# ME450: PROJECT 21
# Fall 2006

Anerobic Membrane Bioreactor (AnMBR)

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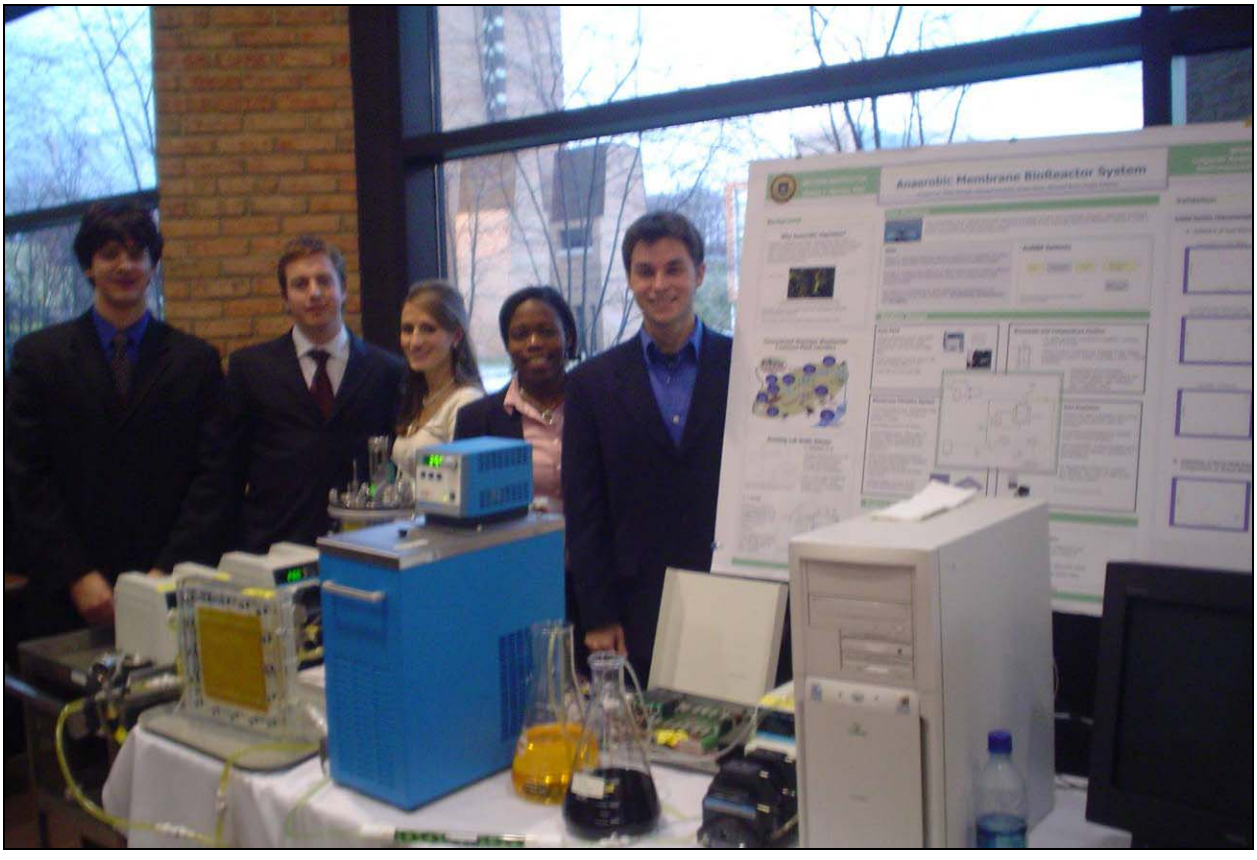

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# 1. ABSTRACT

The sustainability of our limited freshwater resources is a global concern, and domestic wastewater (DWW) treatment systems are needed to relieve this concern. Our sponsors propose a new Anaerobic Membrane Bioreactor system that uses anaerobic digestion coupled with membranes to create a simple, inexpensive, self-sustaining solution. Our project is to design a reconfigurable laboratory-scale test platform to evaluate the feasibility of such a system. This platform will allow researchers to explore different membrane materials and geometries along with configurations that minimize fouling. It will also accurately monitor all processes and permit further research of both supplementary and biogas collection systems.

## 1. EXECUTIVE SUMMARY

An Anaerobic Membrane Bioreactor (AnMBR) has the potential to be a simple and inexpensive solution to domestic wastewater treatment. It exploits natural synergies between the anaerobic microbial treatment and membrane systems and produces methane gas allowing for self-sustainability. Ultimately, the goal is to develop an effective system that can be applicable in both industrialized and developing countries.

To accomplish this goal, a lab-scale test setup was developed to further examine the promise of this technology. Our task was to design such a setup that will allow researchers to explore different configurations and treatment processes as well as monitor parameters such as water quality, gas production, and flow rates. A complete list of customer specifications can be seen in Appendix B. We identified cost, pump power, and temperature controls to be our major design constraints. Table 2 on page 9 shows the complete list of specifications as well as target values.

Each of our specification categories has different challenges. We used computer generated models and physical mock-ups to evaluate our design. Finally, in regards to experimental performance, we will needed to ensure accurate temperature controls (which are crucial to the effectiveness of the experimentation) and utilize gas tight seals to capture all biogas produced.

To arrive at an alpha concept, we first divided the overall system into major component areas: bioreactor, hydrolysis, temperature control, membrane configuration, ion exchange, feed dilution, and connectors, piping, and pumps. Each of our group members examined one or more subsystems in detail and reconvened to generate concepts. We considered the engineering specifications and manufacturability of said concepts, and selected the ones that best met our criteria.

A CAD model was constructed for each subsystem; these were integrated to form a model of the overall alpha concept. Due to the complexity of our system, the team performed extensive research into off-the-shelf components.

## 2. PROBLEM DESCRIPTION

The sustainability of our limited freshwater resources is a global concern and domestic wastewater treatment systems are needed to relieve the current stress on those resources. There are many options available for the treatment of wastewater including the use of anaerobic bacteria for the breakdown of organic material and the production of methane. Anaerobic bacteria have been utilized since the 1800's for waste treatment and are still used today for the processing of high concentration industrial waste. In the context of *domestic* wastewater (much lower waste concentration), our sponsors propose the use of anaerobic digestion coupled with the use of membranes to create a simple, inexpensive and self-sustaining wastewater treatment system. The eventual goal of Anaerobic Membrane Bio-reactor (AnMBR) research is to create a "plug and play" wastewater solution for deployment in industrialized and developing countries alike. Our project was to design a laboratory-scale test platform to evaluate the feasibility of such a system.

# 3. INFORMATION

To better understand the functions and uses of an Anaerobic Membrane Bioreactor, we gathered information about both industrial and lab-scale applications of anaerobic digestion, membrane bioreactors and the individual components of the system. From our literature, Internet and patent searches, we found that there are many different industrial processes available to treat wastewater; however none of these are strictly anaerobic. Additionally, most lab-scale systems are customized for a specific area of research (e.g. membrane fouling) and as such, are not reconfigurable. As a result, we have learned that adding the flexibility to perform tests in multiple areas of research will offer significant improvement over these systems. Table 1 below gives a brief comparison of the characteristics of three of the systems we benchmarked.

**Table 1. Comparison of Overall System Characteristics for Benchmarked Systems**

| System characteristics | Industrial | Labscale | |
|---|---|---|---|
| | Manako City | Zhang | Abdullah et al |
| Volume of Anaerobic Tank | $3 \times 10^6$ L | 4-6 L | 50 L |
| Gas Collection System | No | No? | Yes |
| Membrane Filtration | Yes | Yes | Yes |
| Reconfigurable | No | Yes | No? |
| COD Removal | Yes (n/a) | 95.4 - 93.3% | 96.5-99% |
| Nitrogen/Phosphorous Removal | Yes | No | No |

## Existing Patents

There were no existing patents for an "Anaerobic Membrane Bioreactor system", however, there were many that included the use of anaerobic reactors and membrane filtration at separate stages of the wastewater treatment process. Patent # 6,905,600: *Method and apparatus for the treatment of particulate biodegradable organic waste* (John Lee, Jr.) was the only patent that included an AnMBR. This patent is mainly involved with the process for the treatment of wastewater; however, it uses an AnMBR in its digestion stage to produce methane gas.

## 3.1 BENCHMARKING OF INDUSTRIAL ANMBRS

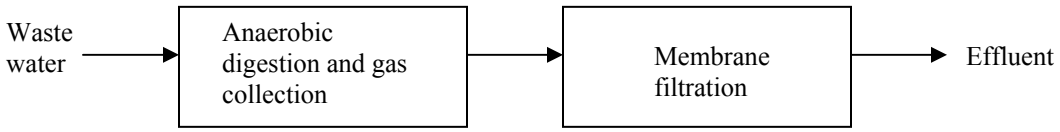
Looking to larger scale applications, municipal wastewater treatment facilities use some of the same components of an AnMBR system. These systems employ a series of filters, settling tanks and bacterial digesters to process their wastewater. First, the water passes into a settling tank where heavy solids (sludge) sink and oils and grease rise to the surface and are skimmed off. The sludge is then pumped to an anaerobic digester for the production of methane and eventually dewatered for use as fertilizer in agricultural applications. The filtered water is fed to an aeration tank where bacteria treat dissolved waste. It then goes to a chemically treated chlorine or UV light disinfection tank to clean out disease causing bacteria and viruses. Finally, the water is polished, commonly through carbon filters, before its discharge into rivers, lakes or oceans [5].

## 3.2 BENCHMARKING OF LAB-SCALE ANMBRS

Due to increasing research interest in AnMBRs for wastewater treatment over the past decade, research articles highlighting various methods and configurations of AnMBRs in a lab-scale setup were readily available in many engineering journals. For external AnMBRs systems (with membrane filtration units outside of the reactor), we noticed a

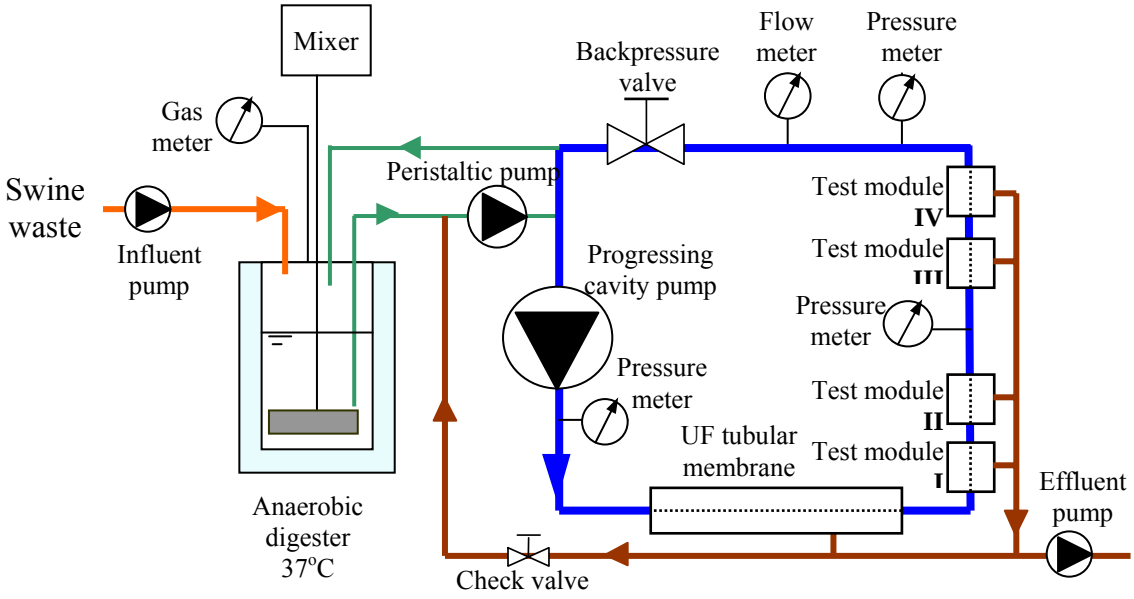
common trend in the basic setup. Each can be broken down into 2 systems: the anaerobic digester/gas collection system and a membrane filtration system (Fig 1). These two subsystems are usually connected by a pump (or pumps) for recirculation, and have a backpressure valve in the filtration system to provide the required trans-membrane pressure. Two such systems are discussed below and compared with the industrial AnMBR in Table 1 above.

**Figure 1: Two main subsystems of lab-scale AnMBRs with external filtration units**



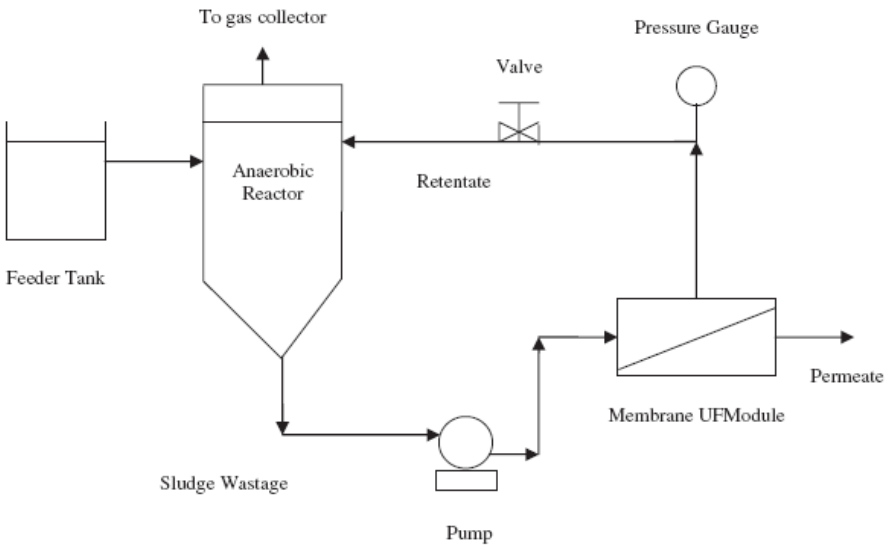

1. J. Zhang: Effect of Shear on Membrane Fouling in AnMBR Treatment of Swine Waste [8]
In this study, Zhang focuses on the effects of shear contributed by an AnMBR, different mechanisms of membrane fouling, and on various cleaning strategies. The set-up, shown below in Fig 2, uses two pumps in the membrane filtration unit to minimize foaming. Since this study depended heavily on various membrane configurations, Zhang also had four additional modules in the filtration system to allow for evaluation of other variables.

