important permeability coefficient is for oxygen. Viton tubing has one of the lowest permeability coefficients for oxygen, $15\cdot10^{-10}\,\frac{cm^3\cdot mm}{cm^2\cdot sec\cdot cmHg}$ [20]. In comparison to other tubing materials Viton tubing also has low permeability coefficients for nitrogen and carbon dioxide. We will also try to minimize the lengths of Viton tubing when building the gassing station. We would like to keep the length of Viton tubing less than 15", but this dimension will depend on how well the tubing can bend.

Support Plate for Outlet Tubing Figure 13 shows how our team came up with the dimensions for the support plate. Using Eq. 1, we were able to solve for the width of the plate. The width, *s*, is equal to the diameter of the largest bottle used 5" and the angle is set to 90˚.

$$s = r\theta \qquad \text{[Eq. 1]}$$

Our sponsor wanted the length of the plate to accommodate the 1L bottles but also be built for the most commonly used bottle, 250mL. We took the diameter of these bottles and multiplied it by the number of bottles and added a 1/4" spacing between bottles.

The material selected for the outlet tubing was based on the machining process. Our team designed a curved support plate for the outlet tubing. After researching machining processes that could bend materials, we concluded the 3-Roller Bending Machine was advantageous because of the availability in the machine shop, the because of the low labor and cost. This machine only accepts aluminum with a thickness less than 1/8".

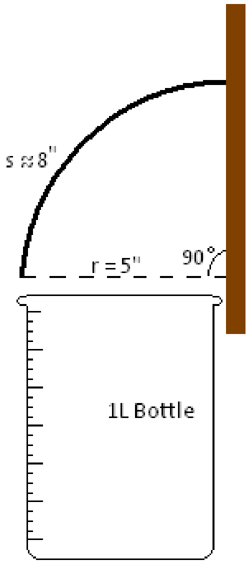


Figure 13: Geometry of support plate for outer tubing

In the days prior to Design Expo, our team learned that the sheet bending machine was sold at an auction a week after Design Review 3. Our team also realized that the curved plate was unnecessary because the bottle holder accommodated the easy insertion of syringes. Therefore, this component will not be in our final design.

Bottle Holder The first parameter considered when analyzing the bottle holder was dimensions. It had to accommodate eight 1L Pyrex® Round Wide-Mouth Media Storage Bottles. The height of the smallest bottle, 250mL, was also measured for accommodation. To determine whether the concept would work, a three-dimensional mock-up was constructed out of cardboard, for the container and rubber hosing, for the wedges, purchased at Home Depot. The sizes of the support flanges in the mock up were also tested by trial and error to optimize support of the range of bottle sizes.

The bottle holder apparatus is composed of two components: the housing and the support “flanges”. To maximize performance, our team decided to choose the material that was best suited for this application. Selection of material for the holder and “flanges” was narrowed down using the Granta CES program based on several parameters (see Appendix O and Appendix Q for complete bottle holder material selection report). The key parameters for both components are stiffness of materials. The first step of determining material properties was by calculating the forces associated with the bottle weight. Our team measured the mass of one bottle with the liquid mixture. To find the desired material constant, we measured the deflection of the mock-up. The equations for the force and deformation are shown below in Eq. 2 and 3. We did a series of calculations to determine the allowable stiffness. We inputted the information to the CES program and were left with a long list of materials that could be used.

$$F = mg = (1.326\ \text{kg})(9.8\text{m/s}^2) \approx 13\ \text{N} \quad \text{[Eq.2]}$$

$$k = \frac{F}{\delta} \quad \text{[Eq. 3]}$$

To continue narrowing down our list, the machining process needed to be taken into account. Drilling holes into a hollow three-dimensional shape and low labor intensity were the criteria that narrowed the search to three allowable processes: laser machining, ultrasonic machining, and electro-chemical machining. Of the three, laser machining was favorable because of the availability of the laser cutter in the machine shop and time left until the deadline. See Appendix S for a detailed description of the manufacturing process selection. The machine only allows shaping of Plexiglas polymer, which narrowed down selection of material. Our team reviewed the stiffness and cost of Plexiglas and confirmed it fit the requirements.

After selecting the material that was necessary for creating the housing, the material that could be allowed for the support “flanges” was made considerably easier. With Plexiglas, the support material would have to be glued to the Plexiglas. We were skeptical using the Granta CES program for selecting a material that would work because the program does not include rubber, which is a material our team was keen on looking into. Further consultation was needed to select a material that would work best with the glue that adheres to Plexiglas. Foam was recommended by Robert Coury, Senior Engineering Technician, at the University Mechanical Engineering & Applied Mechanics Department. We went back to using the CES program and after inputting the stiffness we found polyethylene foam would in fact word.

Selecting Plexiglas and polyethylene foam led to minor changes in the final design of the bottle holder; the redesign is shown below in Figure 14. The design of the box would be five individual pieces of Plexiglas glued together to form an open box. Also, the design of the bottle holder would be split into two boxes that would each hold four bottles. This was done because the laser cutter machine will not work with Plexiglas longer than 32" in length which is smaller than the length of the initial design we had in mind. The polyethylene foam would be cut in a square and glued on top of the Plexiglas. A hole would be punched in the center of the square and using a ruler and an exacto knife lines would be cut to create a large opening for bottles.

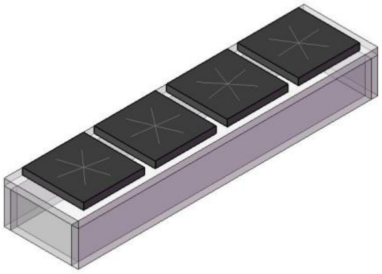


Figure 14: Redesigned bottle holder for gassing station

Methane Meter

Ballast Bottle Set Pressure We chose the set pressure for the ballast bottle to be 1kPa by analyzing Henry's Law, which describes how the liquid-phase solubility of a gas will increase linearly with the pressure of the headspace gas in the reactor bottle. We do not want to affect the reaction equilibrium of the culture in an aqueous solution during the experiment, thus we will want to minimize any changes of the gas concentrations in the culture solution.

Henry's Law states that $e^{p} = e^{kc}$, where p is the partial pressure of the solute above the solution, c is the concentration of the solute in the solution, and k is the Henry's Law constant. By taking the natural logarithm of each side, the equation becomes linear, and we can see that the concentration of the solute in the solution varies linearly with the partial pressure of the gas, $c = \frac{1}{k}p$. The total pressure in the reactor bottle headspace is equal to the sum of all the partial pressures, $P_{tot} = p_{N_2} + p_{H_2} + p_{CO_2} + p_{Ar}$, if the total pressure increases, the partial pressures of the gas will increase linearly along with the concentration of the solute in the solution.

Since the liquid-phase solubility of the headspace gases increases linearly with the headspace pressure we need to keep the headspace pressure as close to atmospheric as possible. As the smallest range of pressure transducers measures from 1 to 2kPa, see Table 6 on page 28, we chose the set pressure to be a simple value of 1kPa, which is just slightly above atmospheric pressure but large enough to be detected with low-cost pressure transducers.

Ballast Bottle Volume An advantage of using a ballast bottle in the methane meter design is that by varying the size of the ballast bottle, the system can accommodate a wide range of flow rates. For an estimated volumetric flow rate of 7SLPD, provided by Dr. Raskin, we recommend a ballast bottle of 250mL. The correct ballast bottle size can be chosen using Table 5 on page 27 and Eq. 4 below. To choose the ballast bottle size, first you estimate an expected volume flow rate of methane and then choose a ballast bottle size which will produce data points at the desired time interval.

We derived Eq. 4 in order to find the time required for the bottle to reach the set pressure of 1kPa, where P_g is the set pressure (measured as a gauge pressure), $\forall_{\mathrm{b}}$ is the volume of the bottle, R is the gas constant for methane, T_{amb} is the temperature of the system and $\dot{m}$ is the mass flow rate of methane. The derivation using Reynold's transport equation for a fixed control volume can be found in Appendix I.

$$\frac{P_g \forall_{\mathrm{b}}}{R T_{amb}\ \dot{m}} = t \qquad \text{[Eq. 4]}$$

We used constant values of P = 1kPa, R = 0.5183 kJ/(kg·K), and T_{amb} = 298 K. For $\forall_b$ we converted the bottle volume from milliliters to cubic meters, and for $\dot{m}$ we assumed the density was constant at ρ = 0.717 kg/m^3 and that the change in density due to the increased pressure of 1kPa was negligible. To determine the range of flow rates which we could measure with different sized ballast bottles, we calculated the time to reach the set pressure for several different volumetric flow rates and three different standard ballast bottle sizes. We started by assuming a bottle size of 250mL and calculated the time required to reach the set pressure for a range of flow rates, Table 5 on page 27.

Ballast Volume (mL)	Volume Flow Rate of Methane (SLPD)	Time (sec)
100 mL	0.1	780
	0.5	156
	1	78
	3	26
	7	11
	10	8
	15	5
250 mL	0.1	1950
	0.5	390
	1	195
	3	65
	7	28
	10	20
	15	13
400 mL	0.1	3121
	0.5	624
	1	312
	3	104
	7	45
	10	31
	15	21

Table 5: Estimated time to reach set pressure for 100, 250, and 400mL ballast bottle

Table 5 shows that the methane metering system is capable of tracking methane throughout a range of flow rates from 0.1 to 15SLPD. For the lower end of 0.1SLPD, we recommend using a ballast bottle of a 100mL or smaller, which will yield data points every 780sec, or 13min. For higher gas flow rates up to or greater than 15SLPD, we recommend using a ballast bottle of 250mL or larger as the time to reach set pressure at larger flow rates decreases to less than 10 seconds for the ballast bottle.

Pressure Transducer We chose pressure transducers by comparing three models which could measure a very small pressure range. The three models were Omega's PX139, PX164, and PX309. We have recommended that our sponsor compare the PX139 and PX 164 pressure transducers in two methane meter prototypes. The PX139 and PX164 are both low-cost transducers which connect to a circuit board whereas the PX309 is an industrial-quality transducer. In addition to being a more durable component, the PX309 has a higher price because it is made of stainless steel. Even though the PX309 is much more expensive, its fundamental characteristics do not differ much from the circuit board type transducers, as shown in Table 6 on page 28.

Model	Price ($)	Pressure Range (kPa)	Sensor Material	Output	Excitation (VDC)	Temp Compensation (°C)	Line & Hysteresis (% FS)
PX139	85	0 - 2.1	silicon	0.25-4.24 Vdc	5	0-50	.5
PX164	145	0 - 1.3	silicon	1.00-6.00 Vdc	8	5-45	.25
PX309	300	0- 6.9	S.S.	100 mV	10	0-50	.25

Table 6: Comparison of pressure transducers

The pressure range of PX139 and PX164 are much more suitable for our set pressure of 1kPa and their output is automatically amplified to Volts instead of being recorded in milliVolts, which would require a signal conditioner. The temperature compensation for the low cost transducers is the same as that of the industrial transducer and the line and hysteresis is less than 1% of full scale for all models. The line and hysteresis determines how fast a pressure transducer responds to the pressure change.

Since there is still a large price difference between PX139 and PX164, we will recommend constructing two methane meter prototypes, each for one reactor bottle, to compare the two transducers. Experiments could then be done to determine if the PX164 shows any advantages over the PX139.

2-Way Solenoid Valve The purpose of a nominally open 2-way solenoid valve is to vent the produced methane when the set pressure is reached. The solenoid valve will remain closed as the system pressurizes. Once the set pressure is reached, LabVIEW® will open the solenoid valve for 0.5sec allowing the gases in the pressurized ballast bottle and head space to flow to the fume hood. This will return the pressure of the ballast bottle and headspace to atmospheric.

After researching several available products from Cole Parmer, McMaster-Carr, Parker, Omega and Asco we determined that there is not much variation in the solenoid valve characteristics or prices. We decided to choose a valve offered by Omega, the supplier of previously chosen pressure transducers. Since methane is a flammable gas, we chose Omega's explosion-proof model, SV-326, with a 12V direct current input.

Room Arrangement Placement of the methane meter within the lab room is determined by minimizing the routing of vented methane to the fume hood, as it is a toxic gas. We have chosen to locate the methane meter to the left of the fume hood, as can be seen in Figure 15.

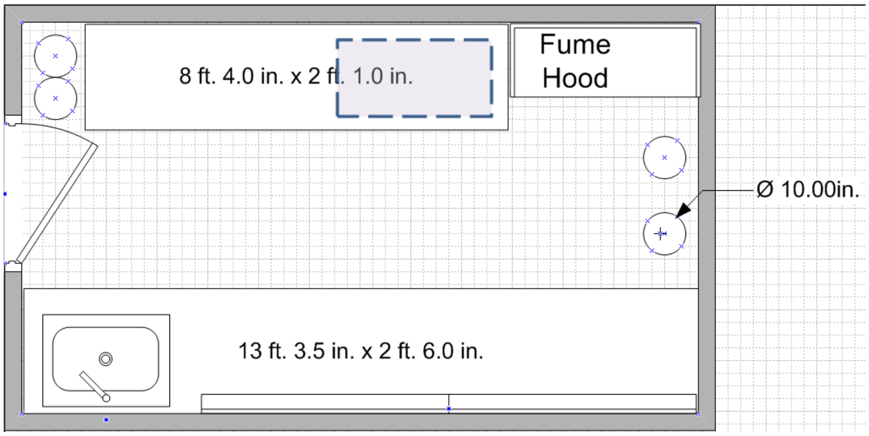


Figure 15: Placement of the methane meter prototype in Lab 18 in EWRE

Tubing Size and Material The nozzles on the pressure transducers have a 0.2" diameter; therefore, we will use 3/16" outer diameter tubing for the methane meter. We have chosen nylon as the tubing material because it has a low oxygen permeability coefficient similar to that of Viton tubing. However, nylon tubing is cheaper because it can withstand lower temperature ranges from 10 to 65°C. Even though the reactor bottles will be in a controlled temperature environment of potentially 65°C, this should not affect the tubing as it is not in direct contact with the temperature regulator.

FINAL DESIGN DESCRIPTION

Gassing Station

Setup The final design of the gassing station is shown in the flow diagram of Figure 16. All fittings used in the gassing station are brass Swagelok fittings, connecting to copper tubing, unless stated otherwise.

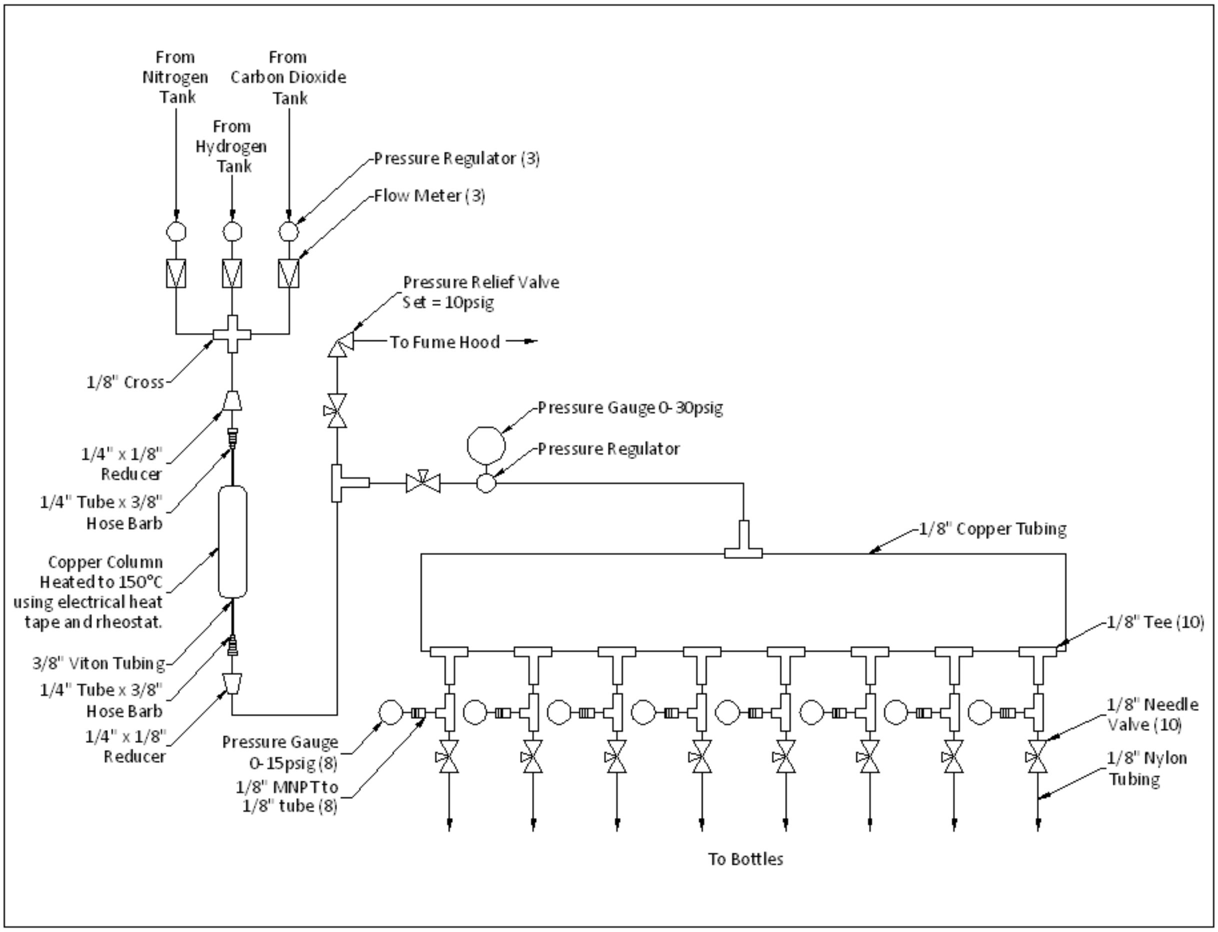


Figure 16: Flow diagram of final gassing station design

Three different gases, nitrogen, hydrogen, and carbon dioxide will flow from the regulators on the large gas cylinders through 1/4" copper tubing. The three gases will enter the station through three flow meters with flow control knobs. These flow meters allow for the user to set different flow rates for the gases which will create different gas mixtures. The copper tubing will be reduced from 1/4" to 1/8" just before entering the flow meters. Upon exiting the flow meters, a cross will be used to combine the three streams into one mixed gas stream.

From the 1/8" copper tubing the gas will flow into a 1/8" to 1/4" expander, then into a 1/4" to 3/8" hose barb. The hose barb will be connected to a 7" length of 3/8" Viton tubing, which connects to the bottom inlet and the same tubing length and size will be connected to the top outlet of the heated glass copper column. The copper column will be heated to 150°C using heat tape and a Rheostat. After the outlet from the copper column the Viton tubing is connected to a 3/8" to a 1/4" hose barb and then to a 1/4" to 1/8" reducer.

This single gas line is then split using a tee, where one line is routed first through a needle valve, then to a pressure relief valve set at 10psig and the to the fume hood. The pressure relief valve is to protect the copper column and bottles from over pressuring (a full hazard-based risk analysis for the gassing station can be found in Appendix R). The other line splitting off at the tee also travels through a needle valve, then to a panel mount pressure regulator with a pressure gauge range of 0 to 30psig. This regulator allows the user to adjust the overall pressure of the mixed gas. The line coming out of the pressure regulator is then split using a tee, where the two lines are symmetrically routed to each end of the nozzle row.

The nozzle row is the assembly of eight tees all lined next to each other. The flow enters the nozzle row at each end to provide equal flow to outlet tubing. The eight tees are then individually connected to a pressure gauge and then a needle valve for outlet flow regulation so the user can read the pressure at each nozzle. If the pressures differ between nozzles, then there is not an equal flow rate and the needle valves can then be used for flow regulation. Finally, nylon tubing is connected after the pressure gauges and routed out the front side of the gassing station to be connected to syringes for filling bottles with the gas mixture. The complete gassing station bill of materials can be found in Appendix J. Also, a Design for Assembly analysis was performed on the number of assembly steps for the gassing station, which can be found in Appendix P.

Function of gassing station The two main functions of the gassing station are to create different gas mixtures and to evenly distribute the mixture to eight bottles. The gassing station will be able to create various gas mixtures by having the ability to individually regulate each gas as it enters the four flow meters at the beginning of the flow. The gas mixture will be evenly distributed to eight bottles because the user has the ability to control the flow rate of each individual nozzle, ensuring that all of the flows are equal.

Methane Meter

Setup The final design of the methane meter is shown in the flow diagram of Figure 17 on page 32. Two 60mL syringes will be inserted into the reactor bottle. One of the syringes will be connected to a pressure relief valve and set to release at 0.3psig. The other syringe will contain 50mL of potassium hydroxide and 10mL of desiccant. The syringe with potassium hydroxide and desiccant will be connected to 3/16" outer diameter nylon tubing, approximately 6" in length. This nylon tubing will be connected to a 60mL syringe which is inserted into the ballast bottle. Another 60mL syringe will be inserted into the ballast bottle and will be connected to approximately 6" of 3/16" outer diameter tubing. The tubing connects to a tee that splits the line and routes it to the gauge pressure port of the pressure transducer and to the 2-way solenoid valve. The pressure transducer will be connected to the data acquisition card with a standard connection fitting provided by Omega and powered by a 12VDC power supply. The data acquisition card is connected to the computer and will interface with the LabVIEW® program. A hose barb of 1/4" NPT by 3/16" will connect the line to the 2-way solenoid valve. All tubing connections to syringes and hose barbs will be secured with zip ties. The other end of the 2-way solenoid valve will be routed to the fume hood. The 12VDC solenoid valve power supply is connected to the computer. The complete bill of materials for the methane meter final design can be found in Appendix K, with the exception of a specified pressure transducer, which will be selected after the two prototypes are tested. Finally, a Design for Assembly analysis was also performed on the methane meter to analyze the number of assembly steps for the methane meter. The analysis can be found in Appendix P.

Description of Flow The gas flow will begin in the reactor bottle where both methane and carbon dioxide will be produced from the anaerobic reaction. There will be no flow during normal operation through the pressure relief syringe inserted in the reactor bottle. The pressure relief line will protect the reactor bottle from over pressuring if moisture blocks flow through the syringe that leads to the ballast bottle. This pressure relief also protects the entire reactor and ballast bottle system if LabVIEW® malfunctions keeping the solenoid valve energized and not relieving the system at a pressure of 1kPa. A full hazard-based risk assessment for the gassing station, including pressure relieving risk reductions, can be found in Appendix R.

As gas is produced by the reaction, the slight increase in pressure within the reactor bottle will force it through the 60mL syringe where the carbon dioxide will be absorbed by the potassium hydroxide pellets. Also, any water vapor will be absorbed by the desiccant, leaving methane gas to flow. The methane will then begin to fill the ballast bottle. As the reaction continues, the methane gas will begin to pressurize the entire gas volume of the reactor and methane meter system. Once this pressure reaches 1kPa, LabVIEW® will be programmed to open the 2-way solenoid valve for 0.5sec, which we assumed to be sufficient to allow the entire system to return to atmospheric pressure (see page 35 for validation of valve opening time). Once the valve closes, the system cycle of pressurizing, sensing set pressure, actuating the solenoid valve and venting methane gas will be repeated.

We chose a nominally open solenoid valve to protect the entire reactor and ballast bottle system in case of a power failure. If the solenoid valve is de-energized, the valve will automatically open and continuously release the produced gas to the fume hood instead of allowing the pressure to build up.

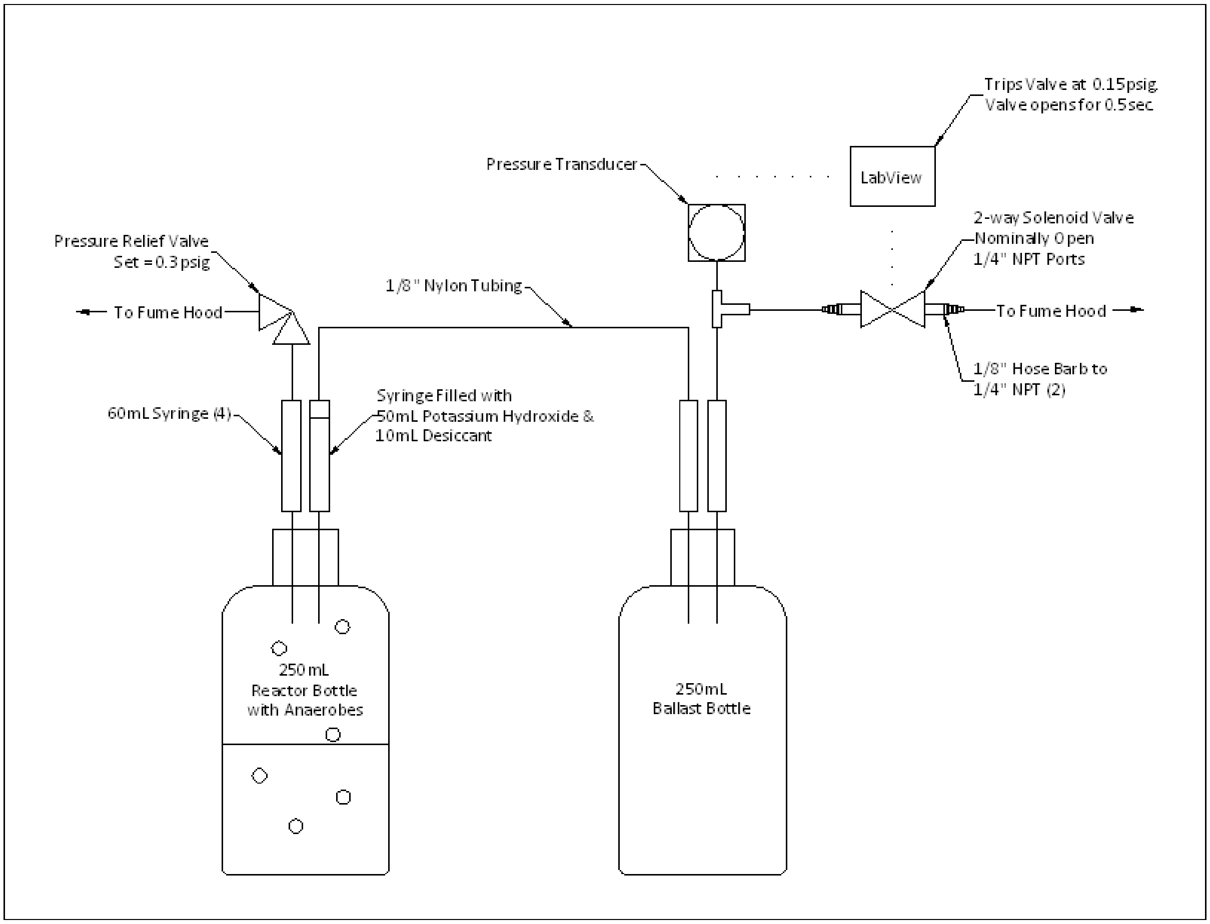


Figure 17: Final Flow Diagram of Methane Metering System

Methane Production Calculation To determine the amount of gas produced, we will first use the ideal gas law, assuming that methane will behave as an ideal gas. By holding constant the volume of the system, *Vc*, the gas constant, *R*, and temperature, *T*, we see from the ideal gas law that if we know the change in pressure of the system, 1kPa, then we will know the number of moles, Δn, that left the system, Eq. 5 below.