**Figure 2: Schematic of AnMBR Setup in Zhang Study**




2. Abdullah et al: Kinetic Study of AnMBR for Treatment for Sewer Sludge [1]
This study focused primarily on the application of kinetic models and microbial kinetics to obtain various performance measures of the AnMBR and parameters describing the bio reactions. In this setup, sludge at the bottom of the reactor if fed by a pump through two cross flow ultra filtration membranes as shown in Fig 3 below. Part of the liquor is filtered out as permeate, while another part is recirculated to the reactor.

**Figure 3: Diagram of Abdullah Study**




# 4. DEVELOPMENT OF DESIGN REQUIREMENTS

## 4.1 CUSTOMER REQUIREMENTS

Engineering specifications were obtained by translating our list of customer requirements into engineering quantities such as flow rates, dimensions, temperatures and pressures. These system functions were grouped by flexibility, accessibility and experimental performance of the system. Once these were determined, we set targets for the specifications, and a QFD Chart (see Appendix F) was used to identify the most important engineering specifications.

*Refinements of Customer Requirements*

During our research phase, we found several complexities of the AnMBR system that need to be addressed. After meeting with our sponsors, we agreed on the following changes to the customer requirements:

- The ion exchange system will be left as a "black box" design. Research is ongoing regarding the use of ion-exchange membranes for filtration, and thus the technology is not mature enough to integrate into our system.
- A cross-flow configuration will be used to filter the wastewater.
- The gas that is emitted will not be collected at this time, due to the low volume. However, the emitted gas will be measured as part of the experimental data.
- The system will only have the capability of running with flat sheet, tubular, and hollow fiber membrane capsules. Hollow fiber membranes are the most commonly used in existing bioreactors, however the flat-sheet method allows the use of novel membranes that may not be available in the more specialized hollow-fiber systems. Also, flat sheet membranes are more commonly used in full-scale, aerobic membrane bioreactors, therefore this technology also holds the most promise for anaerobic waste water treatment systems.

- The reactor will use a 6L total and 5L working volume. The sizing for this was determined by one of our sponsors (Appendix D) and the amount of wastewater concentrate that would need to be produced in order for the system to run unattended.

## 4.2 ENGINEERING SPECIFICATIONS AND QFD

Engineering specifications were obtained by translating the above list of customer requirements into engineering quantities such as velocity, mass, time etc. These system functions were grouped by flexibility, accessibility and experimental performance of the system. Once these were determined, targets were set for the specifications and a QFD (Quality Functional Deployment). Chart was used to identify the most important engineering specifications.

QFD: From the QFD, we found that cost and temperature controls are the major engineering constraints of the design. However, from discussions with our sponsors, we reached a common understanding that our budget constraints are no longer as restrictive. We related the customer's requests and specifications to engineering metrics by using a weighted pairing between the two categories. The QFD also incorporates the benchmarks of the existing systems discussed in section in Sec 3 (page 5) to see whether they meet the customer needs. The QFD can be seen in Appendix F.

Target Setting: Once the engineering specifications were identified, targets were set from sponsor requirements, engineering standards, and engineering intuition. Since the system needs a lot of flexibility in operation, many of the targets will be determined during the experiments themselves. These are labeled "TBD". The flexibility of our system lends itself to customization order to meet these variable targets. These are the parameters for the ion exchange system and parameters for membrane housings. Some targets like "0 kPa" for pressure loss were targets which must be met for satisfactory performance of the system. Targets such as "Time to install membrane" and "# experimental permutations" were educated guesses which we will refine as the project progresses. Table 2 below shows our quantified engineering specification, units and corresponding targets.

**Table 2. Engineering Specification, Units and Targets for AnMBR**

| Category | Quantification | Units | Target |
|---|---|---|---|
| Flexibility | Size of membranes accomodated (dimensions) | mm | $200^2$ |
| | # of membranes accomodated | # | 2 |
| | WW Pump power range | W | TBD |
| | # of experimental test cells | # | 2 |
| | # of Possible Experimental Permutations | # | 120 (5!) |
| | back pressure tolerance of WW pump | kPa | TBD |
| | Max Running time | Years | 2 years |
| | Range of crossflow flowrates (velocities) | $m/s^2$ | (Not needed) |
| | Possibility of Backflushing | Yes/No | Yes |
| | Possibility of intermittent operation | Yes/No | Yes |
| | Possiblity of biogas collection | Yes/No | Yes |
| Accessibility | Volume of container | $m^3$ | 6 L |
| | Total power input required | W | TBD |
| | # steps to access membrane | # | 2 |
| | time install experimental components | min | 10 min |
| | # of tools to install | # | 0 |
| | WW Pump duty cycle (service time) | years | > 2 years |
| | # external Connections for setup | # | < 5 |
| | # pinch points | # | 0 |
| | # potential trip hazards | # | 0 |
| | Distance between Hydraulic and Electrical Components | m | 0.3 m |
| | # of biomass sampling ports | # | 1 |
| | time to install membranes | min | 1 minute |
| | Biogas measurement gages | Yes/No | Yes |
| Experimental Performance | Temperature of Reactor | C | 10-40 C |
| | Pressure loss of anaerobic compartment to surroundings | kPa | 0 |
| | % of emitted gas collected | % | 100% |
| | Accuracy of measurement of biogas flow | kPa | ± Determined by gauge kPa |
| | Flowrate through system | L-day | 5-10 |
| Cost | Total Cost of System | $ | <10,000 |

# 5. PROBLEM ANALYSIS

Currently, AnMBR test setups are inflexible in that they cannot vary large numbers parameters and processes that are important to current research. Therefore, our major design objective was to create an AnMBR test platform that is flexible, reconfigurable and satisfies all the requirements of the chemical and biological processes involved. Our engineering specifications in Section 4.2 illustrate these goals. The purpose of this section is to discuss our design challenges, possible ways to address these challenges and to outline the key engineering fundamentals. We will also address the role of engineering models and testing and how they will aid in making decisions.

## 5.1 DESIGN CHALLENGES

The engineering specifications can be broken down into three major categories: flexibility, accessibility and experimental performance. Each category carries a set of challenges that must be addressed.

**5.1.1 Flexibility**: To make the laboratory-scale AnMBR flexible, we had to accommodate a variety of parameters and setups and the variability that is important to research with AnMBRs. The system also had to have the ability to accommodate hollow fiber, tubular and flat sheet membranes. Therefore, we created a housing for flat sheet membranes and connections for hollow fiber capsules with the option of both series and parallel setups. The system will run without pre-treatment and post treatment processes such as hydrolysis and ion exchange for the time being, but there is the option to easily incorporate these systems in the future. Fouling prevention strategies such as membrane cross-flow, backwashing and intermittent operation are available and the various pumps accommodate a range of flow rates. Additionally, the target temperature of the reaction is between 10°C and 40°C with a 1°C of uncertainty. This requires a control system that allows the user to set the temperature and a heat exchanger capable of holding that setting. Finally, our design has a system for biogas collection and measurment since this is also a major area of AnMBR research.

**5.1.2 Accessibility**: The accessibility of the laboratory setup depends on the placement of components and the method of their connection. Sampling ports are easily visible and accessible and connections require a small number of steps. Membranes can be easily removed and inserted, and the overall experimental setup time is short. We used standard flexible tubing and connectors on all components so that individual systems can be rearranged and broken components can be easily replaced.

In order to gain a history of experimental conditions, our DAQ system monitors conditions at a variety of locations with gauges and LabView. Systems that have temperature controls are monitored with thermocouples. Flow meters are used at the inlet and outlet of the reactor as well as a level switch to monitor mass flow through the reactor.

**5.1.3 Performance Specifications**: The experimental performance specifications are targets that will dictate the quality of the laboratory results. These include temperature control for the bioreactor (and later the hydrolysis phase), pressure and energy loss to surroundings and the measurement precision of biogas collected. Our challenge is to accurately control the temperature at all points in the reactor in order to keep the biomass at the optimum conditions. Additionally the reactor has a gas tight seal so that no biogas escapes with the allowance for inlet, outlet, and sample lines.

To address these challenges, we extensively researched heat exchangers, pumps, quick connects, valves and other components that we wanted to use in our design. We ordered components with sufficient lead-time and coordinated our team so that we could divide the design, modification and construction of components while maintaining a system level perspective. Planning and anticipating potential problem areas were key to the success of the project.

**5.1.4. Issues with Alpha concept that need to be addressed**: In order to gain a history of experimental conditions, we needed to monitor system conditions at a variety of locations with gauges and a computer data collection system (LabView). In our alpha concept, we determined the locations for pressure gages and flow meters. We discussed these locations with our sponsors and determined the optimal arrangement for the final design. However, we have not finalized the locations of all sample ports. Sizing of the membrane housing (see Figure 7, page 13) was also important. The membrane housing

holds the flat sheet membranes but the system also accommodates other types of membranes that come with their own housing via quick disconnect fittings. Finally, our team visited a laboratory AnMBR setup at UIUC to get a more detailed perspective on AnMBR and learn about many of the problems that they encountered.

### 5.2 PHYSICAL BUILD CHALLENGES AND KEY PARTS

In order to anticipate challenges with the physical system, we examined our model as well as inquired about common problems with AnMBR systems. From this examination we found a series of manufacturing and performance challenges to expect as well as a series of key parts that are most important to a successful build.

Manufacturing issues: Our most difficult manufacturing issue was the CNC machining of the flat sheet membrane adapter. This design has evolved into a single membrane module. A flat sheet module provides a closer representation of the operation of a full-scale system and is easier to manufacture. However, the design required curved tool paths that cannot be made on a manual mill. Additionally, the footprint needed to machine the part cannot be accommodated on tools that the University could provide. Therefore, our design was sent to Quad Precision Tool in Rochester, Michigan and they performed the machining.

Issues from similar systems: After visiting the Morgenroth Research Group at the University of Illinios at Urbana-Champaign, we were able to draw some conclusions that have helped us with our design. For example, our reactor uses a magnetic agitator assembly, which provides a seal around the impeller assembly. This will prevent leaks from the primary source as seen by the Morgenroth Group in one of their reactors without this type of seal.

Key Parts: All necessary parts were obtained through vendors and arrived in time to construct a complete prototype. However, the delivery time of the gas flow meter for the escaping methane is such that it will arrive after the end of the ME450 course. Since this component is only providing a measurement, it will not impact any of the feedback properties of our system, and the system will be operational without measuring the gas output of the bacteria.

### 5.3 ANALYSIS OF ALPHA DESIGN

Much of our system consists of hardware that requires testing and calibration. For instance, we needed hardware to address sealing challenges and calibrate the temperature and flow controls. Heat transfer analysis of the temperature controller both will not be necessary since we are purchasing a pre-calibrated system. Finally, “virtual audits” using our CAD models were used to check for interferences and potential manufacturing issues.

### 5.4 ENGINEERING FUNDAMENTALS

The experimental performance of our system depends on our understanding of fluid mechanics, heat transfer and basic control systems. Fluid mechanics are essential in our pump selection, monitoring wastewater flow, fouling control strategies, biogas collection and many other challenges in our system. Chemistry knowledge was helpful, but not essential as we could refer to our sponsors and various technical papers for the reaction requirements.

# 6. CONCEPT GENERATION AND SELECTION

In order to develop our overall system, we broke it into smaller subsystems: anaerobic bio- reactor, hydrolysis, temperature control, automatic feed dilution, membrane configuration, ion exchange, and connectors, piping and pumps. We then held a "freewheeling" brainstorming session where each team member generated concepts on the chalkboard. The objectives for each subsystem were then prioritized and compared to our generated concepts to evaluate their strong and weak points. Finally, an alpha subsystem concept was agreed upon based on its feasibility and potential effectiveness in meeting the stated objectives. We used our alpha concepts as selection criteria when we chose our off the shelf components. This section discusses a few of our concepts; please see Appendix C for a pictorial breakdown by subsystem of all our generated concepts with brief descriptions.

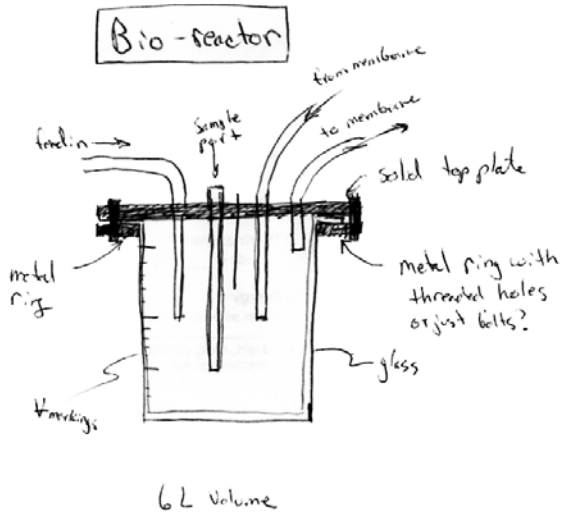
## 6.1 ANAEROBIC BIOREACTOR

This component needs to be gas-tight as well as have sampling and instrumentation ports to carefully monitor the conditions within the reactor. It needs to have a 6L overall volume and be made out of glass.