$$\Delta n = \frac{\Delta P V_s}{RT} \qquad \text{[Eq. 5]}$$

Once we know the number of moles that have left the system, we can determine the volume of methane gas during each cycling of the 2-way valve, ΔV_c, by multiplying the number of moles Δn by the constant ratio of 22.4L/mol of an ideal gas at standard temperature and pressure.

$$\Delta V_c = 22.4 \Delta n \qquad \text{[Eq. 6]}$$

We can then sum the volume of gas released throughout the experiment and divide by the total time of the experiment to find the gas flow rate, v, Eq. 7.

$$v = \frac{\sum \Delta V_{c,i}}{\Delta t} \qquad \text{[Eq.7]}$$

The volume that an ideal gas occupies at standard temperature and pressure is 22.4L/mol of gas. However, if the temperature or pressure varies by only one degree of STP, 273.15K and 101.325kPa, the constant varies by a considerable amount, of approximately 0.2L/mol for only a single unit difference in temperature or pressure. Thus, we recommend that the temperature and pressure of the room are noted during the experiment and Eq. 6 is used in the form of Eq. 8 on page 34, where ΔV_c is the volume of gas released per cycle, $\bar{R}$ is the universal gas constant, T_{room} is the temperature of the room during the experiment, P_{room} is the absolute pressure of the room during the experiment and Δn is the number of moles released from the solenoid valve.

$$\Delta V_c = \frac{\bar{R}T_{room}}{P_{room}}\Delta n \qquad \text{[Eq. 8]}$$

PROTOTYPE DESCRIPTION

Gassing Station We will not be building a prototype of the gassing station because we are redesigning a gassing station that was built in a lab at the University of Illinois Urbana Champagne. All construction of the gassing station will be for the final product that will be used in Dr. Raskin's lab.

Methane Meter For the methane meter, we have recommended building two prototype systems which will be identical except for the pressure transducers. The two prototype designs will be used to compare their performance. After comparing performance and price, the methane meter design can be scaled to 16 bottles to meet sponsor requirements.

The bill of materials for the two prototypes can be found in Appendix L. We suggest using existing parts in the lab for these prototypes. Labs are equipped with 250mL bottles, rubber stoppers and syringes that can be used to build the prototype. Spare tubing might be available in the lab, but it can also be purchased at a local hardware store. Finally, we recommend borrowing a spare data acquisition card for the prototype testing, as this is the most expensive component of the methane meter.

With the intent of using spare lab equipment for the methane meter prototypes, the major costs will come only from purchasing two pressure transducers, PX139 and PX164 and the 2-way solenoid valve, SV-326.

INITIAL FABRICATION PLAN

Both components of the gassing station require manufacturing: (1) the housing and support flanges in the bottle holder and (2) the support plate of the gassing station. For a detailed fabrication plan for the different components, see Appendix M.

For the bottle container housing, the manufacturing process is simple. The 3D drawing our team has already designed in SolidWorks® will be converted to be compatible on BobCAD®, see Figure 14 on page 26. This must be done for the file to be uploaded for use on the laser cutter. The support flanges will be constructed from polyethylene foam roll stock. Using the band saw, our team will be able to cut the stock to our desired dimensions (6.5" x 6.5" x 0.7") and make eight units for the eight holes. With the center coinciding with the midpoint of each line, our team will cut six 4" long slits in the material with an angle of 60˚ between each cut. The center of the circular cutout will be aligned with the center of the square foam and the overlap will be glued using the Plexiglas adhesive used in the Machine Shop.

VALIDATION PLAN

Gassing Station For the gassing station we want to verify that splitting the gas mixture flow and sending the flow into each end of the row of nozzles will create equal flow out all eight nozzles. We also want to verify our assumption that the pressure loss due to fluid flow between the ends of the nozzle row and the center will be negligible. We will verify that these assumptions are correct by observing all eight pressure gauge readings while gas is flowing through the station. If the pressure loss due to fluid flow between the ends of the nozzle row and the center is indeed not negligible, it will be indicated by a lower pressure reading on the center nozzles. If this is the case, we have installed needle valves on each nozzle line to allow the user to regulate the flow of each nozzle so that all pressure gauges show equal readings and thus all nozzles exhibit uniform flow.

Methane Meter

Opening Time of 2-way Solenoid Valve With the help of Mr. Guest, we arbitrarily chose a venting time of 0.5sec. As the ballast bottle will be pressurized to only slightly above atmospheric pressure, 1kPa, we will assume that 0.5sec is sufficient time for the pressure of the ballast bottle to return to atmospheric pressure. Once the system is assembled, this assumption can be tested by recording the pressure over time in LabVIEW® during an experiment. By tracking the pressure over time, one can verify that when the valve opens for 0.5 seconds and the ballast bottle pressure returns to atmospheric. If it does not, then the time set to open can be increased from 0.5sec in LabVIEW®. The verification procedure can then be repeated several times to ensure consistent results.

Time Between Data Points We recommend validating our ballast bottle sizing calculations by verifying that the times we calculated for the ballast system to reach 1kPa are accurate. Once the methane meter prototypes are assembled and connected to the LabVIEW® system, experiments can be run using bottles of 100, 250, and 400mL. Once the data points for the time it takes to pressurize the system are collected, one can check that they match the calculated values in Table 5 on page 27. The experiment should then be repeated several times to ensure consistent results.

Accuracy of Flow Rate Measurements We recommend using a syringe pump to validate the accuracy of flow rate measurements for each prototype (one with the PX-139 transducer and the other with the PX-164). One will attach the desired number of syringes to the syringe pump, then connect them to a single inlet line which will be connected to the reactor bottle with a syringe. The reactor bottle should be set up with water to the level that the cultures will normally fill to model the anaerobic system as closely as possible. Then LabView system should be set to record measurements, and the pump will be run to simulate a mock experiment. The pump should be set to disengage the syringes at a specified rate, which allows you to know the exact flow rate flowing through the system. The flow rate determined in LabView can then be compared to the known flowrate from the syringe pump to determine the accuracy of the flow rate measurements, and which pressure transducer produces better measurements. The procedure can then be repeated several times to verify the comparison between the pressure transducers.

Accuracy of Methane Production Measurements Once a pressure transducer is chosen experiments can be run to test the accuracy of the methane production measurements. This can be done by feeding the anaerobes with a food, such as glucose, where one can predict an amount of gas produced based on the chemical reactions. The results from the experiment can then be compared to the predicted rates. The procedure can then be repeated several times to ensure consistent results.

RECOMMENDED FUTURE STEPS

Gassing Station The remaining steps for the gassing station include ordering remaining parts, assembling parts which have not yet arrived, installing the gassing station, and testing the final product.

The remaining parts which need to be ordered for the gassing station are the rheostat and heat tape for the copper column. These parts are relatively expensive, and it is possible that spares could be found in the lab. Our sponsor can decide whether she wishes to purchase a brand new rheostat and heat tape, or use existing equipment. Also, the two hose barbs, Swagelok part number B-6-HC-A-401, which connect the 3/8" Viton tubing to the 1/4" x 1/8" reducer still need to be ordered. Finally, we designed the purging lines for all 8 bottles to be connected to a nylon manifold which will be routed to the fume hood. These parts will also need to be ordered through Cole Parmer.

Once the remaining parts are added to the gassing station, it can then be installed into the lab room. Three lines of copper tubing, of 1/4" diameter, will need to be routed on the wall around the lab room from the location of the large gas cylinders to the flow meter inlets on the gassing station. The gassing station will also need to be installed in the lab room by using an angle bracket bolted to the underside of the metal cabinets, just across from the fume hood. Finally, the gas purging lines will need to be routed from the outlet of the manifold along the wall to the fume hood.

Finally, the gas cylinders can be connected and the gassing station can be tested. Testing should include verifying that there is equal flow through all eight outlets by equalizing all pressure readings using the regulating needle valves. If there appears to be no flow through any of the lines, the small copper pieces should be checked for any crimping or blockage that might have occurred. Also, the tubing in the back of the board should be observed for any possibly sources of gas loss. If there seems to be significant gas loss near any of the threaded fittings, Teflon® tape can be applied to the threads to achieve a better seal.

Methane Meter The next step in the development of the methane meter is to construct two prototypes which can be used to compare the performance of two pressure transducers, the PX-139 and PX-164 from Omega. The best performing transducer based on cost and accuracy of results can then be used to expand the design to the final design size for 16 separate reactor bottles..

To construct the prototype methane meters we recommend using spare lab equipment including 250mL bottles, rubber stoppers, syringes, and nylon tubing. This will keep the costs of the prototypes to a minimum. The instrumentation and some of the fittings will still need to be ordered, however, and the bill of materials for the prototype can be found in Appendix L.

Also, we recommend that our sponsor borrows an existing data acquisition card for the prototype, as this component is very expensive to purchase. We have already asked SLUG, the Student LabVIEW® Users Group if they have spare data acquisition cards, but they responded that there were none available. Per our section advisor's recommendation, SLUG should have extra data acquisition cards for student use.

For testing we recommend that our sponsor follows the validation plan outlined on page 35. This plan includes validation for the opening time of the 2-way solenoid valve, time between data points, accuracy of flow rate measurements, and accuracy of methane production measurements.

CONCLUSIONS

In the time since the first design review, our team has developed several concepts for the gassing station, methane meter, and temperature regulator. After creating selection matrices for each part which required design, we chose final designs which best met our selection criteria. For the gassing station, we designed concepts for the outlet tubing setup and a bottle holder. The final design orients the syringes vertically over the bottle, eliminating any forces that would cause the bottles to tip. The design of the bottle holder design accommodates for various bottle sizes and supports the bottles when the syringes are inserted. Our team decided to use the inline syringe concept for carbon dioxide scrubbing as it allows for changing the scrubbing chemical during an experiment. Finally, for the methane meter, we recommend using a ballast bottle with a pressure transducer and 2-way solenoid valve to measure the methane. This system will work by releasing specific volumes of methane through the solenoid valve after the ballast bottle reaches a specific pressure. Our team recommends programming LabVIEW® to measure how often the solenoid valve is actuated. Finally, for the last component of our project, our sponsor has agreed to our recommendation to purchase a water bath with stirring capabilities, but has postponed the purchase due to modifications in the methane meter objective.

REFERENCES

[1] “Natural Gas Facts,” American Petroleum Institute., [Online] Available: http://www.naturalgasfacts.org/factsheets/current_situation.html [2008, Jan 24].

[2] Wise, D.L., 1981., Fuel Gas Production From Biomass., Vol I. Boca Raton: CRC Press.

[3] Price, E. C., and Cheremisinoff, P. N., 1981., Biogas: Production and Utilization., Ann Arbor: Ann Arbor Science.

[4] “Anaerobic digestion,” Biomass Technology Group., [Online], Available: http://www.btgworld.com/technologies/anaerobic-digestion.html [2008, Jan 26].

[5] Chae K.J., Jang A., Yim S.K., and Kim, I.S., 2008., “The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure,” Bioresource Technology., 99: 1–6.

[6] Morel, E., Tartakovsky, B., Perrier, M., and Guiot, S., 2007., "Temperature-Based Control of an Anaerobic Reactor Using a Multi-Model Observer-Based Estimator," Environ. Sci. Technol., 41: 978-983.

[7] Louleh, Z., Cabassud, M., and Le Lann M-V., 1999., "A new strategy for temperature control of batch reactors: experimental application," Chem Eng J., 75: 11-20.

[8] “Method and apparatus for cryogenic separation of carbon dioxide and other acid gases from CH4,” freepatentsonline., [Online], Available: http://www.freepatentsonline.com/4923493.html [2008, Feb 20].

[9] Robeson, L. M., 1999., “Polymer membranes for gas separation,” Current Opinion in Solid State and Materials Science., 4: 549–552.

[10] Cooney M., Maynard N., Cannizzaro C., Harris D., 2006, “On-line Measurement of Gas Production Rates”, Biotechnol. Prog., **22**(5), pp. 1456-1460.

[11] “Potassium Hydroxide,” Cole-Parmer., [Online], Available: http://www.coleparmer.com/catalog/product_index.asp?cls=23410 [2008, Feb 16].

[12] “Gases, vapors, fumes, dusts, and mists. - 1926.55 App A”, U.S. Department of Labor, Occupational Safety and Health Administration, [Online], Available: http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10629 [2008, Feb 20].

[13] “Influence of high shear on performance and microbial community structure of an anaerobic membrane bioreactor (AnMBR) treating synthetic black water” *Sent via email as draft from Professor Raskin.

[14] “Back to Basics CO_2 Incubator: A Laboratory Staple,” Cole-Parmer., [Online], Available: http://www.coleparmer.com/techinfo/techinfo.asp?htmlfile=CO2-incubator.htm&ID=67 [2008, Feb 13].

[15] “Stable BOD Incubator,” Cole-Parmer., [Online], Available: http://www.coleparmer.com/ catalog/product_view.asp?sku=3906200 [2008, Feb 13].

[16] “Kane Heat Mat w/ Rheostat,” Dog, Cat, Etc., [Online], Available: http://www.dogcatetc. com/ 010kmc-phm36r.html [2008, Feb 17].

[17] “Barnstead Six Place Magnetic Stirring Water Bath, 120V #1286Q,” Barnstead International., [Online], Available: http://www.med1online.com/pc-13824-822-barnstead-six-place-magnetic-stirring-water-bath-120v-1286q.aspx [2008, Feb 17].

[18] “GUIDE TO SAFETY FOR COMPRESSED GAS CYLINDERS” Texas A&M University Safety Manual., [Online], Available: http://engineering.tamu.edu/safety/guidelines/Guide_Comp_Cylinders.pdf [2008, Mar 7].

[19] “Safety and Health Regulations for Construction” U.S. Department of Labor, Occupational Safety and Health Administration., [Online], Available: http://www.osha.gov/pls/oshaweb/ owadisp.show_document?p_table=STANDARDS&p_id=10696 [2008, Mar 10].

[20]” Tubing Selection Guide” Cole-Parmer Technical Library., [Online], Available: http://www. coleparmer.com/techinfo/techinfo.asp?htmlfile=SelectingTubing.htm&ID=700 [2008, Mar 7].

APPENDIX A GASSING STATION CONCEPT GENERATION (OUTLET TUBING)

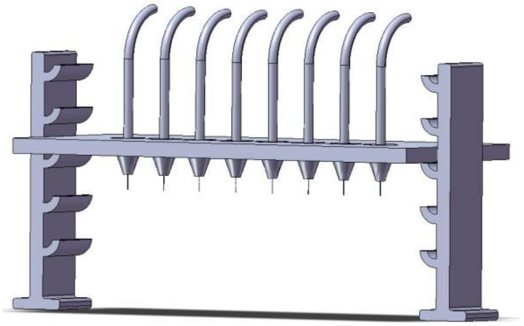


Figure A. 1: Plate design

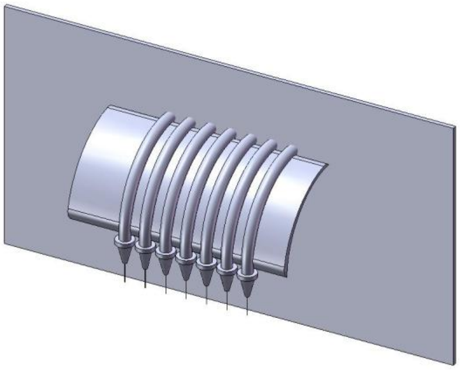


Figure A.4: Curved plate design

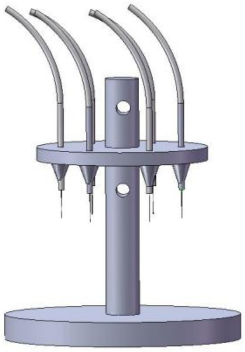


Figure A.2: Lazy Susan design

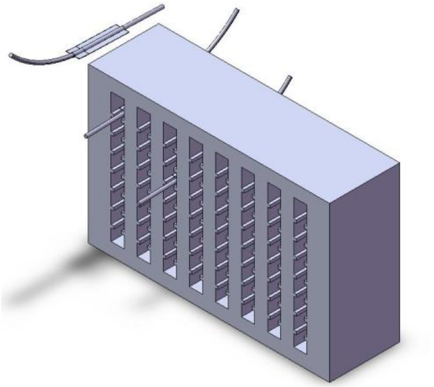


Figure A.5: Slotted design

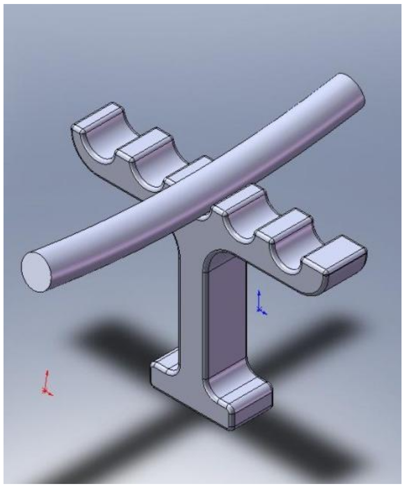


Figure A.3. Menorah design

APPENDIX B GASSING STATION CONCEPT GENERATION (BOTTLE HOLDER)

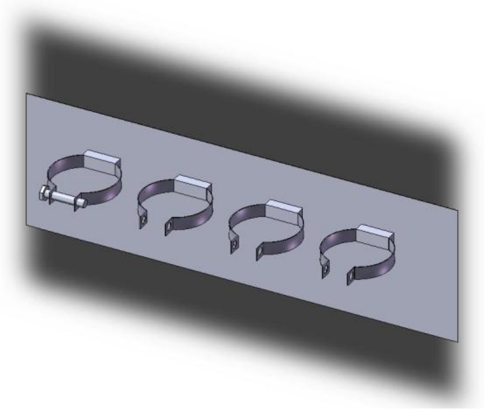


Figure B.1: Hose clamp design

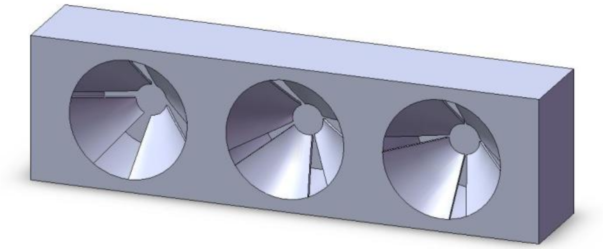


Figure B.2: Cup Holder Design

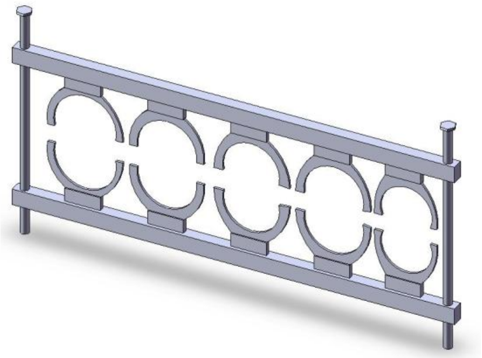


Figure B.3: Clamp Design

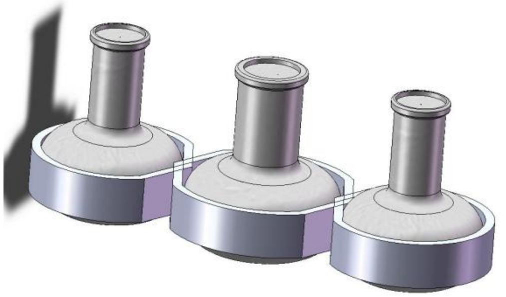


Figure B.4: Rubberband Design

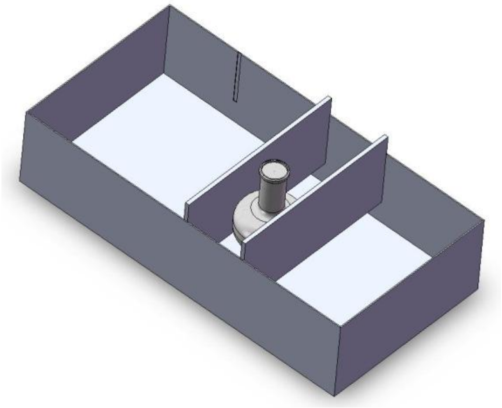


Figure B.5: Slider Design

APPENDIX C TEMPERATURE REGULATOR CONCEPT GENERATION

Capacity		20.3
Temp range		-10 to 60°C
Price		$4,625
Uniformity		±0.5°C
Dimensions	overall	32"W x 70"L x 28-1/2"D
	interior	27"W x 56-1/2"L x 20"D
Power		115 VAC, 60 Hz, 8.9 A

Figure C.1: Cole Parmer StableTemp ® BOD Incubator

Figure C.2: Kane Heat Mat with Rheostat

Specifications

- Made of heavy duty polyethylene
- Heating element is molded in mat
- 110-120 volt A.C.
- Operates efficiently
- Totally safe and durable
- Insulated bottom (no heat loss to floor)
- Easy to install
- Temperature control adjusts temperature down
- Use to warm young puppies or kittens, or an aging animal
- Easy to clean
- Rheostat Included with heat mat
- Price: $113

Specifications

- Bath Dimensions (H x W x D): 7" x 19" x 13" (17.8cm x 48.3cm x 33cm)
- Shipping Weight: 20 lbs. (9 kg)
- Dimensions (H x W x D): 6.7" x 18.4" x 14.7" (17cm x 47cm x 37cm)
- Bath Capacity: 28.4L
- Watts: 1180
- Electrical Hertz: 60
- Stirring Speed (rpm): 50-1200
- Uniformity: ±0.1°C
- Price: $3,454

Figure C.3: Barnstead International 1286 Water Bath Magnetic Stirrer

APPENDIX D METHANE METER CONCEPT GENERATION (CO$_2$ SCRUBBER)

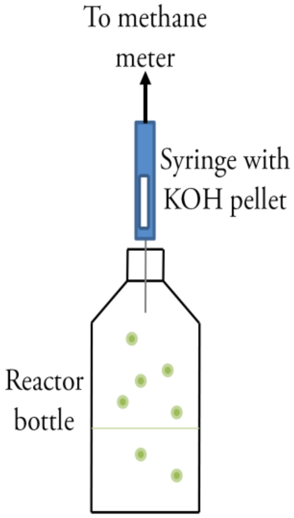


Figure D.1: Inline Syringe Scrubber

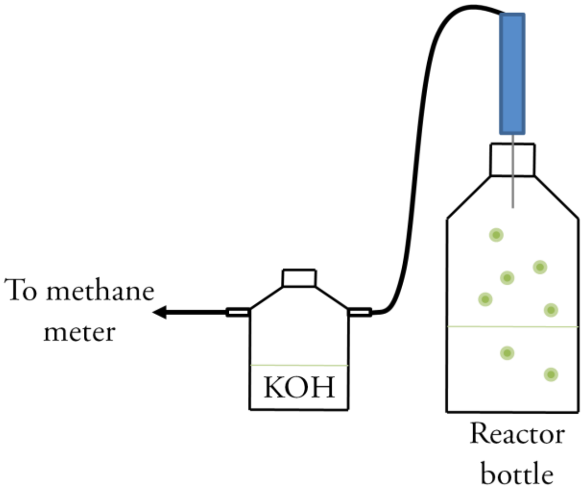


Figure D.2: Inline Bottle Scrubber

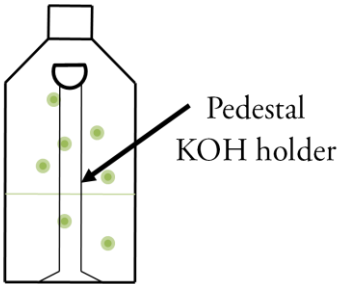


Figure D.3: Pedestal to hold KOH Pellet

APPENDIX E METHANE METER CONCEPT GENERATION (METHANE METERING)

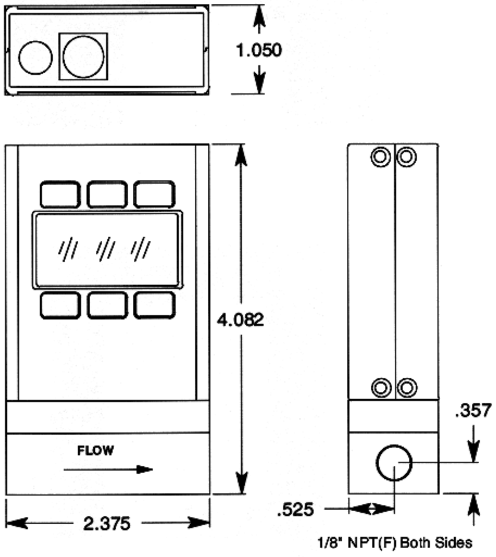


Figure E.1: Low-flow volumetric gas flow meter from DigiFlow Systems, M-5SCCM-D/5M.