The sampling system was the main focus of our first concept. Three lines of tubing would be run through the top of the reactor and reaching to different lengths within it to sample the different strata of bacteria. Syringes were attached to the end of the lines to draw fluid out in a precise amount. This idea would work very well, but it requires space in a very crowded lid. The second concept worked with the idea of creating the reactor out of Plexiglas so that it would be feasible to install sample ports on the sides of the vessel. This would give us plenty of room on the lid for inlet/outlet piping as well as the gas collection system. However, since the reactor needs to be sterilized and the contents need to be visible, it should be made out of glass. Our last idea was a slight modification of our first; we would have created one sample port on the lid that could be inserted, based on graduations on the tubing, to specific depths in the tank (Figure 4). Fluid would have been withdrawn with a syringe.

Our selected concept incorporates the best parts of each generated concept. It will be made of a 7L glass vessel (6 L working volume), with a gas-tight seal containing inlet/outlet lines as well a single sample port. The sealing mechanism will consist of a gasket sandwiched between metal rings that can be tightened with wing nuts.

**Figure 4: Bioreactor Concept**



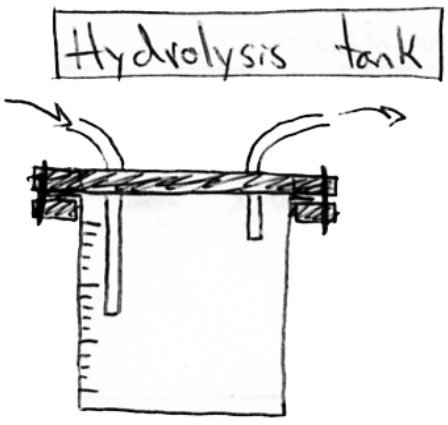

- Clear glass
- Easy to seal
- Room in top plate for tubing, instrumentation, and sample ports
- 6L working volume

## 6.2 HYDROLYSIS

This system is a "priming" tank to hold the pre-mixed wastewater and let it decompose until it is ready to be pumped into the bioreactor. This component needs to be air tight, at room temperature and have a 6L volume.

This unit is subjected to the same requirements of the reactor. Thus, its design will mirrored our selected concept for that system. It would have been made of clear glass, easy to seal, and will incorporate a system of tubing and instrumentation on its lid. Please see Figure 5 on page 11. However, the current system is able to control the hydraulic retention time of the waste water, therefore the implementation of the hydrolysis tank has been delayed indefinitely. Our system is flexible enough to allow the implementation of this subsystem in the future.

**Figure 5: Hydrolysis Selected Concept**




- Clear glass
- 6L volume
- Easy to seal
- Room in top for instrumentation and tubing

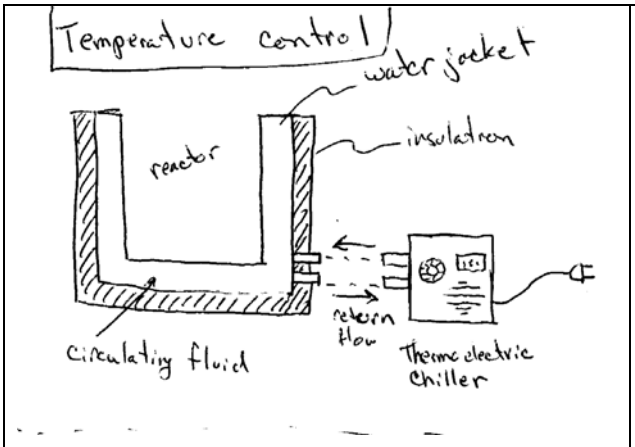
## 6.3 TEMPERATURE CONTROL SYSTEM

This system needed to be an easy, low maintenance, durable and inexpensive way to control the temperature of the bioreactor. This is very important to our system because of the sensitivity of the anaerobes to temperature.

We considered several options. One design consisted of a water jacket with an inlet for cold tap water for cooling and heating wires inside the jacket for heating. There would be insulation to minimize losses and a stirring mechanism in the bottom to evenly distribute the temperature. However this would be very challenging for us to construct ourselves and because of the material considerations and it would not be easy to replace or repair parts as they would be trapped in the water jacket. It would also be impossible to place sample ports around the sides of the reactor. Our second idea was to place the heating coils directly inside of the reactor to allow us to insert sample lines into the sides. However, this reintroduces the issue of replacement and repair since the bioreactor's process is very fragile and it also would create hotspots within the vessel. Another idea was placing flexible tubing wrapped with heating tape around the reactor. Tap water would flow through the tubing and controlling the input voltage could control the heating tape. Cooling would be achieved by turning off the heat and only running cold water through the tubing. This idea would not be practical as there would be minimal surface area to transfer heat making it inefficient as well as the risk of hotspots.

Our chosen design appears in Figure 6 on page 14. It will efficiently and evenly heat and cool the reactor and minimize heat losses. It has good manufacturability and the heating mechanism is both simple and easily accessed. The water jacket that we used was built into the bioreactor itself. The thermoelectric chiller was a separate acquisition that meets and exceeds the temperature range of the bioreactor itself. It uses a PID control system to precisely control the system temperature within the bioreactor.

**Figure 6: Temperature Control-Selected Concept**




- Simple control of thermoelectric device
- Uniform heating of reactor with water jacket
- Insulation to improve efficiency
- Fewer moving parts with thermoelectric chiller

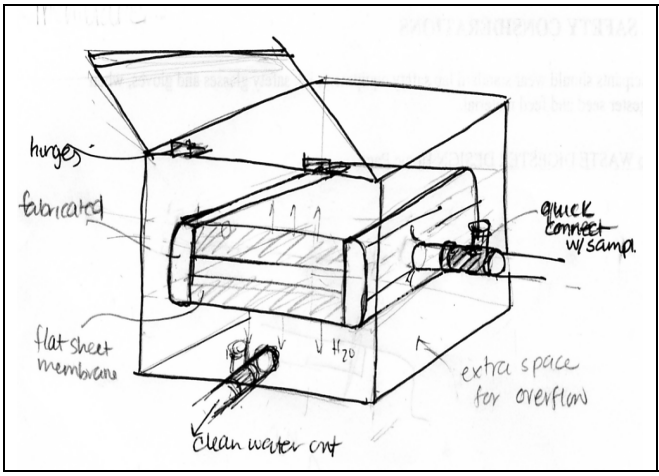
## 6.4 MEMBRANE CONFIGURATION

In this subsystem, adaptability was found to be the most important criteria. It needed to be able to accommodate tubular, as well as flat sheet, membranes. It also needed to be sealed while operating to maintain a pressure gradient across the membrane.

Our initial concept was to construct one "box" that would house all test membranes. Effluent from these membranes would be collected together. While this would make the system very compact, it would hinder the versatility of the system and it would be difficult to isolate effluent from individual membranes. Our second concept allowed for piping with a series of valves that could be opened or closed to direct the flow to be either parallel or in series.

Our chosen concept works with a clear, sealed housing for each membrane. This would allow the user to easily reconfigure the system and change membranes. The purpose of sealing the membrane would be to maintain the pressure gradient. Piping between these housing would be in accordance with the concept discussed previously allowing for a variance of flow.

**Figure 7: Membrane Configuration-Selected Concept**

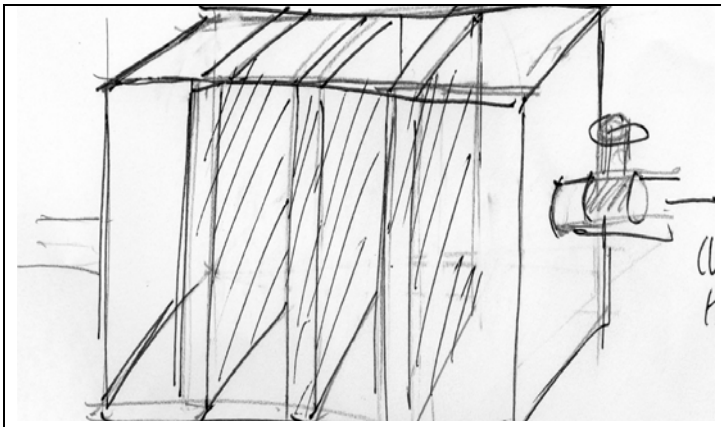



- Reconfigurable housing module for flat and tubular membranes
- Clear housing
- Sealed container to maintain pressure gradient
- Easy access to chamber for swapping membranes with hinged top

## 6.6 ION EXCHANGE

While the ion exchange system was deemed to originally to be feasible, during the course of our project, it was decided that this system will be treated as a black-box design, and was not incorporated into the final prototype. However, the flexibility of our system permits the addition of this subsystem at a later date.

**Figure 8: Ion Exchange- Preliminary Concept**



- Clear housing
- Sealed container to maintain pressure gradient
- Easy access to chamber with hinged top

## 6.7 AUTOMATIC FEED DILUTION

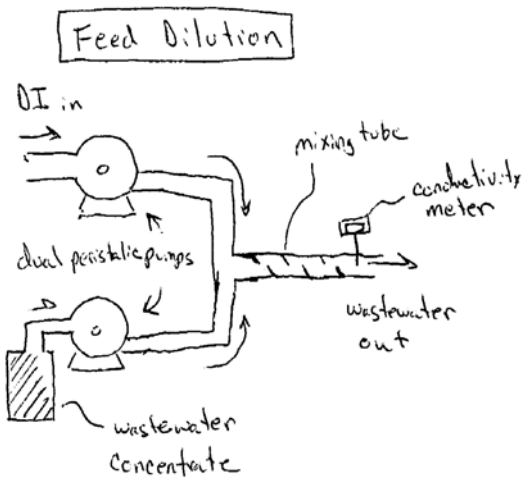
This system needs to automatically deliver specific concentrations of the lab wastewater concentrate into the DI water to be processed by the AnMBR. Accurate measurement, delivery and control are essential to this subsystem.

Our first idea was to dispense DI water by means of a valve that could be set to the appropriate flow and dispense concentrated sludge from a holding tank with a mechanically driven auger. The speed of this auger would be set to add the sludge at a specific rate. Due to the low flow considerations and the accuracy that is required in this

process we eliminated this concept. Our next idea also used a mechanical driver to rotate a container on a circular plate. There would be three positions: a DI water dispenser, a sludge dispenser and a release. As the container would rotate it would trip a switch to release a set amount of each liquid and then open a trap door in the bottom of the plate that would release the mixed solution. We eliminated this idea based on the fact that it would be extremely hard to control, would involve many moving parts, and may not survive the two plus years that the system will run. The final idea that we did not choose worked on the same principle as a faucet except the cold and hot water taps would be replaced by the DI water and sludge. Valves would control the amount of flow. We did not choose to pursue this because valves would be an unreliable method to control the fluid.

Our selected concept appears in Figure 9 on page 14. A pair of peristaltic pumps will easily and accurately control flow and ensure proper mixing. This system will also allow us to integrate monitoring devices without difficulty.

**Figure 9: Feed Dilution-Selected Concept**




- Simple mass flow/concentration control of DI water and WW concentrate by varying speed of peristaltic pumps.
- Uniform mixing of water and concentrate
- Space for conductivity instrument

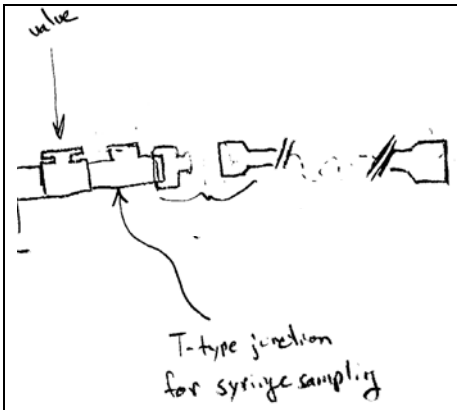
## 6.8 CONNECTORS, PIPING AND PUMPS

This aspect of the design does not require multiple concepts, as there are set pressure requirements and we would like one standard system of tubing and connectors. Our tubing diameters vary depending on the subsystem. All of the tubing is made of Tygon, due to its low gas permeability, which is necessary to support the anaerobic bacteria within the system. Also, all of the tubing was ordered from the MasterFlex series of tubing from Cole-Parmer, in order to be compatible with our peristaltic pumps.

The automatic feed dilution system uses L/S-13 and L/S-16 sized tubing in order to provide approximately a 1:15 dilution ratio for our feed. L/S-18 tubing was used for the recirculation tubing, since this larger (approximately 3/8" ID) tubing allowed a greater range of cross-flow rates when combinged with the 10-600 RPM peristaltic pump that is used for recirculation. To ensure the maximum amount of configurability options and monitoring, all piping to and from units was originally designed to include a valve-sample port-quick connect series pictured in Figure 10 below. Our current design incorporates a T fitting with half of a quick disconnect, which does not let any flow through when it is not connected. This way, samples can be taken during operation, by

simply connecting the other end of the quick disconnect fitting, and a length of Tygon tubing.

**Figure 10: Piping and Connectors-Selected Concept**




- Maximum configurability of subsystems with:

(valve)+(sample port)+(quick connect)

- Same parts throughout system
- Chemical resistant tubing, valves and connections

## 6.9 ALPHA DESIGN

The CAD model and schematic shown in Figures 11 and 12 on page 16, respectively, illustrate the alpha concept. This concept is a compilation of the selected subsystems from the previous section with the addition of membrane configuration, lines and pump configuration. Additionally, they show preliminary placement of pressure gages and flow meters. Notable details are the number and locations of pumps and the details of the bioreactor configuration seen in Figures E1 and E2 in Appendix E.