	M Meter	V Meter	Units	Sample FS Ranges
Accuracy	±1%	±1%	Full Scale	0.5 (S)CCM
Repeatability	±0.5%	±0.5%	Full Scale	1 (S)CCM
Turndown Ratio	100:1	100:1		2 (S)CCM
Response Time	10	10	Milliseconds	5 (S)CCM
Full Scale Press. Drop	Consult DigiFlow			10 (S)CCM
Temperature Range (Operating)	-10 to +50	-10 to +50	°C	20 (S)CCM
Zero Shift	0.02% / ATM	0.02%	FS/°C/atm	50 (S)CCM
Span Shift	0.02% / ATM	0.02%	FS/°C/atm	100 (S)CCM
Humidity Range	0-100% non-condensing	0-100% non-condensing		200 (S)CCM
Excess Flow Rate	20X	20X	Full Scale	500 (S)CCM
Common-Mode Pressure	125	15	PSIG	1 (S)LPM
Supply Voltage	7 - 30	7 - 30	Vdc	2 (S)LPM
Supply Current	35	30	mA	5 (S)LPM
Voltage Output - Std	0-5 or 0-10	0-5 or 0-10	Vdc	10 (S)LPM
Media	Air, Argon, Nitrogen, Oxygen, Hydrogen, Helium, Carbon Dioxide, Methane, Propane, Carbon Monoxide, Ethane, Nitrous Oxide, Neon, etc.			20 (S)LPM
Connections	10-32 for 50 SCCM & under 1/8" for 50+ SCCM - 20SLPM, 1/4" for 50 & 100 LPM, 1/2" for 250 SLPM 3/4" for 500 to 1000 SLPM		UNF NPTF	50 (S)LPM
Wetted Materials	Anodized AL, 303 & 302 Stainless Steel, Viton®, Silicone RTV, Glass reinforced Nylon			100 (S)LPM 250 (S)LPM 500 (S)LPM 1000 (S)LPM

				1500 (S)LPM
	M Meter	**V Meter**	**Units**	**Sample FS Ranges**
Accuracy	±1%	±1%	Full Scale	0.5 (S)CCM
Repeatability	±0.5%	±0.5%	Full Scale	1 (S)CCM
Turndown Ratio	100:1	100:1		2 (S)CCM
Response Time	10	10	Milliseconds	5 (S)CCM
Full Scale Press. Drop	Consult DigiFlow			10 (S)CCM
Temperature Range (Operating)	-10 to +50	-10 to +50	°C	20 (S)CCM
Zero Shift	0.02% / ATM	0.02%	FS/°C/atm	50 (S)CCM
Span Shift	0.02% / ATM	0.02%	FS/°C/atm	100 (S)CCM
Humidity Range	0-100% non-condensing	0-100% non-condensing		200 (S)CCM
Excess Flow Rate	20X	20X	Full Scale	500 (S)CCM
Common-Mode Pressure	125	15	PSIG	1 (S)LPM
Supply Voltage	7 - 30	7 - 30	Vdc	2 (S)LPM
Supply Current	35	30	mA	5 (S)LPM
Voltage Output - Std	0-5 or 0-10	0-5 or 0-10	Vdc	10 (S)LPM
Media	Air, Argon, Nitrogen, Oxygen, Hydrogen, Helium, Carbon Dioxide, Methane, Propane, Carbon Monoxide, Ethane, Nitrous Oxide, Neon, etc.			20 (S)LPM
Connections	10-32 for 50 SCCM & under 1/8" for 50+ SCCM - 20SLPM, 1/4" for 50 & 100 LPM, 1/2" for 250 SLPM 3/4" for 500 to 1000 SLPM		UNF NPTF	50 (S)LPM
Wetted Materials	Anodized AL, 303 & 302 Stainless Steel, Viton®, Silicone RTV, Glass reinforced Nylon			100 (S)LPM 250 (S)LPM 500 (S)LPM 1000 (S)LPM 1500 (S)LPM

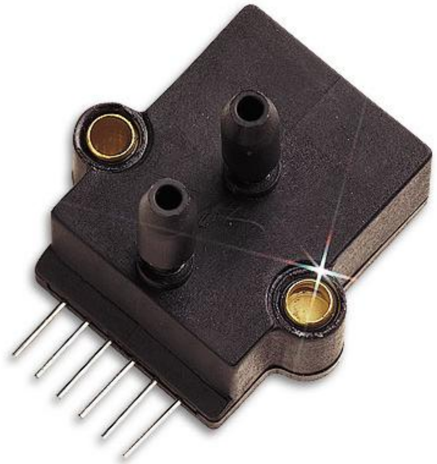


Figure E.2: Silicon pressure sensor with millivolt output from Omega engineering, PX137

SPECIFICATIONS
Excitation: 11 to 30 Vdc
Output: 4 to 20 mA (2 wire)
Accuracy: 0.3% BFSL maximum
(includes linearity, hysteresis, and repeatability)
Total Error Band: 1% FS
(includes temperature effects within compensated temperature range)
Operating Temperature: -40 to 80°C (-40 to 176°F)
Compensated Temperature: -25 to 75°C (-13 to 167°F)
Process Temperature: -40 to 100°C (-40 to 212°F)
1 Year Stability: <0.25% FS
Proof Pressure: 2x FS (750 psig for 500 psig range)
Burst Pressure: 3x FS or 750 psig, whichever is less
Wetted Parts: brass, borosilcate, silicon, RTV, and epoxy
Vibration: 10 g, 55 to 2000 Hz
Shock: 30 g
Process Connection: 1/8 NPT male
Electrical Connection: 0.4 m (18") 24 AWG cable
Weight: 142 g (5 oz.)

Figure E.3: Silicon/brass pressure transducer with 4-20mA output from Omega engineering, PX182B.

SPECIFICATIONS
Excitation: 11 to 30 Vdc
Output: 4 to 20 mA (2 wire)
Accuracy: 0.3% BFSL maximum
(includes linearity, hysteresis, and repeatability)
Total Error Band: 1% FS
(includes temperature effects within compensated temperature range)
Operating Temperature: -40 to 80°C (-40 to 176°F)
Compensated Temperature: -25 to 75°C (-13 to 167°F)
Process Temperature: -40 to 100°C (-40 to 212°F)
1 Year Stability: <0.25% FS
Proof Pressure: 2x FS (750 psig for 500 psig range)
Burst Pressure: 3x FS or 750 psig, whichever is less
Wetted Parts: brass, borosilcate, silicon, RTV, and epoxy
Vibration: 10 g, 55 to 2000 Hz
Shock: 30 g
Process Connection: 1/8 NPT male
Electrical Connection: 0.4 m (18") 24 AWG cable
Weight: 142 g (5 oz.)

SPECIFICATIONS
Mounting Position: Any (preferably with the solenoid system upright)
Max. Ambient Temp.: 54°C (130°F)
Voltage Tolerance: ±10%
Power Consumption (in Warm State):ac: 30 Va/8 W; dc: 8 W in rush;15 VA/8W (hold);dc:8 W

Figure E.4: Omega-flo® 3-way general purpose solenoid valve, ¼"NPT, SV-1415.

APPENDIX F GASSING STATION SELECTION MATRICES

		Plate		Lazy Susan		Menorah		Curved Plate Design		Slotted Design	
Selection Criteria	**Weight**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
Easy to manufacture	0.05	1	0.05	1	0.05	4	0.2	4	0.2	1	0.05
Easy to adjust height	0.17	5	0.85	4	0.68	4	0.68	4	0.68	5	0.85
Low cost	0.05	5	0.25	4	0.2	5	0.25	5	0.25	4	0.2
Minimal setup steps	0.1	3	0.3	4	0.4	4	0.4	5	0.5	3	0.3
Ease of inserting syringes	0.14	2	0.28	2	0.28	5	0.7	5	0.7	5	0.7
Accommodates various bottle sizes	0.16	3	0.48	3	0.48	5	0.8	4	0.64	5	0.8
Large workspace area	0.05	2	0.1	1	0.05	4	0.2	4	0.2	4	0.2
Stability	0.1	5	0.5	4	0.4	3	0.3	5	0.5	5	0.5
Durable	0.04	5	0.2	4	0.16	4	0.16	5	0.2	4	0.16
Minimal moving parts	0.05	4	0.2	4	0.2	4	0.2	5	0.25	5	0.25
Easy to adjust tubing length	0.09	4	0.36	2	0.18	4	0.36	4	0.36	4	0.36
Total Score			3.57		3.08		4.25		4.48		4.37
Rank			4		5		3		1		2

Table F.1: Outlet Tubing Selection Matrix

Selection Criteria	Weight	Hoseclamp		Cup Holder		Clamp		Rubberband		Slider	
		Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Easy to manufacture	0.05	3	0.15	2	0.1	2	0.1	5	0.25	3	0.15
Durable	0.1	4	0.4	4	0.4	4	0.4	2	0.2	5	0.5
Low cost	0.1	5	0.5	4	0.4	4	0.4	5	0.5	5	0.5
Minimal moving parts	0.05	3	0.15	3	0.15	3	0.15	5	0.25	3	0.15
Minimal set up steps	0.1	1	0.1	5	0.5	5	0.5	2	0.2	4	0.4
Bottles can't tip over	0.15	5	0.75	5	0.75	3	0.45	4	0.6	3	0.45
No extra storage space needed	0.1	5	0.5	5	0.5	5	0.5	5	0.5	3	0.3
Fits any bottle diameter	0.2	5	1	5	1	4	0.8	5	1	5	1
Fits any bottle height	0.15	3	0.45	5	0.75	4	0.6	5	0.75	5	0.75
Total Score			4		4.55		3.9		4.25		4.2
Rank			4		1		5		2		3

Table F.2: Bottle Holder Selection Matrix

APPENDIX G TEMPERATURE REGULATOR SELECTION MATRIX

		StableTemp ® BOD Incubator		Heating Pad		Water Bath Shaker		1286 Water Bath Magnetic Stirrer		Homemade Water Bath	
Selection Criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Easy to manufacture	0.11	5	0.55	5	0.55	5	0.55	5	0.55	1	0.11
Temperature accuracy	0.14	5	0.7	4	0.56	5	0.7	5	0.7	4	0.56
Low cost	0.09	1	0.09	3	0.27	5	0.45	1	0.09	3	0.27
Minimal setup	0.08	4	0.32	3	0.24	4	0.32	5	0.4	5	0.4
Accommodation of 8 bottles	0.1	1	0.1	5	0.5	1	0.1	1	0.1	5	0.5
Accommodation of bottle sizes	0.1	5	0.5	2	0.2	5	0.5	5	0.5	5	0.5
Compact unit	0.09	3	0.27	5	0.45	3	0.27	3	0.27	3	0.27
Durable	0.05	5	0.25	3	0.15	5	0.25	5	0.25	4	0.2
Minimal parts	0.03	4	0.12	3	0.09	5	0.15	5	0.15	3	0.09
Energy efficiency (minimize heat loss)	0.05	4	0.2	1	0.05	3	0.15	3	0.15	4	0.2
Does not interfere with tubing	0.1	2	0.2	5	0.5	2	0.2	5	0.5	5	0.5
Accommodate stir bar	0.06	5	0.3	5	0.3	1	0.06	5	0.3	4	0.24
Total Score			3.6		3.86		3.7		3.96		3.84
Rank			5		2		4		1		3

Table G.1: Selection matrix for temperature regulator

APPENDIX H METHANE METER SELECTION MATRICES

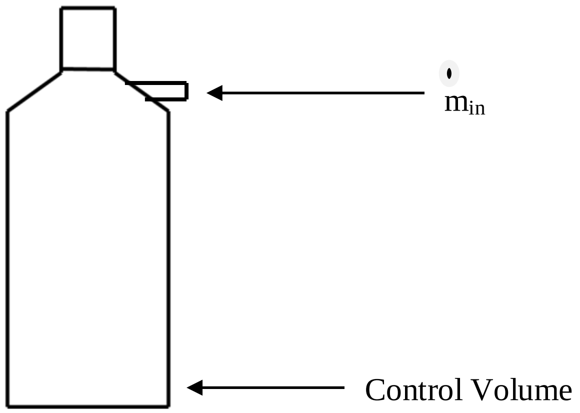
		Inline Syringe Scrubber		Suspended Basket from Challenge		Suspended From Rubber Stopper		Inline Liquid Base Bottle Scrubber		Pedestal	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
No contact culture	0.15	5	0.75	4	0.6	4	0.6	5	0.75	4	0.6
Held Securely	0.05	5	0.25	4	0.2	3	0.15	5	0.25	3	0.15
Easy to manufacture	0.1	5	0.5	5	0.5	3	0.3	5	0.5	1	0.1
Retains stopper sealing ability	0.15	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75
Low Cost	0.05	5	0.25	3	0.15	5	0.25	2	0.1	3	0.15
Easy to set up	0.1	4	0.4	3	0.3	3	0.3	3	0.3	3	0.3
Can set up in glove box	0.05	5	0.25	3	0.15	3	0.15	5	0.25	3	0.15
Durability	0.05	4	0.2	4	0.2	3	0.15	5	0.25	4	0.2
Minimal Parts	0.05	4	0.2	4	0.2	3	0.15	4	0.2	4	0.2
Sufficient Clearance for Syringe	0.1	5	0.5	4	0.4	3	0.3	5	0.5	4	0.4
Allows for changing during experiment	0.1	5	0.5	1	0.1	1	0.1	5	0.5	1	0.1
Scrubbing Efficiency	0.05	4	0.2	3	0.15	4	0.2	5	0.25	3	0.15
Total Score			4.75		3.7		3.4		4.6		3.25
Rank			1		3		4		2		5