**Figure 11: Alpha concept schematic for AnMBR lab setup**

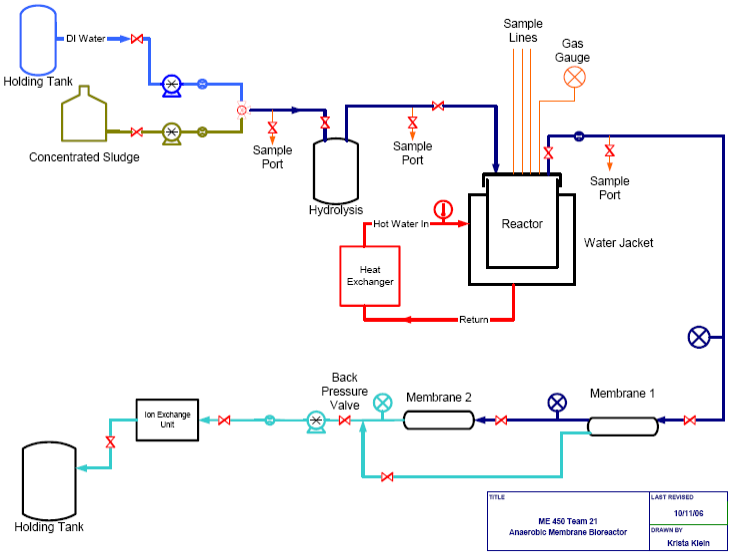
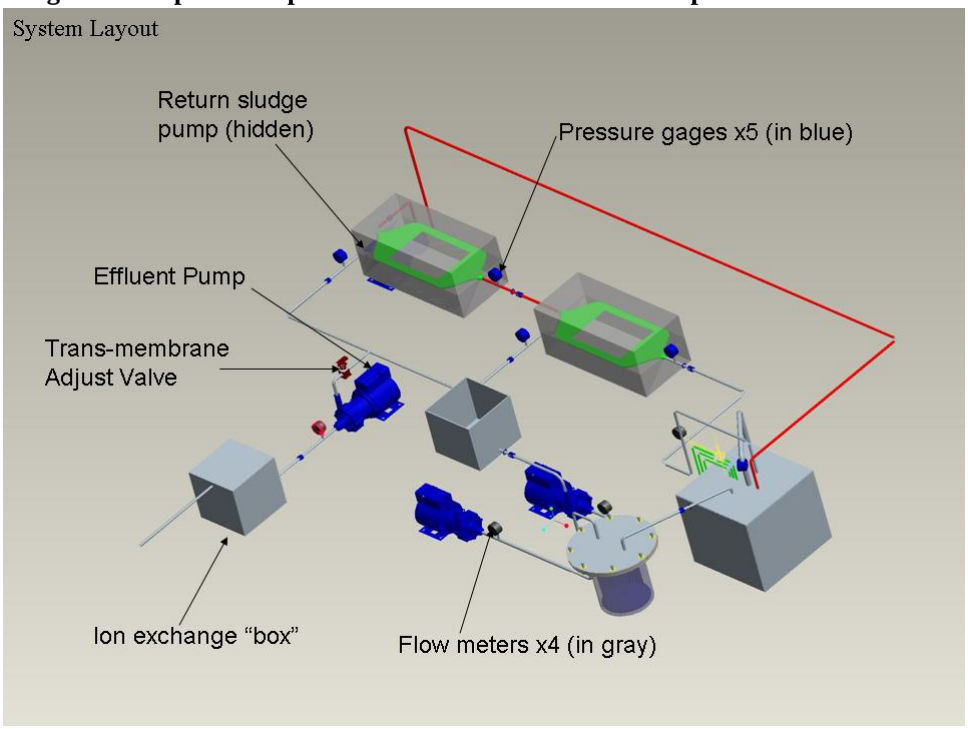


**Figure 12: Alpha concept CAD model for AnMBR lab setup**




# 7. SELECTED CONCEPT DESCRIPTION

## 7.1 ENGINEERING DESIGN PARAMETER ANALYSIS

The only component that we are designing for manufacture is our flat sheet membrane housing. All other components will be purchased.

**Flat-sheet membrane holder**

A membrane holder was designed to provide a self-contained housing for a 200 mm x 200 mm flat sheet membrane, which will be provided by Sterlitech. The design is a scaled version of a similar membrane holder currently in use by our collaborators at the University of Urbana-Champaign in Illinois. The inlet and exit port sizes were chosen to match the flow rates in our recirculation loop. The design incorporates two acrylic pieces, which sandwich the membrane between them. One side provides an inlet for the waste water flow, while the other will provide drainage for the filtrate. The system was sealed with two 1/4 inch thick O-rings. Many of the design parameters for the membrane holder were determined by the fixed size of the membrane. The main variable was the depth of the waste water cavity, since the cross sectional area (defined by the edge of the membrane crossing the flow times the depth of the cavity) determines the velocity of the waste water flowing over the membrane. The membrane holder was connected to the rest of the system via the same quick connect fittings that are used throughout the system itself. Since this is a scaled version of a design in currently in use we have a high degree of confidence in its success.

**Pump drive selection**

As recommended by Zhang [8], et al., a low shear force is necessary to prevent the breakup of the bacterial flocs in the system. To provide low shear force within the feed and recirculation of the system, we chose to use peristaltic pumps in the same manner as

used in Zhang's system. The pump selection was limited in several respects. During our visit to the University of Illinois Urbana-Champaign, we found that the progressing cavity pump had durability issues and were advised to seek other options. The pumps also had to have an input for computer control and had to be run at 100% duty cycle for continuous operation of the system. Moreover, the pumps have to be able to run at a maximum flow rate of 15 L/day for the feed system, and 60 L/day for the recirculation loop, with as low of a flow rate as possible. Finally, the pump heads in the feed pumps had to be stackable in order to avoid the purchase of another pump. Thus, we chose to use MasterFlex L/S computer controlled digital drives. Two drives with a 1.6-100 rpm gearing were purchased for the feed into and out of the bioreactor, and one drive with a 10-600 rpm gearing was purchased for the recirculation loop.

**Pump head selection**

The L/S series of peristaltic drives can accommodate a variety of pump heads. We chose the Easy-Load II pump heads, since they are stackable, and accommodate the range of tubing that was required to provide the necessary flow rates for the system. Also, the use of four rotors instead of three provides less pulsation in the system, which can help avoid floc breakup. As compared to the other available pump heads, the Easy-Load II pump heads can provide the highest range of flow rates for a given drive gearing and tubing size. In addition, the pump heads have variable occlusion, which will provide adjustability to decrease wear on the peristaltic tubing itself.

**Tubing selection**

Several criteria determined the tubing selection. First, all of the tubing must have low oxygen permeability to eliminate oxygen leakage into the system. Also, the concentrate and water feed tubing had to have a specific volumetric flow ratio to provide the correct mixture of the waste water. In the recirculation loop, the tubing had to provide an adequate range of flow rates corresponding to 2-4 times the permeate flow rate through the membrane.

**Bioreactor**

The bioreactor was manufactured by Applikon. We chose this design from one of two companies who manufacture such jacketed vessels. The options for the bioreactor were chosen based on the available fittings from the manufacturer, price and reputation.

## 7.2 FINAL DESIGN DESCRIPTION

The final design now includes three main systems, as opposed to the original five. These are the automatic feed, the anaerobic bioreactor, and the membrane filtration systems. We will also be creating a flat sheet membrane housing that will work within the filtration system. After some dialogue with our sponsors, it was decided that the hydrolysis and ion exchange systems are outside the scope of this project, and will be integrated at a later time. Changes to the alpha concept for each system are discussed in the following sections. The final system schematic is shown in Figure 13.

### 7.2.1 Automatic Feed

The automatic feed system consists of a single Cole-Parmer peristaltic pump with dual heads for the synthetic waste concentrate and de-ionized water lines. The concentrate and water tanks will have capacities of at least 30L each to allow for minimum 2 days of

unattended continuous operation. As a result, the waste concentrate will be fed at a minimum rate of .096 mL/s, while the water is fed at a rate of 1.28 mL/s. This gives combined influent flow rate of 1.38 mL/s into the bioreactor. The tube diameters are 0.8 mm ID and 3.1 mm ID for the concentrate and water respectively. These lines will join before entering the bioreactor to ensure adequate mixing.

### 7.2.2 BioReactor and Temperature Control

The bioreactor is a 7L glass jacketed vessel from Applikon, with a working volume of 5.9L. Its temperature will be maintained by a Cole-Parmer Polystat 6 Liter digital temperature control system and bath (-20ºC – 150ºC ± 0.05ºC). It will circulate water between the inner and outer layers of the vessel at a rate of either 9 or 15 L/min, depending on the reactor heat loss to the surroundings. The sealed headplate has a total of 18 ports for the following:

**Table 3. Headplate Port Assignment**

| Part | Port |
|---|---|
| Magnetic stirrer | threaded port |
| Nipple (for pH sensor) | 18mm |
| Electrode holder (for level sensor) | ¾” |
| Thermometer pocket (for temperature sensor) | 10mm |
| Sample pipe, adjustable | 10mm |
| Sample Pipe for Inlet (fixed) | 10mm |
| Sample Pipe for Outlet (adjustable) | 10mm |
| Level Sensor | - |
| Air outlet pipe (for methane gas) | 10mm |
| Septum holder | 18mm |
| Blindstoppers for remaining for 18 mm ports | 18mm |
| Blindstoppers for remaining 12 mm ports | 12mm |
| Blindstoppers for remaining 10 mm ports | 10mm |

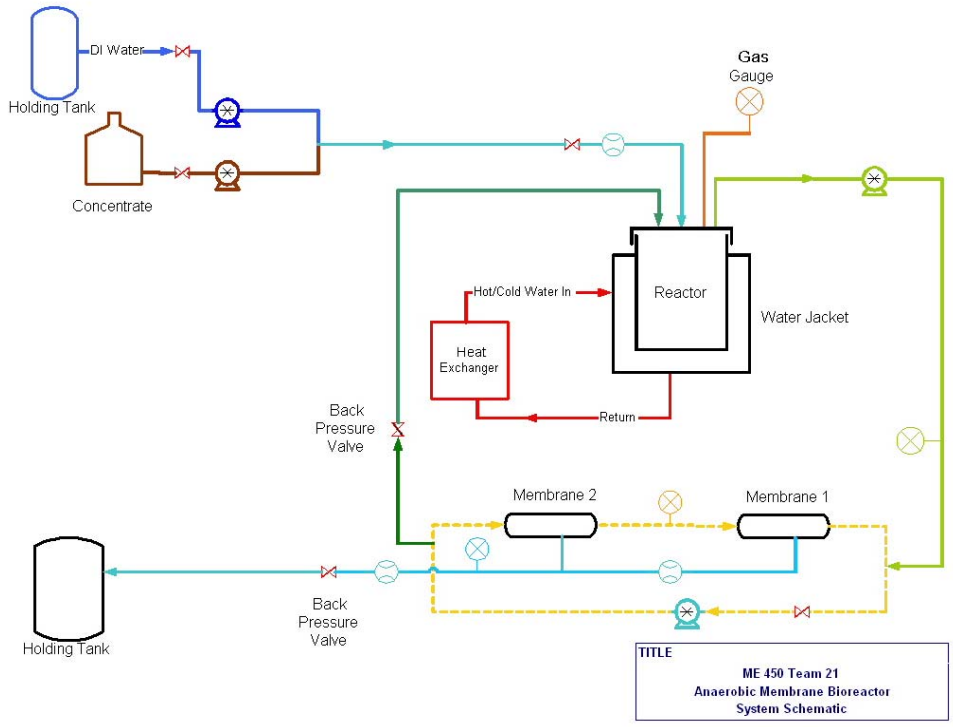
Detailed part information for the bioreactor can be found in Appendix G. The effluent from the bioreactor is pumped through a second peristaltic pump to the membrane filtration system.

### 7.2.3 Membrane Filtration System

The membrane filtration system is situated in a recirculation loop that includes 2 membranes in parallel or series, a third peristaltic pump, and two backpressure valves. It has one inlet line from the bioreactor pump and two exit lines for waste and filtrate collection respectively (see Figure 13).

The recirculation loop operates at flow rates of 2Q-4Q, where Q represents the permeate flow rate through the membrane. The recirculation loop is constructed of Tygon tubing with a diameter of 7.9 mm ID. The system will have the capability of accommodating two membranes, though initially it will be validated using only a flat sheet membrane with dimensions of 200mm x 200mm. The other membrane will be of a tubular format with a length of 1m and will be operated at pressures of 20-70kPa. The flat sheet membrane will be enclosed in a sealed Plexiglas adapter (Figures 15 and 16 on page 22), which has inlet and outlet cross-sectional area of 595 $mm^2$. The membrane has a pore size of 0.45µm.

**Figure 13: System Schematic**




### 7.2.4 Flat Sheet Membrane Housing

Based on previous literature and the input of our sponsors, a 200 mm x 200 mm polyethersulfone (PES) membrane with a pore size of 0.45 µm was selected. To study the fouling characteristics of the membrane in an application similar to a full-scale device, we were instructed to develop a membrane holder device that will allow the wastewater flow to be filtered by a single membrane (Figures 15 and 16, page 19). A membrane holder was designed and consists of two pieces, in between which the membrane will be clamped. The assembly was sealed by two ¼ inch thickness O-rings. The interior O-ring provided a seal between the filtrate and wastewater cavities, and the external O-ring will seal the complete system, and also serve to balance the clamping forces so that the ¼ inch bolts that join the two halves together do not exert any torque on the membrane holder components themselves.

**Material Selection**

Our team has designed membrane holder that will be fabricated out of Plexiglas. The choice of material allows us to see the fouling of the membrane, leaks, and any obstructions to the flow, such as debris in the membrane holder.

**Flow Considerations**

Since the volumetric flow rate across the membrane has to be between 2-4 times that of the feed into the bioreactor, the membrane holder has to be able to handle at most 60 liters per day of waste water flow. Also it is important that the flow across the membrane be as fast as possible for a given flow rate to develop the maximum shear force which

will hinder the development of a cake layer on the membrane surface. Therefore, a 1/8-inch separation was used for the depth of the wastewater cavity in the membrane holder, since a smaller depth risks clogging by the cake layer buildup on the membrane surface, and a larger depth will decrease the flow velocity over the membrane surface.

The filtrate cavity also has a depth of 1/8 inch to accommodate the filtrate that will be removed from the membrane by drainage from this cavity.

**Connections**

The membrane holder will use ¼ inch quick connect fittings that will allow easy disconnections from the rest of the system.

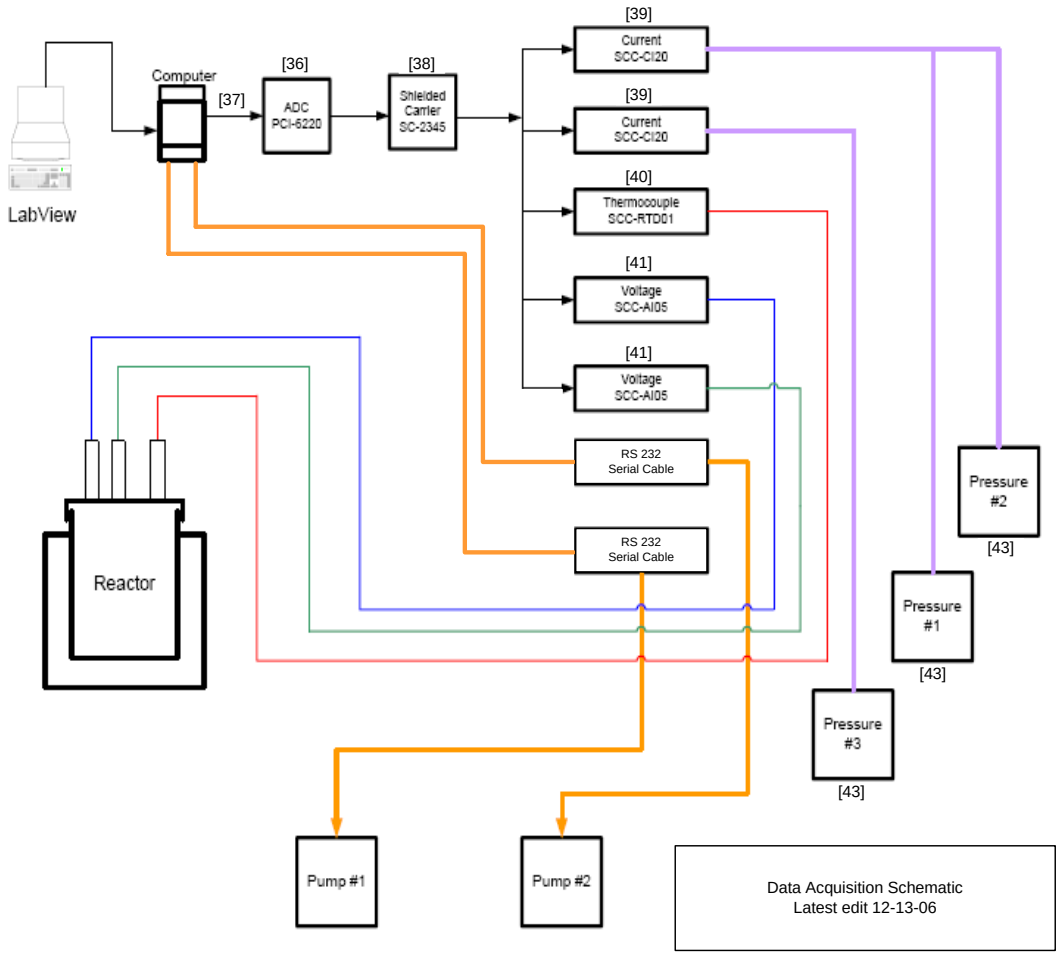
### 7.2.5 Data acquisition and control

In order to monitor the bioreactor processes and acquire data relevant to research, we designed an electronic data acquisition system. Additionally, we wanted to control the pumps with a system that will monitor the level in the reactor and change the pump speeds accordingly. Therefore, our final design (Figure 14) utilized National Instruments hardware and LabView and can accommodate both input and output signals.

The first task was to place and find sensors based on our application. We decided on using 3 pressure transmitters; 1 on each side of the membranes (see Figure 14 on page 21) to monitor trans-membrane pressure. We also required a pH transmitter, a thermocouple and a level sensor to monitor conditions in the bioreactor. The pH transmitter and thermocouple and level sensor come with the bioreactor. Our system will also use flow meters to monitor the effluent flow rate as well as the flow into and out of the reactor. Unfortunately, we could not find flow transmitters that can read low flows. We have therefore decided on 2 flow meters that do not output an electronic signal.

Finally, we needed to determine the appropriate signal processing hardware. We decided on the National Instruments PCI-6221 Analog/Digital converter with the SC-2345 shielded carrier. The SC-2345 accommodates signal conditioning modules for all of our sensor outputs and also accommodates modules available for current outputs for the peristaltic pumps. These signal conditioners and the Analog/Digital converter allow the computer to interface with sensors and pumps. We can then use LabView to acquire data and store the history of bioreactor conditions and membrane pressures. Additionally, we will use LabView to control the pumps. The schematic in Figure 14 shows all the required hardware and the final parts list can be found in Appendix G.

**Figure 14: Data Acquisition System Schematic**




## 7.3 MANUFACTURING AND ASSEMBLY PLAN

Our project has focused on designing a system as opposed to designing its actual components. As a result, all of our components, with the exception of the membrane housing, were ordered and shipped to us at U of M. A complete bill of materials and referenced sub-system components can be found in Appendix G. We then assembled the ordered parts according to our schematic shown in Appendices H, I and J. This section will be focused on the construction of our membrane housing, which we designed ourselves. There are a few deviations from our original plan which we will discuss below.

### 7.3.1 Membrane housing

The membrane housing was custom built to accommodate our available membrane size of 200 x 200 mm. The housing was easily manufactured and is specifically tailored to our needs. The individual components used to make our housing are listed below in Table 4. We financed the housing material with our allotted $400 from the class budget.

**Table 4: Membrane Housing Components**

| Material | Number | Total Cost |
|---|---|---|
| Plexiglas Blocks | 2 | $50 |
| 1/4" – 20 bolt, nut, washers | 16 | ($0.50 ea.) $8 total |
| Inner Rubber O-ring | 1 | $8.95 |
| Outer Rubber O-ring | 1 | $12.30 |
| Quick Connect assemblies | 6 | ($12.50 ea) $75 |
| Porous Membrane Support | 1 | Provided |

The housing was machined out of 2 Plexiglas sheets with a CNC mill as shown in Figure's 15. The actual machining was done at Quad Precision Inc. where there are several machines available to accommodate our manufacturing needs. A problem that they encountered was keeping the drill bit from heating up so much that the Plexiglas actually melts. The resulting thermal expansion caused our first piece of Plexiglas to crack. Fortunately, we had spare pieces.

**Figure 15: Bottom Half of Housing**

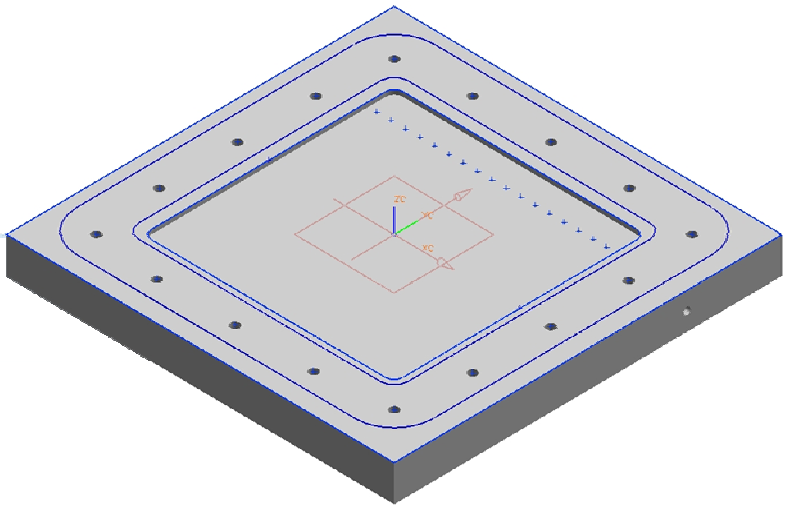
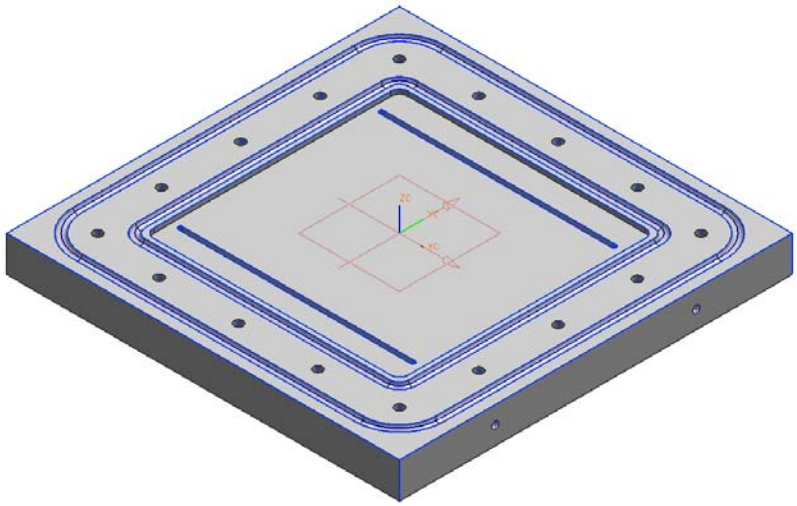


**Figure 16: Top Half of Housing**



There were a few challenges associated with the final assembly and validation of the membrane housing. Our first problem was that we designed the holes in the side of the housing to be threaded for ¼-20 hardware. Unfortunately, we needed the threads to accommodate pipe threading which are tapered, which is different than bolt threading. As a result, we were unable to find a proper fitting online or at the store. So, we had to custom make our tube adapters as is shown in the table above. Our first attempt at making a custom fitting was using the mill to create a barbed hose fitting out of aluminum rod. We found out however that this component was very difficult to thread. Our next option was to drill a hole axially through a ¼-20 bolt. This option was much better and we were able to produce them faster.
Our second challenge was the O-rings. The O-rings that we had ordered did not have the right circumference and were too rigid to stay in the tight corners of the channel we had cut for them. As a result, we used some left-over LS-16 tubing that was cut to the perfect length and glued with silicone aquarium sealer. The resulting custom-made O-rings worked perfectly. We were able to pressurize our membrane housing up to 100kPa (which was the limit of our pressure gauges) without leaks.

### 7.4 VALIDATION PLAN

In order to make sure our system works properly we will need to validate the manufactured components, subsystems and the complete system. The only parts that we manufactured are the membrane housing and some tubing connectors. We validated the membrane housing independently and the manufactured connectors were validated with their respective subsystems. With this in mind, the following was our validation schedule as of November 9, 2006:

- Data acquisition validation (11/8 to 11/25)
  - Install hardware
  - Labview programming
  - Sensor calibration
- Membrane housing validation (11/17 to 11/25)
  - Run under operating flow rates
  - Check for leaks
  - Check trans-membrane flow rate
- Auto feed dilution validation (11/12 to 11/22)
  - Set up pumps, tubing and tanks
  - Manufacture connectors
  - Run system and check for leaks
  - Verify feed concentration (using conductivity sensor)
- Recirculation loop validation (11/15 to 11/25)
  - Set up pumps and tubing
  - Manufacture connectors (pressure sensors)
  - Check for leaks
  - Verify trans-membrane flow
- Reactor validation (11/17 to 11/25)
  - Connect sensors
  - Check for liquid and gas leaks
- Temperature control validation (11/20 to 11/22)
  - Connect temperature control to reactor

    - Measure steady state reactor temperature
- Overall system validation (11/25 to 12/1)
    - Connect sub-systems
    - Manufacture additional connectors
    - Check for leaks
    - Verify flow to / from recirculation loop is within intended range

In actuality, we ran into some problems with hardware shipments and we were not able to completely assemble our system in the time frame that we planned. Some engineering specifications such as "visible area" and "pump power range" are locked based on the equipment that we have chosen and testing would be redundant. Other specifications such as "number of steps to install components" and "number of potential trip hazards" will have to be examined at the end of the setup since they will depend heavily on the arrangement of components. Generally speaking, our system needs to deliver the correct flow rates, hold a given temperature, acquire data flawlessly and prevent leaks gas or liquid. Our plan gives these issues priority over more minor engineering specifications.