Table H.1: CO_2 Scrubber Selection Matrix

Selection Criteria	Weight	Tedlar Bags on Scales		Bottles to capture gas for Pressure Transducer		Webcam to Take pictures of Pressure Gauge		Piston which measures Volume produced		Bubbling Technology	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Low Cost	0.05	3	0.15	1	0.05	5	0.25	2	0.1	1	0.05
Easy to manufacture	0.05	5	0.25	5	0.25	3	0.15	1	0.05	1	0.05
Automated CH4 reading	0.25	5	1.25	5	1.25	1	0.25	3	0.75	2	0.5
Accurate CH4 reading	0.25	4	1	5	1.25	3	0.75	3	0.75	3	0.75
Compact	0.07	1	0.07	4	0.28	3	0.21	3	0.21	4	0.28
Durable	0.06	2	0.12	4	0.24	4	0.24	4	0.24	3	0.18
Minimal Parts	0.02	5	0.1	4	0.08	3	0.06	3	0.06	3	0.06
Proximity to Temp Controller	0.1	2	0.2	4	0.4	4	0.4	3	0.3	4	0.4
Safety	0.15	1	0.15	2	0.3	2	0.3	2	0.3	4	0.6
Total Score			3.29		4.1		2.61		2.76		2.87
Rank			2		1		5		4		3

Table H.2: CO_2 Scrubber Selection Matrix

APPENDIX I REYNOLDS TRANSPORT EQUATION



To find time required for the bottle to reach set pressure of 1 kPa, we need the Reynold's Transport equation for mass conservation.

$$\frac{dM_{sys}}{dt} = \frac{\partial}{\partial t}\int_{CV} \rho dV + \int_{CS} \rho(V.d\vec{A}$$

This reduces to:

$$\emptyset = V\frac{\partial}{\partial t}\rho - \dot{m}_{in}$$

$$\frac{\partial \rho}{\partial t} = \frac{\dot{m}_{in}}{V}$$

By separation of variables:

$$\int_{\rho_1}^{\rho_2} d\rho = \frac{\dot{m}_{in}}{V}\int_0^t dt$$

$$\rho_1 - \rho_2 = \frac{\dot{m}_{in}}{V}t$$

Using Ideal Gas Law:

$$\frac{P_2}{R_2T_2} - \frac{P_1}{R_1T_1} = \frac{\dot{m}_{in}}{V}t$$

Where $P_2 = P_{gauge}$, $T_1 = T_2 = T$, and $R_1 = R_2 = R$,

$$t = \frac{P_gV}{RT\dot{m}_{in}}$$

APPENDIX J GASSING STATION BILL OF MATERIALS

Vendor	Catalog Number	Item Description	Quantity	Total Cost
Swagelok	B-200-3	1/8" Tee	22	$220.00
Swagelok	B-200-4	1/8" Cross	1	$50.00
Swagelok	B-ORS2	1/8" Needle Valve	10	$296.20
Swagelok	B-400-1-2	1/8" MNPT - 1/4"	5	$11.25
Swagelok	B-200-1-2	1/8" MNPT - 1/8"	5	$11.75
Swagelok	B-6-HC-A-401	3/8" Hose barbs to 1/4" Tube	2	$15.40
Swagelok	B-400-6-2	1/4" Tube to 1/8" Tube union	2	$6.14
Swagelok	B-201-PC	1/8" port connector	18	$57.06
Swagelok	B-200-6	1/8" union	2	$34.80
Swagelok	B-400-6	1/4" union	10	$26.60
Swagelok	B-4CP2-10	Pressure relief valve	1	$14.24
Cole Parmer	E-03217-28	Nitrogen Flowmeter	1	$139.00
Cole Parmer	E-03217-24	Hydrogen Flowmeter	1	$139.00
Cole Parmer	E-03217-16	CO2 Flowmeter	1	$139.00
Cole Parmer	E-03217-16	Optional Gas Flowmeter	1	$139.00
Cole Parmer	C-06403-10	hose clamp	2	$2.00
Cole Parmer	SA-06412-18	3/8" Viton tubing	1	$235.00
Cole Parmer	EW-98200-02	Single-stage regulator for gas tanks	2	$570.00
Cole Parmer	EW-34671-00	1/8" copper tubing	2	$60.00
Cole Parmer	EW-34671-10	1/4" copper tubing	2	$108.50
Alltech	81896	panel mount regulator	1	$70.17
Alltech	81895	mounting nut	1	$11.24
Alltech	86800	pressure gauge	1	$26.62
VWR	60110-222	Clamp stand and rod (case of 10)	1	$209.10
VWR	21572-501	clamp holder	1	$11.79
VWR	21570-126	clamp medium	1	$24.39
VWR	21570-125	clamp small	1	$23.23

Vendor	Catalog Number	Item Description	Quantity	Total Cost
NOSHOK	Model 148	Standard Pressure Gauge	8	$160.00
Home Depot		Plywood	1	$12.00
Professional Plastics	SACR.750EP	0.7 thick clear extruded acrylic P/m	2	$387.26
Cases by Source	FS02	1.0” Soft Foam Sheet (36”x26”x1”)	2	$24.06
Ace Glass	12080-10	Rheostat	1	$ 228.11
Thermolyne	HT650X1	Heat Tape to 450 degrees C (series X7, X9)	1	$148.00
Copper Column			1	$90.00
McMaster-Carr	8628K48	Nylon 6/6 Tube Tight Tolerance, 1/4" OD, 1/8" ID, 5' Length	10	$29.90
			Total Cost	**$3591.81**

APPENDIX K METHANE METER BILL OF MATERIALS

Vendor	Catalog Number	Item Description	Quantity	Est. Total Cost
Omega	PX182B	Pressure Transducer	16	$ 3,360.00
Omega	SV-326-12VDC	2-way solenoid valve	16	$ 2,208.00
Wheaton	W216809	250mL ballast bottle-12/case	3	$ 108.48
Cole Parmer	EW-10009-14	Case of 60mL syringes	1	$ 121.00
Cole Parmer	EW-88020-20	KOH pellets 500g	1	$ 59.75
Cole Parmer	EW-95880-06	3/16" nylon tubing	1	$ 32.00
Swagelok	B-4CP2-10	Pressure relief valve	16	$ 227.84
Swagelok	B-2-HC-1-2	hose barb for solenoid valves	32	$ 108.16
National Instrumetns	PCI-6014	DAQ	1	$ 599.00
Cole Parmer	EW-30623-69	Nylon 3/16” barbed tee	2	$ 25.00
		Total Cost		**$ 6,849.23**

APPENDIX L METHANE METER PROTOTYPE BILL OF MATERIALS

Vendor	Catalog Number	Item Description	Quantity	Est. Total Cost
Omega	PX139-0.3D4V	Pressure Transducer	1	$ 85.00
Omega	CX136-4	Circuit connector	1	$ 3.00
Omega	PX164-005D5V	Pressure Transducer	1	$ 145.00
Omega	CX136-3	Circuit connector	1	$ 2.50
Omega	SV-326-12VDC	2-way solenoid valve	2	$ 276.00
Swagelok	B-2-HC-1-2	hose barb for solenoid valves	4	$ 13.52
Cole Parmer	EW-30623-69	Nylon 3/16" barbed tee	1	$ 12.50
			Total Cost	**$ 537.52**

APPENDIX M INITIAL FABRICATION PLAN FOR THE GASSING STATION

Part Name: Housing component
Object: Bottle Container
Raw Material Stock: Plexiglas (18" x 32" x 1/2")

No.	Process Description	Machine	Speed (rpm)	Tool	Fixtures
1	Upload and run Housing file	Laser Cutter	150	90% Cutting Intensity	Laser Cutter Carriage

Part Name: Support flange
Object: Bottle Container
Raw Material Stock: Polyethylene foam (36" x 26" x 1")

No.	Process Description	Machine	Speed (rpm)	Tool	Fixtures
1	Cut foam into eight squares of length (6.5" x 6.5" x 1/2")	Bandsaw	300		
2	From center, cut six 4" slits in material with angle of 60˚ between cuts			Exacto Knife	Vice

Part name: Support plate for outlet tubing
Object: Gassing Station
Raw Material stock: Aluminum sheet (20" x 30" x 0.7")

No.	Process Description	Machine	Speed (rpm)	Tool	Fixtures
1	Upload and run Support Plate file	Laser Cutter	250		Laser Cutter Carriage
2	Insert aluminum sheet and adjust rollers to dimensions (16" x 8" x 1/32")	Sheet Machine	200		

APPENDIX O MATERIAL SELECTION

The two materials our team selected for analysis was a (a) the support material on top of the bottle holder and (b) the frame for the bottle holder. Our team's objective was to find materials that were low in cost and durable. This was achieved by considering the constraints: dimensions and calculating the loads of the bottles. The functions, objectives and constraints helped in selecting the most correct material.

The function of the support material on the top of the bottle holder is to cushion the bottles that are inserted into the holder. In addition, our team was looking for a material that was non-abrasive, CFC-free, ozone friendly, recyclable, odorless, and lightweight. Selection of material for the support material was narrowed down using the Granta CES program based on several parameters. The key parameter is stiffness. The first step of determining material properties was by calculating the forces associated with the bottle weight. Our team measured the mass of one bottle with the liquid mixture. To find the desired material constant, we measured the deflection a mock-up bottle holder. The equations for the force and deformation are shown below in Eq. 2 and 3.

$$F = mg = (1.326\ \text{kg})(9.8\text{m/s}^2) \approx 13\ \text{N} \qquad \text{[Eq.O.2]}$$

$$k = \frac{F}{\delta} \qquad \text{[Eq.O.3]}$$

We inputted the information to the Granta CES program and applied these property limits which screened out the materials which would not meet the design requirements. The materials we were left with were: phenolic foam, natural rubber, polyethylene foam, polyurethane foam, and polystyrene foam. Further narrowing is achieved by ranking the candidates by their price, availability in the area, and ability to maximize performance. This narrowed the selection to polyethylene foam, which is the material we used in our final product.

The bottle holder serves the purpose of providing housing for the bottles when gases are being introduced. Our sponsors ask that the material be transparent for reasons of safety. This property alone narrowed down the available materials. Granta CES program left us with: Soda-lime glass, Plexiglas, polyethersulfone (PES) membranes, silica glass, and Styrene Maleic Anhydride (SMA) Plastic Resin. The team used the force equations previously calculated to see if the load of the four bottles would make the frame, of each material, bend on the sides. We used the mechanical properties provided by CES for the equations. All of the materials were fairly comparable so ranking the candidates was not helpful. For further narrowing, our team decided to look at the manufacturing process. Drilling holes into a hollow three-dimensional shape, availability in the machine shop, and low labor intensity were criteria that led us to laser machining as the best process for the construction of the bottle holder. The only material that could be used for the laser cutter was Plexiglas.

APPENDIX P DESIGN FOR ASSEMBLY

Using Boothroyd-Dewhurst design for assembly method we analyzed the gassing station and methane meter for assembly complexity. The first step in analyzing our designs was to determine the minimum number of parts. We used the flow diagrams for the final gassing station and methane meter designs, Figures 16 and 17 on pages 29 and 32, respectively. Both the gassing station and the methane meter components are part of standard assembly and their necessity can be verified using Munro and Associates, Inc. table for part elimination. Also since both of the designs involved standard assembly of parts the redesign changes are very small and hardly affect the assembly time and cost.

Gassing station TableP.1, lists components and manual handling and insertion times for the gassing station based on dimensions, angles of symmetry and ease of use. We also used our experience from assembling the gassing station to determine more representative manual handling and insertion codes. Many components in Table P.1 are repeated due to the order in which the gassing station needs to be assembled. Also it is important to note that copper tubing has different lengths depending on where it fits in the system; therefore, we treated each one as a separate part. As can be seen from Table P.1 the total time for gassing station assembly is 24min and 11sec and the total operational cost is $5.81. Therefore, using Equation P.1, where N_m is the minimum number of parts and T_m is the assembly time we calculated that assembly efficiency is 32.7%.

$$Assembly\ Efficiency = \frac{3 \cdot N_m}{T_m} \qquad \text{[Eq. P.1]}$$

The assembly efficiency of the original design is 32.5%. The changes between the original design and the final design are highlighted in light orange in Table P.1. The inefficiency of assembly is caused by the need of a wrench and two hands to tighten copper tubing into tees, needle valves or reducers. Tubing made out of other material, more specifically nylon or Viton, which is easy to stretch and fasten with hose clamps, could not be considered for the design. This is due to the gas permeability coefficients of nylon and Viton tubing. Since the system needs to create accurate gas mixtures and keep the anaerobic environment in glass bottles, copper tubing was the best material choice because it is impermeable to gasses. To ease the assembly we also chose Swagelok fittings because they are equipped with a relatively simple mechanism for securely attaching tubing and other fittings. In order to reduce assembly time the mechanism within Swagelok needs to be redesigned, so that the operator can use just his hands to tighten the fittings. The redesign of this mechanism is out of the scope of our project.