## 8. PROJECT PLAN

The project has been managed by flexibly dividing our group in terms of what needs to be accomplished. In the research phase of the project, each group member took charge of a smaller system within the entire experimental setup. As a result, each group member became an "expert" in his or her system and was be able to communicate its requirements, limitations and role in the overall process to the rest of the group. This has aided the group in the concept generation process, where we collaborated on each design component as a team to generate new designs and adapted existing designs to our applications. However, for the duration of the project, each member will assume new responsibilities. There are three main areas of tasks that we need to address: computer control systems (LabView), data acquisition hardware, and membrane housing construction/manufacture and reactor setup/configuration. Please see Appendix A for the Gantt chart, which details the complete timeline, and the interdependencies between tasks. The Gantt chart also describes the critical path for the tasks.

### 8.1 COMPUTER MODELING

In order to get a sense of the system as a whole we created mechanical drawings, CAD models and both electrical and mechanical schematics of the assembly. More than just the major components, these graphical representations included location of monitoring devices, valves, bypasses and sample points. Mike Cholette was in charge of the CAD models and Krista Klein was responsible for the schematic drawing. .

### 8.2 HARDWARE

The majority of the system was composed of off-the-shelf components. There are several reasons for this. First, the complexity of the system dictates that there are many individual components. These components have to be sealed against air entering the system, methane exiting, and mixing of the treated waste in the various stages of treatment. Our most significant component that we purchased the bioreactor along with its accessories (monitoring devices, impeller, etc.). Also, the modularity of the system lent itself to the use of uniform connections and standardized pieces. Finally, the system needed to be monitored and controlled automatically, so that experiments can run unattended for at least two days.

Our team has been examining various sources for the system components and we have selected specific products and vendors. In order to ensure that all necessary items are ordered, we have created a master parts list for the system (see Appendix G), complete with contact information, prices and item/part numbers. This is shared and reviewed with our sponsors to ensure that all parts are acceptable in terms of cost and operating parameters.

### 8.3 CONSTRUCTION AND TESTING

As parts are obtained, we assembled the individual subsystems before integrating them into the overall system. All group members participated in this step, however the member that "specialized" in the specific component will be responsible for making sure it is done correctly and within the constraints and specifications.

Upon completion, we tested water flow rates, pressures, and temperatures through the system as well as individual components. This required us to calibrate the measurement and control systems. We also needed to ensure that our reactor is sealed against both liquid and gas leaks. See section 9 for more detailed descriptions on construction and validation.

## 9. VALIDATION METHODS AND TEST RESULTS

Validation of the AnMBR system was conducted by validation of each component, using LabView for some device calibration, by conducting experiments, and by general inspection. As a result of these tests (described below) the system is leak free, and the expected feed concentrations have been confirmed for non-particulate solutions (water and DI water) and all sensors (pressure, temperature and level) with the exception of the pH sensor, have been calibrated. The temperature sensor (RTD) is accurate within 1°C for temperatures above 30°C, but is 3°C lower than the water bath readout for the 20°C setting. The level sensor triggers an LED indicator on the LabView interface which switches from green to red when the water reaches the sensor. We have also determined that the pumps deliver precise quantities when calibrated for a given speed but vary otherwise. Further tests will be needed to characterize the error in flow rate with varying pump speeds.

### 9.1 EXPERIMENTAL METHODS

#### 9.1.1. LabView Calibration for Pressure, RTD and Level Sensors

Calibrations for these sensors were conducted automatically using LabView's Data Acquisition VI. This automatic calibration compares user input values to the automatic signals acquired from the signal conditioning hardware.

Pressure Sensors. Before using the automatic calibration for the sensors, the gain for each sensor was calculated from the offset of a calibration curve of voltage vs. pressure. The points on this curve were obtained by taking a range of voltage readings from LabView where gain was equal to zero.

Temperature Sensor (RTD). User defined inputs were taken from a thermometer and calibrated in LabView.

Level Sensor. For this calibration, the bioreactor was filled until the water level reached the sensor, and the corresponding change in voltage recorded and set as a Boolean (LED) in LabView.

### 9.1.2 Pump Calibration

The pumps were calibrated by verifying that volumes pumped from automatic calibration were accurate for a specified time. To verify the volumes, the expected mass of water was calculated based on the set flow rate and compared to the actual amount pumped by weighing on a digital scale. Measurements were taken for each pump at speed of 55rpm and tests were timed.

Automatic Calibration: This is a three step process that can also be found in the MasterFlex Pump Manual. First, the tube size is specified by pushing the size button until the corresponding LED is highlighted. The pump then indicates a preset flow rate for the given tube size and can be set into the calibration mode by pressing the "Calibrate" button. Finally, the "Start button" is pressed and the pump dispenses the preset amount for that flow rate. Since the pump accuracy is based off of a percentage of the RPM, in order to calibrate the pumps it is necessary to do so at the target speed.

**Expected Mass Calculation:** For a given flow rate, $Q$ (mL/min), the expected mass, $m$ (kg), was calculated for a set time (1 minute), using

$$m = \rho v ,$$

where $v$ is the expected volume to be delivered by the pump.

### 9.1.3 Bioreactor Temperature

Since the temperature in the bioreactor is essential to the survival of the anaerobic bacteria, it was important to verify that the temperature in the bioreactor was accurate to within ±1°C of both the temperature sensor and water bath readouts. Temperature measurements were taken for input temperatures of 20°C, 30°C, 35°C and 40°C (dialed in to the Cole-Parmer chiller). When steady state was reached, measurements were recorded from the LabView readout for the RTD, the thermometer reading in the bioreactor, the thermometer in the chiller water bath, and the digital readout of the chiller. Steady state was reached in approximately 30 minutes for the 30°C, 35°C and 40°C settings, and approximately 1 hour for the 20°C setting.

### 9.1.4 Feed Concentration

Two experiments were conducted with different concentrate solutions (tap water, apple juice and orange juice) and varying pump speeds were used to ensure that correct ratio of mixture of feed was being delivered by the feed pump. The first was conducted with the tap water/DI mixture to determine if concentration changed with pump speeds of 10, 55, and 80 rpm. The second experiment was conducted to observe the change in concentration with different mixtures. Here, the conductivities of two other mixtures of apple juice/DI water and orange juice/DI water were measured for a pump speed of 55 rpm.

**Conductivity Measurement.** This was measured using a conductivity meter. Three or four readings were recorded and averaged for each measurement. A reading was taken by pouring a small amount of the liquid into the sampling area of the meter and pressing the "Cond" button.

**Conductivity Calculations.** Since the tubing is sized for a 1:15 ratio of concentrate to DI water, the expected percent of concentrate in the mixture is 6.25%. To verify this, the conductivity of the concentrate ($C_{conc}$ ) was measured and used to calculate the expected conductivity of the mixture ($C_{mix}$) as given below:

$$C_{mix} = ((1/16) \times C_{conc}) + C_{DI}$$

The actual conductivity of the mixture was then measured and used to calculate the actual percent of concentrate in the mixture as follows:

$$\%Conc = \frac{C_{mix} - C_{DI}}{C_{conc}}$$

### 9.1.5 General Inspection

Once the system was completely assembled, water was passed through the system to verify that all leaks were repaired and all hoses were well connected. This was done continually as the above tests were performed with specific attention given to the membrane system specifically.

## 9.2 TEST RESULTS

### 9.2.1 Pump Calibration

All three pumps we found to be accurate within 5 grams of water per sample for the feed pump, and within 1 gram for the recirculation and bioreactor pumps, for a speed of 55 rpm below, shows the results for each pump.

**Table 5: Comparison of Expected Mass vs. Calculated Mass for Pumps at 55 RPM**

| Trial | Feed Pump | | Recirculation Pump | | Reactor Pump | |
|---|---|---|---|---|---|---|
| | Actual (g) | Expected | Actual (g) | Expected | Actual (g) | Expected |
| 1 | 95.05 | 100 | 200.92 | 200 | 54.70 | 55 |
| 2 | 94.65 | 100 | 200.45 | 200 | 54.65 | 55 |

### 9.2.2 Bioreactor Temperature

We found that the RTD reads within ±1°C of the actual reactor temperature (measured by the thermometer), however it has as much as a 3°C variation with the chiller readout as shown in Tables 6 and 7 below.

**Table 6. Summary of Comparisons between RTD, Chiller and Actual Water Temperatures**

| | Error | | |
|---|---|---|---|
| **T_Chiller (reading) C** | **RTD vs Reactor Temp (C )** | **RTD vs Chiller Readout** | **Reactor vs Chiller Readout** |
| 20 | 0.5 | -2.5 | 3 |
| 30 | 0.5 | 2 | -1.5 |
| 35 | 0 | 2 | -2 |
| 39.9 | -0.2 | 1.7 | -1.9 |

**Table 7. Temperature Measurements for Chiller, Reactor and RTD Sensor**

| T_Chiller (reading) C | T_Chiller (Actual) | | T_Reactor_Water | | RTD | |
|---|---|---|---|---|---|---|
| | Temperature | Error | Temperature | Error | Temperature | Error |
| 20 | 21 | 1 | 23 | 3 | 22.5 | 2.5 |
| 30 | 31.2 | 1.2 | 28.5 | -1.5 | 28 | -2 |
| 35 | 36.1 | 1.1 | 33 | -2 | 33 | -2 |
| 39.9 | 41.5 | 1.6 | 38 | -1.9 | 38.2 | -1.7 |

### 9.2.3 Feed Concentration

From these experiments, we found that concentration remained constant regardless of pump speed (Figure 17). We also determined that for the non-particulate mixture of tap water (concentrate) and water, the percentage of concentrate in the mixture was within 1% of the expected value of 6.25% (1/16$^{th}$ part) in Figure 18. For the particulate mixtures of apple juice/water and orange juice/water however, the percentage of concentrate was higher (10-14%) in Figure 19. This could be attributed to the non-homogenous nature of these solutions which would result in varying concentrations for any given sample of the mixture. To confirm and account for this, further tests will need to be conducted to verify the concentrations of the actual feed mixture.

**Fig. 17 Concentration Remains Constant with Pump Speed**

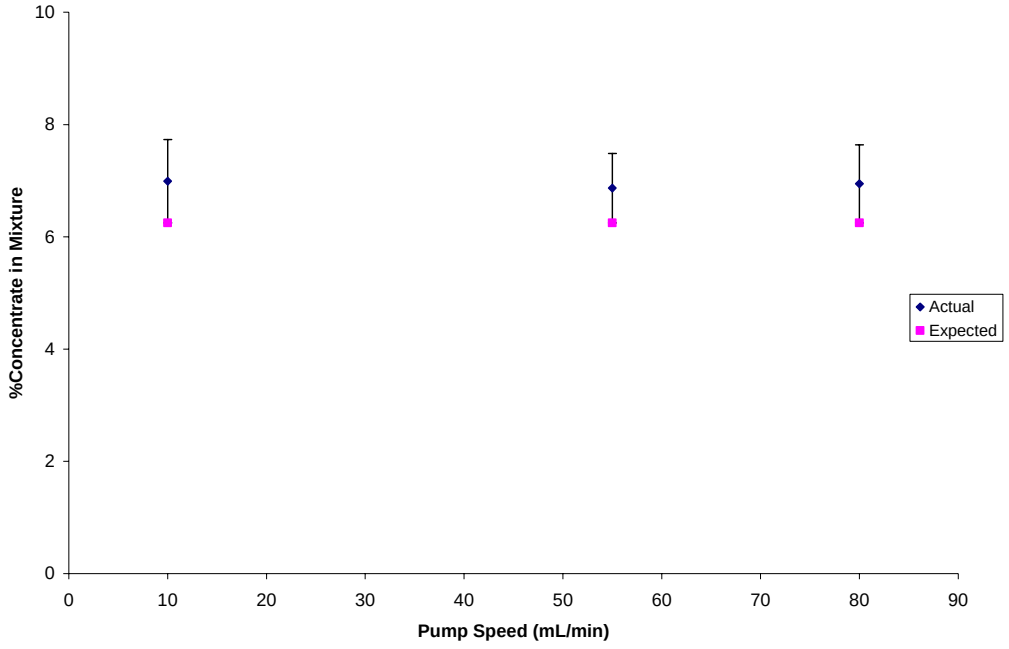


**Fig 18. Percent Concentration of Tap Water is within 1% of Expected Value**

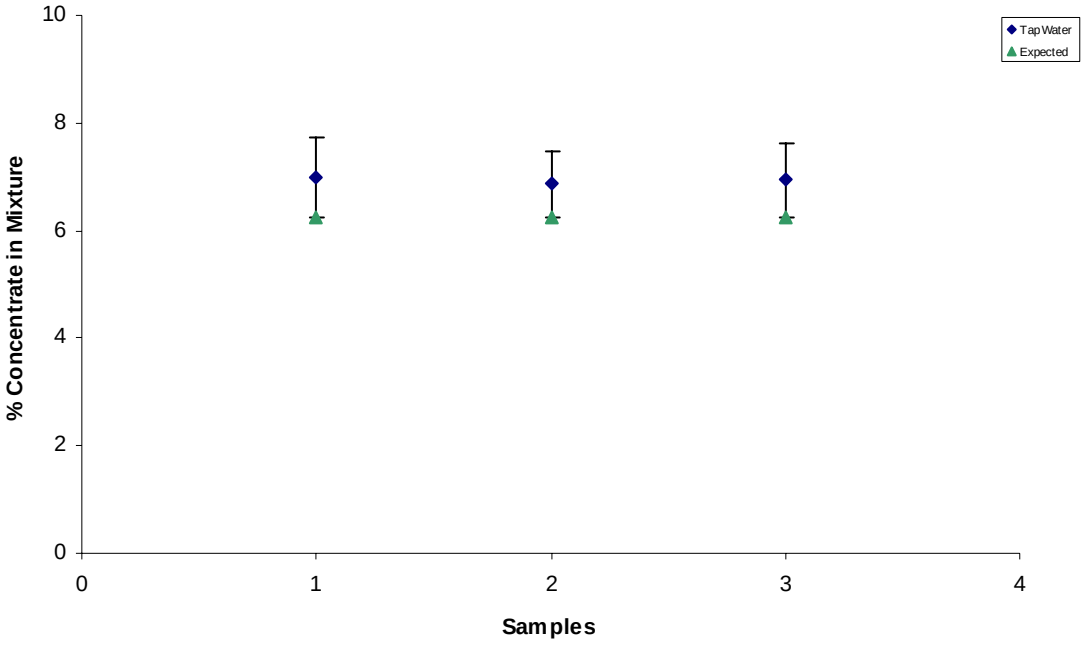
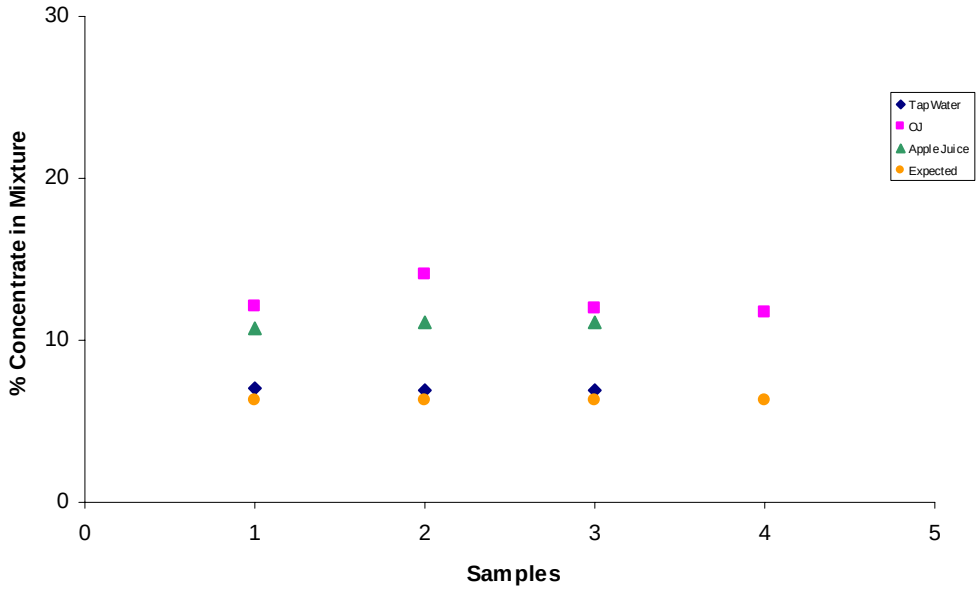



**Fig 19. Percent Concentrations in Apple and Orange Juice Mixtures were 4-8% Higher than Expected**




## 9.2.4 Membrane Holder

The membrane holder had no major leaks and withstood pressure up to 100 kPa. One non-critical leak occurred between the inner gasket and the membrane surface, but this was most likely due to the capillary action of the membrane. After we received the membrane, it was discovered that the dimensions were different than that which was advertised, and therefore the membrane had to be cut by hand. This could have

contributed to the leak itself. However, the leak was contained by the outer gasket, and therefore was deemed non-critical.

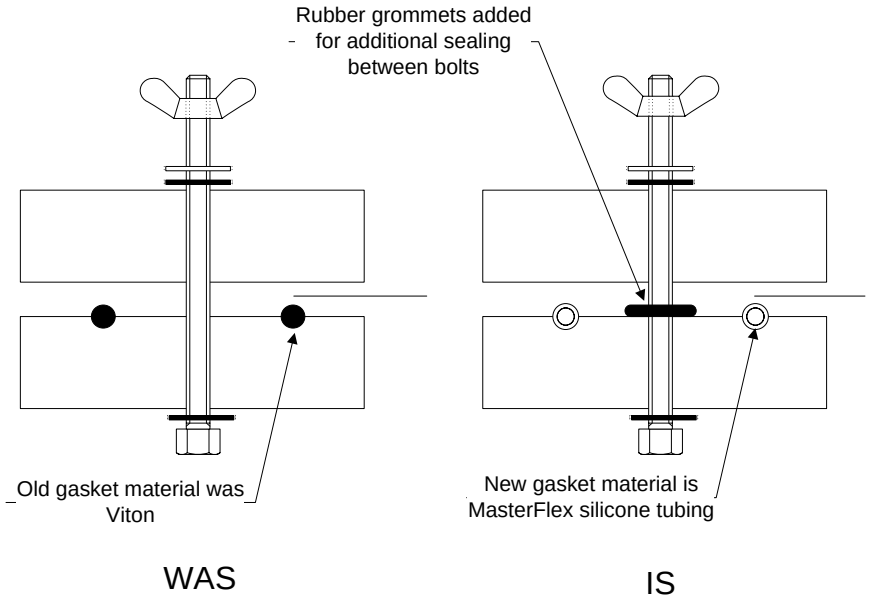
**Future Calibrations**
Due to time constraints, we were unable to calibrate the pH sensor and flow meters, however they are fully functional. The pH sensor will need to be calibrated for the LabView system as well as with buffer solutions.

## 10. ENGINEERING CHANGE NOTICES

The two engineering changes were regarding the temperature control system, and the membrane holder. The first engineering change notice is regarding the water jacket that provides the temperature control of the bioreactor. The automatic feed system will be adding synthetic waste water that is close to room temperature, and the water jacket itself is bounded by room-temperature air. To cool the bioreactor to 5 degrees Celsius, it may be necessary to cool the coolant to a temperature below 0 degrees Celsius. The recirculating chiller will be able to provide this range, provided that ethylene glycol is added to the water in the reservoir as per the manufacturer's instructions for the chiller. Therefore if the system is operating within this temperature range, it will be necessary to add ethylene glycol to the system to prevent the coolant from freezing.

The second ECN is regarding the sealing of the membrane holder. The Viton gasket, which was not able to adequately conform to the geometry of the membrane holder, was replaced with a length of silicone MasterFlex tubing with a 0.25" outer diameter. The end of the tubing was sealed to itself with silicone caulk, which was also used to help seat the tubing in the grooves designed to hold the original Viton gasket. Furthermore, the holes around the bolt holes between both of the membrane housings needed to be sealed. Therefore, rubber grommets were added which deform when the wing nuts are tightened down to seal the gap between the membrane holder's top and bottom halves. A figure of the change may be seen in Figure 20

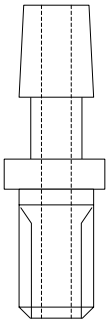
**Figure 20 : New gasket and grommets for membrane holder**



Custom fittings (see Figure 21) also needed to be machined in order to fit the ¼-20 threads of the membrane adapter to a 3/8" barbed fitting for the recirculation and drainage points. The fittings were machined from 3/8" round 6061 aluminum stock.

A representation of a fitting may be seen below in Figure 21

**Figure 21: Barbed fitting for membrane holder**



# 11. ENVIRONMENTAL ASPECTS

AnMBR systems replace traditional municipal wastewater treatment methods of aerobic digestion and chemical treatment with anaerobic digestion and membrane filtration. Currently, many facilities utilize membranes (MBR) while anaerobic digestion has not been explored in the context of domestic wastewater until now. In the following sections, we will examine the case for a full-scale MBR system, as well as the potential energy consumption of our lab scale system.

## 11.1 MEMBRANES

Membranes can have a significant advantage over older methods such as sequential batch reactor (SBR) systems. There are increasingly stringent DEQ regulations for effluent water quality and higher population demand on treatment centers and MBRs can help satisfy these public requirements and well as provide some additional benefits. In the following sections we will examine the changes that took place when the Dundee, MI wastewater treatment plant replaced their SBR system with an MBR system [B]. While there are some drawbacks to MBRs, it has significant advantages in water quality and contaminant removal.

### 11.1.1 Chemical Treatment

One of the few disadvantages to MBR is that SBR features better nutrient removal and MBR systems require the addition of alum (aluminum sulfate) to aid in phosphorus removal. The EPA's standard for aluminum is 0.05-0.2 mg/L in drinking water and classifies it as a secondary regulation—something that merely causes cosmetic or aesthetic effects [A].

SBR has very poor contaminant and fecal coli form removal and requires chlorine gas for effluent disinfection. To remove the chlorine, the effluent then has to be purged with

sulfur dioxide. Not only does the gas pose a significant health hazard to operators, but also it is an unnatural solution and there are added costs associated with the chemicals. MBR systems on the other hand naturally remove these contaminants

### 11.1.2 Effluent Quality

At the Dundee plant they were able to obtain much higher water quality with their MBR system on the same land footprint. Please see Table 8 below for specific values.

Table 8. Effluent Quality for SBR and MBR Systems [B]

| Parameter | SBR | MBR |
|---|---|---|
| $CBOD_5$ mg/L | 11.9 | 0.9 |
| $CBOD_5$ % Removal | 86.3 | 99.6 |
| SS mg/L | 15.9 | 0.4 |
| SS % Removal | 76.1 | 99.7 |
| Ammonia Nitrogen-N | 6.0 | 0.55 |
| Total Phosphorus-P mg/L | 0.77 | 0.42 |
| Dissolved Oxygen mg/L | 7.9 | 8.2 |

### 11.1.3 Energy Requirements

At the Dundee plant, there was a notable increase in energy costs with the addition the MBR system. These costs can be attributed to aeration requirements for fouling prevention in the membranes. This cost may be offset by energy produced by the anaerobic reaction detailed in section 11.2 below. Also, a better membrane design that combats fouling may also help this problem.

## 11.2 ANAEROBIC DIGESTION

Although municipal wastewater treatment facilities do not use anaerobic digestion as a primary treatment, some do use it to reduce the volume of their biomass solids. This digestion produces biogas with 60-70% methane content and an energy content of about 650 Btu per cubic foot. This process has proven sustainability. One 12 MGD (million gallons per day) treatment plant in Dupage County, Illinois uses methane produced by anaerobic digestion coupled with hydrolysis to power a 1.5 MW generator [C].

Methane production in the context of domestic wastewater treatment will be explored in further research with our system. While we do not know the potential gas production, we can determine the amount of energy required by our lab-scale system. These values are outlined in Table 9 below.

Table 9. Component Power Requirements

| System Component | Power Requirement (W) |
|---|---|
| 1 Temperature Controller | 1200 |
| 1 Masterflex L/S 10-600rpm | 172.5 |
| 2 Masterflex L/S 1.6-100rpm | 344.4 |
| 1 Computer Power Supply | 350 |
| 1 DC Power Supply | 345 |
| TOTAL | 2.413 kW |

Based on an energy conversion efficiency of 25% for a combustion engine and 85% for a power generator, we can expect 2.54E-2 kWh/$m^3$ to be produced. Our system will require 94.98 $m^3$/hr of methane to operate. We must keep in mind that these figures are for the lab-scale system only. Our goal for this system was not to create enough methane to offset its operation. Instead, our goal was to measure and determine the operational parameters of the amount of methane that a given amount of wastewater can produce. Ideally, a full-scale system will produce relatively more methane, while depending on relatively less energy to operate. Also, since this is energy that is offset from the system's use, the system would be saving power in any case.

Methane energy: $650Btu = 5.33E-3kWh/m^3$ (note: value for solid biomass. DWW contains unknown lower concentrations of methane capability)

Efficiency: $0.25(Combustion) * 0.85(Generator) = 0.21$

Total Methane Energy (including power conversion): $\frac{5.33E-3}{.21} = 2.54E-2kWh/m^3$

Methane Required for 0 Net Energy Use : $\frac{2.413kW}{2.54E-2kWh/m^3} = 94.98m^3/hour$

# 12. RECOMMENDATIONS

Based on our experience on this project, we are prepared to make various recommendations for future work. While we consider our project to be a success, there is still a lot of work to be done before the AnMBR is complete. In this section, we will lay the framework for future projects based on our original specifications and experience on this project. There are three broad categories in which we can group our recommendations: setup, system characterization, testing and system controls and safeguards.

## 12.1 SETUP

Finalizing the system setup is the next important step. This would entail placing the components in their semi-permanent locations and finding a way to organize the fluid lines, sensor cables and other associated hardware. We found during the course of our project that it is extremely important that the flexible fluid lines are free of twists, bends and kinks to ensure pressure is transmitted evenly through out the system and the flow rates are consistent. It is key to restrict the movement of the lines such that this does not happen, but it is also important to maintain overall system flexibility by making this setup easy to reconfigure.

## 12.2 SYSTEM CHARACTERIZATION AND TESTING

While we were able to validate many subsystems, there are certain tests that will need to be carried out before the system is ready to accept biomass. First, we recommend validating the auto feed with DI water and feed concentrate. We found that the auto feed mixing ratio depended on what was being mixed. Using tap water and DI water, the

mixing ratio was as expected (about 16 to 1). But when we used orange juice and water, the mixing ratio was not as expected. We attributed this error to the particulate nature of the solutions, but it would certainly be prudent for future groups to test the auto feed mixture concentration using DI water and feed concentrate.

Second, we recommend finding the steady-state temperature of the fluid in the recirculation loop. Our group is concerned that the temperature in the loop will be below levels that are acceptable for biomass survival. If this is the case, insulation of the recirculation lines may be required.

Third, we recommend an analysis of the flow characteristics of the system, possibly by running a dye through the lines. It will be important for the longevity of the process that there are no "dead" spots in the flow where vortices are allowed to develop. These zones could allow biomass to accumulate and obstruct the lines.