Methane meter Table P.2, lists components and manual handling and insertion times for the methane meter based on dimensions, angles of symmetry and ease of use. Nylon tubing is repeated as a separate component throughout Table P.2 as its length varies depending in the system. The total time for methane meter assembly is 2min and 50sec and the total operational cost is $0.68. Using Equation P.1 we calculated assembly efficiency to be 61.2%. The assembly efficiency of the original design is 57.7%. The extra part that the original design required is highlighted in light orange in Table P.2.

Table P.1: Design for assembly analysis for original and final designs of the gassing station

Part	Number of times the operation can be performed consecutively	Manual handling code	Manual handling time per part	Manual insertion code	Manual insertion time per part	Operation time in seconds [2]*([4]+[6])	Operation cost in cents 0.4*[7]	Number of parts needed
Regulator	3	83	5.6	38	6	34.8	13.92	3
Copper tubing	2	54	7.25	38	6	26.5	10.6	2
Union	3	50	4	39	8	36	14.4	3
Copper tubing	3	51	7.25	38	6	39.75	15.9	3
Flow meter	3	20	1.8	38	6	23.4	9.36	3
Copper tubing	2	51	7.25	38	6	26.5	10.6	2
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Tee	2	40	3.6	39	8	23.2	9.28	2
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Cross	1	50	4	39	8	12	4.8	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Reducer	1	70	5.1	39	8	13.1	5.24	1
Hose barb	1	70	5.1	39	8	13.1	5.24	1
Viton tubing	1	21	2.1	30	2	4.1	1.64	1

Copper column lid	1	10	1.5	06	5.5	7	2.8	1
Hose clamp	1	13	2.06	90	4	6.06	2.424	1
Copper wool	1	13	2.06	99	12	14.06	5.624	N/A
Copper column	1	10	1.5	92	5	6.5	2.6	1
Viton tubing	1	21	2.1	30	2	4.1	1.64	1
Hose clamp	1	13	2.06	90	4	6.06	2.424	1
Hose barb	1	70	5.1	39	8	13.1	5.24	2
Reducer	1	70	5.1	39	8	13.1	5.24	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Tee	1	40	3.6	39	8	11.6	4.64	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Needle valve	1	40	3.6	39	8	11.6	4.64	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Pressure relief valve	1	50	4	39	8	12	4.8	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1

Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Pressure regulator	1	10	1.5	38	6	7.5	3	1
Panel mount regulator face	1	10	1.5	38	6	7.5	3	1
Copper tubing	1	51	7.25	38	6	13.25	5.3	1
Tee	1	40	3.6	39	8	11.6	4.64	1
Copper tubing	2	51	7.25	38	6	26.5	10.6	2
Tee	2	40	3.6	39	8	23.2	9.28	2
Copper tubing	7	51	7.25	38	6	92.75	37.1	7
Tee	6	40	3.6	39	8	69.6	27.84	6
Port connector	8	51	7.25	38	6	106	42.4	8
Tee	8	40	3.6	39	8	92.8	37.12	8
Port connector	8	51	7.25	38	6	106	42.4	8
Panel mount pressure gauge	8	10	1.5	38	6	60	24	8

Copper tubing	8	51	7.25	38	6	106	42.4	8
Needle valve	1	40	3.6	39	8	11.6	4.64	1
Copper tubing	8	51	7.25	38	6	106	42.4	8
Nylon tubing	8	10	1.5	00	1.5	24	9.6	8
Syringe	8	10	1.5	00	1.5	48	19.2	8
Rubber stopper	8	31	2.25	01	2.5	9.5	3.8	8
Syringe	8	10	1.5	00	1.5	48	19.2	8
Nylon tubing	8	10	1.5	00	1.5	24	9.6	8
Nylon hose barb	8	30	1.95	01	2.5	35.6	14.24	8
Manifold	1	00	1.13	38	6	7.13	2.852	1
Nylon hose barb	1	30	1.95	01	2.5	4.45	1.78	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
						Total assembly time in minutes	**Total cost of assembly in dollars**	**Theoretical minimum number of parts**
						24.19	**5.81**	**158**
						24.80	**5.95**	**161**

Table P.2: Design for assembly analysis for original and final designs of the methane meter

Part	Number of times the operation can be performed consecutively	Manual handling code	Manual handling time per part	Manual insertion code	Manual insertion time per part	Operation time in seconds [2]*([4]+[6])	Operation cost in cents 0.4*[7]	Number of parts needed
Rubber stopper	2	31	2.25	01	2.5	9.5	3.8	2
Syringe	4	10	1.5	00	1.5	12	4.8	4
Potassium hydroxide	1	30	1.95	00	1.5	3.45	1.38	N/A
Desiccant	1	32	2.7	00	1.5	4.2	1.68	N/A
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Pressure relief valve	1	50	4	39	8	12	4.8	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Nylon tee	1	40	3.6	39	8	11.6	4.64	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Pressure transducer	1	10	1.5	01	2.5	4	1.6	1

Hose barb	2	70	5.1	39	8	26.2	10.48	2
Needle valve	1	40	3.6	39	8	11.6	4.64	1
Nylon tubing	1	10	1.5	00	1.5	3	1.2	1
Syringe	1	10	1.5	00	1.5	12	4.8	1
						Total assembly time in minutes	**Total cost of assembly in dollars**	**Theoretical minimum number of parts**
						1.88	**0.45**	**23**
						2.08	**0.50**	**24**

APPENDIX Q DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

After implementing the gassing station, the information learned from methane production might provide a solution for a cleaner source of energy by allowing multiple experiments to be done simultaneously and providing an organized setup for laboratories. However, there are several immediate impacts on the environment that should be considered during material fabrication for the gassing station. For our final design we chose to analyze effects of Plexiglas, also known as Poly(methyl methacrylate) (PMMA), and polyethylene foam used in the bottle holder. We compared the environmental effects using SimaPro software by generating an EcoIndicator 99 analysis. An EcoIndicator 99 analysis provides us with different graphs which show effects of these materials on various aspects of the environment. Figures Q.1 through Q.4 illustrate these results. To perform this analysis, the total mass utilized in the final design was calculated. In our final design, we used 3.2 kg of Plexiglas and 140 grams of Polyethylene foam.

Figure Q.1 provides a graph of total emissions during the fabrication of foam and Plexiglas. These emissions are divided into four main categories: raw, air, waste and water. Both products have a great impact on raw materials in comparison to the other categories. Also, the emissions produced by Plexiglas highly exceed those of polyethylene foam. Figure Q.2 shows the environmental impacts of these emissions. From this graph, we can see that both materials have a great impact on ecotoxicity and acidification. When compared to polyethylene foam, Plexiglas has a higher impact on both of these categories by 0.3 units. An EcoIndicator 99 also provides an analysis on effects of these materials to human health in relation to ecotoxicity and resource categories, as shown in Figure Q.3. The effects on ecotoxicity and resource categories are relatively negligible in comparison to human health. To get a better understanding of all of the effects, Figure Q.4 illustrates a Single Core Comparison in “Points”. A Single Core comparison in “Points” is a summation of all the environmental effects from previous figures. The previous graphs showed that Plexiglas causes a greater impact on the environment; therefore, it is expected that the summation of these effects will also outweigh that of polyethylene foam. Based on this analysis, our team would consider looking into other materials that would have less impact in future assembly of bottle holders. If additional gassing stations are needed by our sponsor, we would need to determine if transparency is a specification that is necessary. This specification eliminated more environmentally friendly materials.

Our team does not know how the impacts of polyethylene foam and Plexiglas relate to impacts from other materials. In addition, we do not know the effects of these materials once they are put in use. Even though one material might seem better than the other one in Simapro, that does not mean that either one is environmentally friendly. SimaPro only provides us with information on the environmental effects as the materials are being fabricated. In order to determine the effects of products made from these materials, life cycle analysis needs to be completed.

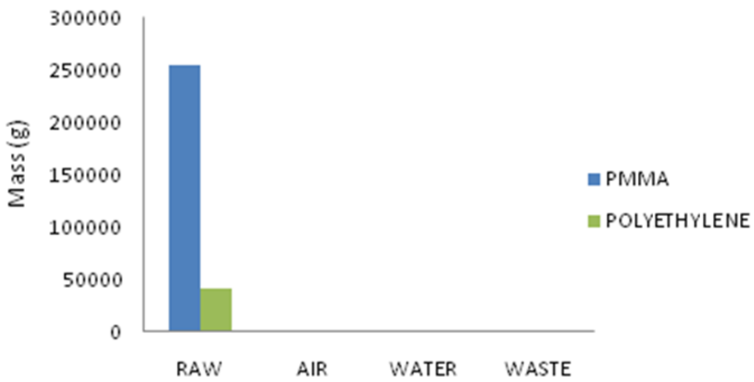


Figure Q.1: Total emissions

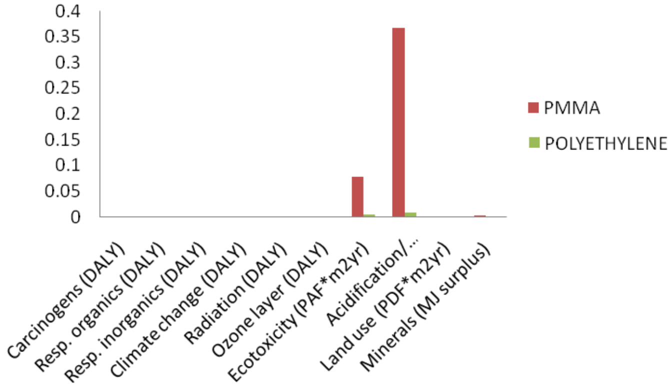


Figure Q.2: Relative impacts in disaggregated damage categories

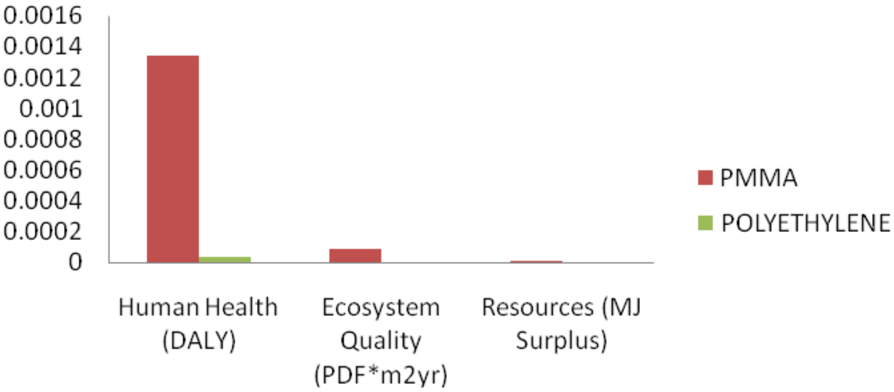


Figure Q.3: Normalized score in human health, eco-toxicity and resource categories

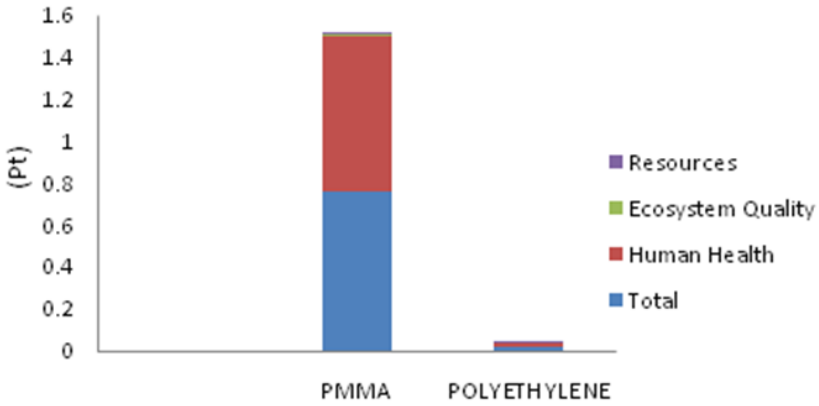


Figure Q.4: Single score comparison

APPENDIX R DESIGN FOR SAFETY

RISK ASSESSMENT

We performed risk assessments of both the gassing station and methane meter to analyze all sources of risks, and how to design to protect against such hazards. A risk assessment and Failure Modes and Effects Analysis (FMEA), are similar in that they both first identify either a system failure and its effects, or a hazard of a system. Both methods then assess the failures or risks to determine how to eliminate the chance of a failure or risk in the design. The difference between FMEA and a risk assessment is that FMEA addresses component failures and risk assessment deals with human failures.

In our approach to reduce risks we have aimed to mitigate our risks to an acceptable level, as the concept of zero risk does not exist. This is apparent in our project in such examples as installing pressure relief valves or securing the hose lines with zip ties. In both cases the probably of the hazard affecting the user is greatly decreased, however there is still a margin of error within the pressure relief valve, and the hoses could still become disconnected, even though they are snug fit and secured.

For our risk assessment we used the Designsafe ®software to consider all the hazards possible to all users of both the gassing station and methane meter systems.

Gassing Station

We determined that the only high risk hazard for the gassing station is a possible deviation from safe work practices with respect to handling and storing the large gas cylinders. If the cylinders are not handled and stored properly, they could possibly be tipped over and the valve on the top of the cylinders could break off and send the large cylinder shooting off as it depressurizes. The risk of human error with handling the gas cylinders can be reduced by proper training of the standard procedures for moving and securing the cylinders. We have spoken with the lab managers in the EWRE building where the gassing station will be set up, and they do follow the standard procedures for setting up gas cylinders. Once the standard procedures are considered, the finally assessment of this hazard has only a moderate risk level.

Other risks for the gassing station that were at moderate level include puncture wounds from the syringes, head bump on overhead cabinet, the possibility to disturb oxygen concentration in room from release of purging gases to atmosphere instead of fume hood, burns from the heat tape around copper column, and the explosion of bottles due to an overpressure situation. We have mitigated the first two risks to a low level by the use of standard procedures for handling syringes, and placing warning signs on the shelf edge, respectively. We have also designed the system to reduce the chance of the purging gases leaking into the room air by routing all of the purging needles and pressure relief valves to the fume hood. Also, the pressure relief valves protect the bottles from over pressuring and possibly exploding.

Methane Meter

The high risk hazards for the methane meter are derived from the presence of methane gas in the system. They include the possibility of sparks coming into contact with the flammable gas, the possibility of static electricity coming into contact with the methane gas, and the potential of a fire. We have lowered this risk to moderate by keeping the methane gas contained and continuously routed to the fume hood, and installing an explosion-proof solenoid valve, the only electrically-actuated component that contacts the methane gas. However, Designsafe® did help us realize that we had not verified whether the pressure transducer could expose the methane gas to any conducting parts which could present a spark. We have called Omega Engineering ®, and the pressure transducers only have a plastic interface with the methane gas, so there is no potential for a shock to form. In the case of a fire, we have reduced risks to a moderate level by placing a fire extinguisher and posting evacuation routes in the lab room.

Some risks which were initially at a moderate level include puncture wounds from the syringes, and hoses disconnecting during operation potentially exposing the user to methane or disturbing the oxygen concentration in the room. These risks were reduced to a low level by the use of standard procedures, and using zip ties to secure all hose connections, respectively. Also at an initial moderate level was the potential to spill aqueous solution on electrical components, and the potential of missing features in the LabVIEW® program. To reduce risks we will locate the electrical components away from the reactor bottles containing aqueous solution, and we will recommend analysis of the functions in LabVIEW® during initial testing to ensure all necessary functions are programmed. Another moderate risk was the potential of burns from the heated temperature bath which will contain the reactor bottles. We recommend posting warning signs to notify users of the high temperatures and reduce this risk to a low level.

The remaining moderate risks were the possibility to corrode metal parts by trace amounts of hydrogen sulfide produced, and the possibility of over pressuring the methane meter system. We have recommended that the users be aware of variations in the measurements over time, possibly indicating a degradation of metal components due to hydrogen sulfide exposure. Finally, we have chosen a nominally open solenoid valve for the design so that in the de-energized state it will open and release all methane straight to the fume hood. We have also installed a pressure relief valve in the design to protect the methane meter system in the case that the solenoid valve for some reason becomes stuck in the closed position.

designsafe Report

Application:	Team 28 Gassing Station	Analyst Name(s):	
Description:	Assessment of Gassing Station for Dr. Raskin, in Lab 18 EWRE Building.	Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

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

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Possible if bottle break and glass pieces are around, or the edges of the curved aluminum plate could be sharp.	Slight Occasional Possible	Moderate	use pressure relief valves to prevent bottles from overpressuring, file and/or tape edges of aluminum plate	Slight Remote Unlikely	Low	
All Users All Tasks	mechanical : stabbing / puncture syringes used for entering bottles	Minimal Frequent Possible	Moderate	standard procedures	Minimal Occasional Unlikely	Low	
All Users All Tasks	mechanical : head bump on overhead objects overhead shelf to which the station is fixed	Minimal Occasional Possible	Moderate	warning sign(s)	Minimal Remote Unlikely	Low	
All Users All Tasks	ergonomics / human factors : posture leaning over to attach bottles	Minimal Remote Unlikely	Low	standard procedures	Minimal Remote Negligible	Low	
All Users All Tasks	ergonomics / human factors : deviations from safe work practices not properly attaching large gas	Serious Frequent Possible	High	standard procedures	Serious Remote Possible	Moderate	
All Users All Tasks	fire and explosions : lack of oxygen supply if purging gases were to enter the room and diminish oxygen content	Serious Remote Unlikely	Moderate	all gas lines should be routed to fume hood, proper training for users to know where gases are being routed	Slight Remote Unlikely	Low	
All Users All Tasks	heat / temperature : burns / scalds heat tape on rheostat is set to 150 C	Slight Remote Possible	Moderate	warning sign, placement of copper column	Slight Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	ingress / egress : material storage interference bracket connecting to overhead cabinet will have bolts that	Minimal Remote Negligible	Low	use other shelves for bottle storage	Minimal Remote Negligible	Low	
All Users All Tasks	ingress / egress : blocked / locked room is very small, boxes or other mat'l may block path to exit door	Minimal Occasional Unlikely	Low	train user to understand importance of keeping lab tidy and boxes out of	Minimal Remote Negligible	Low	
All Users All Tasks	environmental / industrial hygiene : emissions if gases flow to room instead of fume hood, could disrupt oxygen content	Slight Occasional Unlikely	Moderate	design purging gas lines to fume hood; train users to connect all purging lines	Slight Remote Unlikely	Low	
All Users All Tasks	ventilation : loss of exhaust purging lines detach from bottles, or somehow become clogged and system cannot vent to fume hood	Slight Remote Unlikely	Low	train users to connect all purging lines	Slight Remote Unlikely	Low	
All Users All Tasks	ventilation : concentration if gases do not flow to fume hood they can disrupt the oxygen concentration	Slight Remote Unlikely	Low	train users to connect all purging lines	Slight Remote Unlikely	Low	
All Users All Tasks	ventilation : lack of fresh air room is in basement and very small	Slight Remote Unlikely	Low	keep door open at times, ensure users take breaks and leave the room occasionally	Minimal Remote Negligible	Low	
All Users All Tasks	chemicals and gases : carbon dioxide tubes could detach somewhere and CO2 would flow to room	Slight Occasional Possible	Moderate	proper construction of CO2 lines	Minimal Remote Unlikely	Low	
All Users All Tasks	chemicals and gases : hydrogen tubes could detach somewhere	Slight Occasional Possible	Moderate	proper construction of H2 lines	Slight Remote Unlikely	Low	
All Users All Tasks	chemicals and gases : nitrogen tubes could detach somewhere	Slight Occasional Negligible	Low	proper construction of N2 lines	Minimal Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	fluid / pressure : explosion / implosion bottles could explode is overpressured	Serious Remote Unlikely	Moderate	include pressure relief valves in design	Slight Remote Unlikely	Low	

designsafe Report

Application:	Team 28 Methane Meter	Analyst Name(s):	
Description:	Assessment of methane meter design for Dr. Raskin to be in Lab 18 EWRE building.	Company:	University of Michigan
Product Identifier:		Facility Location:	EWRE building
Assessment Type:	Detailed		
Limits:			
Sources:			

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

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : stabbing / puncture syringes used to enter bottles	Slight Occasional Possible	Moderate	standard procedures	Slight Remote Unlikely	Low	
All Users All Tasks	mechanical : break up during operation hoses disconnecting during operation	Slight Remote Possible	Moderate	proper construction and use of zip ties on hose barb connections	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : energized equipment / live parts connections lost to solenoid valve, DAQ card	Minimal Remote Possible	Low	use proper connection components	Minimal Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : lack of grounding (earthing or neutral) connection lost to ground	Slight Remote Possible	Moderate	use proper connection components	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : water / wet locations aqueous solution spilled on electrical components	Slight Remote Possible	Moderate	locate electrical components away from temperature bath and reactor bottles	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : software errors LabView program missing features	Minimal Remote Probable	Moderate	run test experiments to ensure all required features of program are incorporated	Slight Remote Unlikely	Low	
All Users All Tasks	ergonomics / human factors : posture attaching bottles to system	Minimal Remote Unlikely	Low	standard procedures, awareness	Minimal Remote Negligible	Low	
All Users All Tasks	fire and explosions : sparks coming into contact with methane gas	Catastrophic Remote Possible	High	use only explosion-proof electrical components	Slight Remote Unlikely	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	fire and explosions : flames methane gas is ignited	Catastrophic Remote Possible	High	place fire extinguisher in room and train users in fire safety, post evacuation routes	Serious Remote Unlikely	Moderate	
All Users All Tasks	fire and explosions : flammable gas methane gas produced	Serious Occasional Possible	High	keep gas contained and routed to fume hood	Serious Remote Unlikely	Moderate	
All Users All Tasks	fire and explosions : inadequate egress / evacuation routes	Serious Remote Possible	Moderate	post evacuation route	Serious Remote Unlikely	Moderate	
All Users All Tasks	fire and explosions : static electricity could spark methane	Catastrophic Remote Possible	High	contain methane in inert tubes and route to fume hood	Serious Remote Unlikely	Moderate	
All Users All Tasks	heat / temperature : burns / scalds temperature bath temperature	Slight Occasional Possible	Moderate	post signs warning of bath temperature	Minimal Remote Unlikely	Low	
All Users All Tasks	ingress / egress : blocked / locked path to door of small room blocked	Minimal Occasional Unlikely	Low	train user to understand importance of keeping lab tidy and boxes out of	Minimal Remote Negligible	Low	
All Users All Tasks	environmental / industrial hygiene : emissions lines to fume hood could become disconnected	Serious Remote Possible	Moderate	proper construction of tubing, use of zip ties at hose barb connections	Slight Remote Unlikely	Low	
All Users All Tasks	environmental / industrial hygiene : corrosion H2S could degrade metal components	Slight Occasional Possible	Moderate	be aware of measurements, replace with stainless steel components if corrosion become apparent	Slight Remote Possible	Moderate	
All Users All Tasks	ventilation : loss of exhaust lines to fume hood could become disconnected	Serious Remote Possible	Moderate	proper construction of tubing, use of zip ties at hose barb connections	Slight Remote Unlikely	Low	
All Users All Tasks	ventilation : concentration lines from bottles to fume hood could become disconnected and disrupt O2 concentration	Slight Remote Possible	Moderate	proper construction of tubing, use of zip ties at hose barb connections	Slight Remote Unlikely	Low	
All Users All Tasks	ventilation : lack of fresh air room is in basement and very small	Slight Remote Unlikely	Low	keep door open at times, ensure users take breaks and leave the room occasionally	Minimal Remote Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	chemicals and gases : carbon dioxide CO2 is produced in reactor bottle	Slight Remote Unlikely	Low	KOH pellets will be used to absorb CO2	Minimal None Negligible	Low	
All Users All Tasks	chemicals and gases : methane CH4 is produced in reactor	Slight Remote Possible	Moderate	keep contained in inert tubing and route directly to fume hood	Slight Remote Unlikely	Low	
All Users All Tasks	chemicals and gases : hydrogen sulfide slight amounts of H2S are produced in reactor bottle	Slight Remote Unlikely	Low	keep off-gases contained in inert tubing and route directly to fume hood	Slight Remote Unlikely	Low	
All Users All Tasks	fluid / pressure : explosion / implosion system could overpressure and	Serious Remote Unlikely	Moderate	use of pressure relief valve	Slight Remote Unlikely	Low	

APPENDIX S MANUFACTURING PROCESS SELECTION

It is becoming increasingly necessary to find an alternative form of energy. Due to this need, the gassing station we have designed might be of interest to those studying optimization of methane production. In addition, a few of the anaerobic gassing stations we looked at for comparison before finalizing our design were being used in microbiology research laboratories. It is likely that likely that other professors and researchers in various scientific disciplines could use a similar piece of equipment therefore our real-world production volume is estimated around 500.

Methane can be produced using various systems in laboratories; the methane meter our team designed is specific to microbial communities. However, the design of our methane meter is a factor that significantly affects the real-world production volume, because the design is specific to our project. Variations of the design might better suit laboratories depending on the system they are using to optimize production. Our team estimated the production volume of this component to be 50. The methane meter, the second component of our project is also an instrument that will be useful to society.

The two materials our team selected for analysis was a (a) the support material on top and (b) the frame for the bottle holder. Both materials were selected using CES Materials Selector and the manufacturing process best fit for both materials was using laser technology. There were several advantages to this process: low labor, a reduced chance of warping and precision. Lasers are ideal for both cutting applications. Our team also believes a laser cutter is best suited for the real-world production volume of 500. The cost of laser technology in recent times has made it an affordable means of manufacturing.

Another part of our system, the backboard of the gassing station, was designed using a power tool to drill holes. This was the easiest manufacturing approach when the production volume was one, but if the production volume were to be increased, it might be more practical to use a mechanized drill. The cost of manufacturing will be higher than the laser cutting, but for this component of the project, tolerances must be considered. Our team considered using molds and changing the material to plastic. While this lowered the cost significantly, this manufacturing process also led to uncertainty in tolerances which is crucial for operation of the gassing station.