Finally, future teams should characterize the pump flow rates as a function of the distance from the calibration flow rate. Our team found the accuracy of the pump flow rate was heavily dependant on the flow rate at which the pump was calibrated. If the pump is used at significantly higher (or lower) flow rates that the calibration flow rate, the error in the actual flow rate delivered will be significant. More tests are certainly desirable to characterize this behavior and implement strategies to correct for this effect.

### 12.3 SYSTEM CONTROLS AND SAFEGUARDS

The AnMBR is intended to run for two years. During much of this time, the reactor will need to operate unattended. The surrounding area will be filled with electronic equipment and the collection of any spilled biomass will be invaluable. It will therefore be important that the system setup is robust enough to avoid spills and contain overflows.

In order to avoid reactor overflows, we recommend implementing pump control using serial communication. While we were able to show that this type of control is possible, the details of how to program the controls into LabView are highly involved. Our team has made serial cables and has an existing LabView program that can be adapted to control the pumps. We also have working level and pressure sensors that could be used for feedback to such a control system. Additionally, future teams could look into using tools such as a linear potentiometer to implement PID control. This sensor would work with existing data acquisition hardware and the control would be much more robust.

To safeguard the system, we recommend that future teams find ways to isolate electronic components from possible overflow or leakage areas while preserving biomass for collection. This may mean a "tub" that contains the system as a whole or some other means of spill containment. The system would need to be sized correctly so that it can completely contain "worst case" spills (i.e. over the weekend, when the reactor is unattended).

## 13. CONCLUSIONS

Our final design has numerous strengths and a few weaknesses that should be noted. As stated in Section 7.4, the system needs to deliver the correct flow rates, hold a given

temperature acquire data flawlessly and not leak gas or liquid. In this respect we were a success. The LabView program, data acquisition hardware and all but one of the sensors are working and calibrated. The entire system was validated up to 100kPa with one non-critical leak (see Section 9.2.4) and the temperature controller was validated. Additionally, the auto feed system holds the correct ratio and the pumps were calibrated to deliver the correct flow rates with a given tubing size. With respect to the critical design characteristics, the project is a success.

Our project is also a moderate success in terms of the original specifications (see Section 4.2). We were able to design our reactor to hold the desired temperature range and achieve the desired flow rates. Additionally, we were able to encompass a range of cross-flow velocities using a recirculation loop. The quick connects that we installed make rearrangement, disassembly and reassembly easy and fast. The auto shut off quick connects also allow rearrangement of the system components in mid operation. All the components have fasteners that are finger-tightened and do not require tools to open and access the components.

There are a few major issues with our design that we were unable to address. The first issue was the cost goal. We originally wanted to manufacture our design for less than $10,000. Our actual expenditure was around $21,000. Originally, we had not defined what our team would build and what components we would purchase. Given more time, we may have been able to come closer to this cost target. Yet, with the time constraints we were faced with as well as the number of systems we had to design, we found that purchasing major components was advantageous. The expenditures were discussed with our sponsors in detail and we focused our design efforts on the issues that were most important to them.

We were also not able to address particular engineering specifications that were dependent on having a complete and fully operational system in place. Specifications such as “number of potential trip hazards”, “number of potential pinch points” and “visible area” depend on the final setup. Since our design is not in its final placement, these specifications cannot be evaluated. Additionally, we were not able to characterize our system completely. Specifications such as “max running time” were out of the timeframe of the project, but we certainly believe that our system is robust enough to handle such operation.

Our system can accommodate 2 types of membranes, but only 1 size flat sheet membrane. Even though only a 200mm by 200mm can be accommodated, this is the most practical size that is available for research in the materials that our sponsor required. Therefore we feel that we have met our requirements.

Given the scope of our project, the time constraints and the design issues we had to address, our team feels that we have met the project goals. While there is still much work to be done, we have left subsequent teams in a position to complete the design and meet most of our original specifications. For recommendations on this future work, please see Section 12.

## 14. ACKNOWLEDGEMENTS

We would like to thank Adam and Tanna Borrell, Dave Berry, Andres Clarens and the Morgenroth Research Group at UIUC for all their guidance and help throughout the course of our project. We would also like to thank Professor Steven Skerlos and Professor Lutgarde Raskin for providing us with this design opportunity and for all their guidance and encouragement throughout the semester.

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## 16. TEAM BIOGRAPHIES

**Peter Balogh**

I am a fifth-year Mechanical Engineer and French minor. I'm originally from Debrecen, Hungary, and my family moved to the United States when I was 7 years old. My love for science and mathematics can be attributed to my father's background in chemistry. While in high school, I worked for his research team at the University of Michigan. After graduation from high school and a local community college at the same time, I moved back to Hungary for a year to learn more about the culture and history. After returning from Hungary, I enrolled in the School of Engineering. I also joined the Solar Car team, as member of the mechanical and aerospace engineering teams on the 2003 project. Unfortunately, the 2003 solar car failed to be completed on schedule. After sacrificing so much of my time and GPA, I decided that I can't give up the project, and stayed on for the next two years. I ended up leading the engineering teams during our races as Crew Chief. The team ended up winning the North American Solar Challenge, and placing third in the world at the World Solar Challenge. After Solar Car, I worked as a machinist for the Mobile Robotics Lab on the OmniTread serpentine robot project. I plan to graduate in April of 2007.

**Michael Edward Cholette**

I have lived in Clarkston, MI for most of my life. When I lived there it was a small town, with little to do but leave. I played soccer, baseball and ice hockey and I even picked up some golf and tennis. However, it was ice hockey that I enjoyed the most. I began skating when I was 5, played for my high school and I still skate today. A more recent interest of mine is travel. In the last 2 years I have been to Chile, Australia, Belize, Honduras and Mexico with trips planned to Europe and Japan planned for the next year. Travel is something that has changed my perspective in a way that was only possible through the experience.

At the University of Michigan, I enrolled in the School of Engineering from the beginning. I have worked at Steve and Barry's University Sportswear for 4 years (going on 5) and I am an assistant manager. Professionally, I have interned with Caterpillar twice and once with engineering lab in Madison Heights, MI where I learned that I enjoy the challenges of design.

I became an engineer mostly because I like math and science and I thought that I was good at it. However, mechanical engineering did not occur to me until my original plan of becoming an electrical engineer deteriorated from a loathing of programming. Out of a major, I was looking for a home and decided to try mechanical engineering. I took ME 211 and it was not what I thought it was going to be, but I loved it. I enjoyed the problem solving and I became fascinated with mechanical design. I also appreciated the versatility of a mechanical engineering degree and the creativity involved in mechanical design. Above all, I enjoy making mechanical systems and components do what I want them to do.

**Krista Klein**

I am from Rochester, Michigan and this is my fourth year here. I have always had an interest in finding out how things work, putting things together without the directions, coming up with new ideas, and problem solving. I like proving things with numbers

because it doesn't leave room for debate, but I have an appreciation for multiple routes to the same answer. I've wanted to be an engineer since I was in middle school, and almost made the mistake of going to Michigan State when I was choosing schools 4 years ago. Choosing this major has defiantly been challenging, but I've learned so much and there's no where else I'd rather be or anything else I'd rather be doing.

I worked in technical sales for a water treatment company over the summer. I'm interested in pursuing something similar to it when I graduate in the spring. I like the fact that I would go somewhere different every day and meet new people and deal with different situations—I was never bored. I don't think I would be happy sitting in a cubicle all day in front of a computer. I also have a lot of interest in international business. At the end of the semester I will have (finally) completed a minor in Spanish and would like to use this skill as part of my engineering job. I'm not sure exactly what I want to do; I don't have a "dream job" yet. I want to go into industry after I graduate at the end of the year but eventually go to grad school at some point. I am also in the Michigan Ski Club, a sorority, SWE and I am the Vice President of the Engineering Honor Council.

**Michael Rose**

I am from Novi, MI, and this is my fourth year at U of M. I have always been interested in innovation; starting with LEGO's and eventually building a go-cart and powered skateboards in my garage. I saw mechanical engineering as a career path that would allow me to design and create new things. I am currently interested in renewable energy methods and robotics. I also have a passion for music and am president of an a cappella group on campus.

Currently, I am a Co-op at the Tank-Automotive Research Development and Engineering Center (US ARMY TARDEC) making prototype remote-controlled HMMWVs (Hummers). I eventually want to get my MBA and own my own engineering firm somewhere warm like California.

Surrounded by lakes my whole life, my family and I became active in the preserving the freshwater resources that are still available. In high school, I did a science fair project directly tied into my family's concern about the runoff of animal feces into the lake (from Concentrated Animal Feeding Operations) and our search for "greener" alternatives. I won the competition with my project entitled "Stool Fuel," which sought to comparatively analyze the energy content of different animal's feces for eventual use as an energy source. Needless to say, I was really excited to hear about a project that would be turning waste into clean water and energy. I look forward to the challenges and experience this project has to offer.

**Freda Yawson**

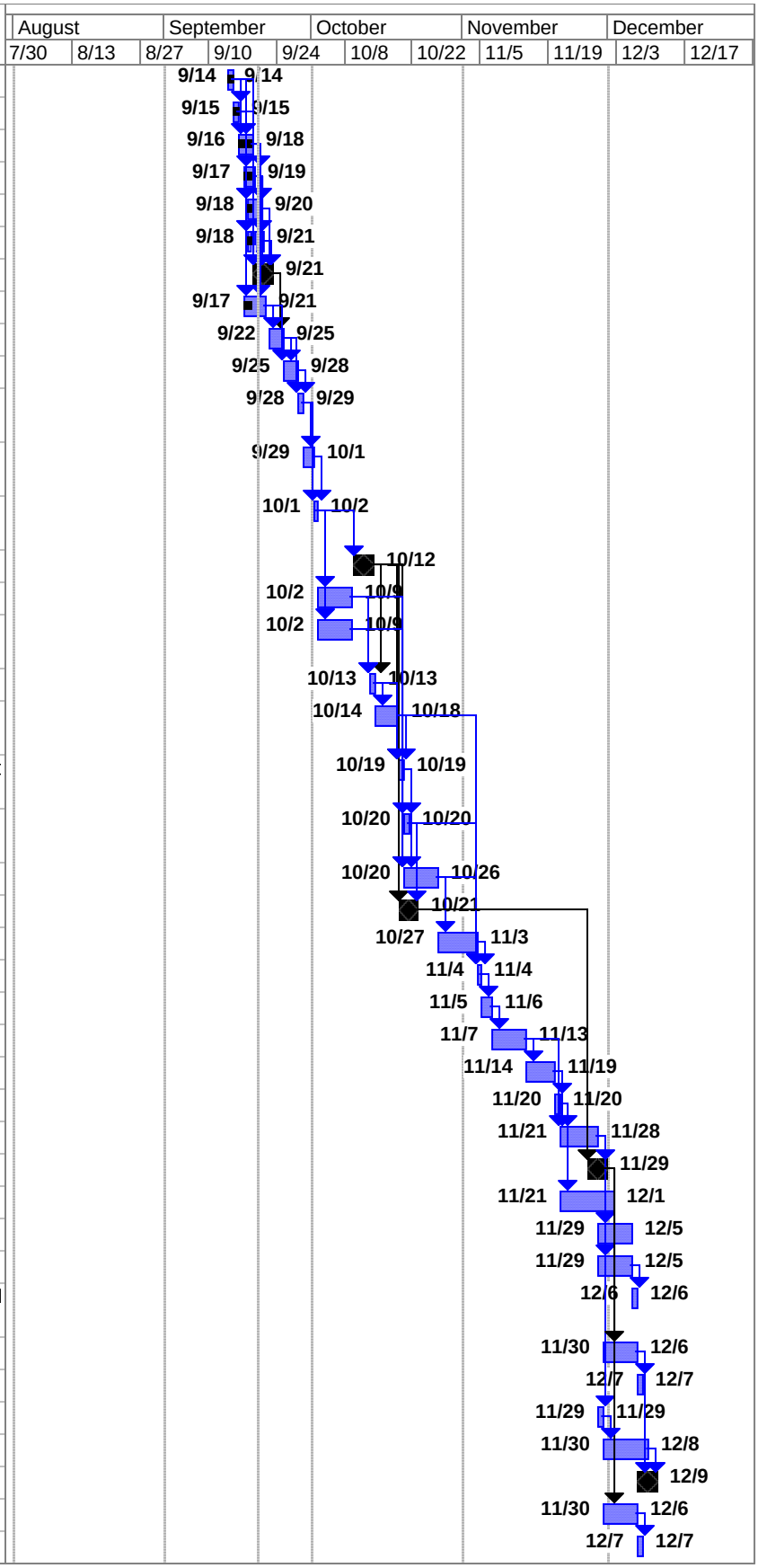
I am a 5$^{th}$ yr senior in Mechanical Engineering who wants to save the world (in the distant future that is)! I was born in Accra, Ghana to very academic parents who studied in Russia and traveled widely in Europe before coming back to Ghana (not fair!). At the age of 7, we moved to Michigan when my Dad was offered a teaching position at Wayne State University. After a few years here, I went back to Ghana for three years, for the traditional boarding school experience where I made exceptional friends, learned to play table tennis, and gained some discipline and independence along the way. Upon returning to Michigan at the age of 15 to finish my last two years of high school, I was encouraged to join the Engineering Academy at my high school because of my love for math and

science. I got involved in the Robotics Team and later became the President of our Academy as well. Somewhere along the way I took a strong interest in cars and decided that I wanted to design them. All of this led to a few summer internships at GM, the College of Engineering, and the Solar Car team in 2003.

In the past few years though, I've seen my focus begin to shift from cars and design to international development (although I've continued to co-op with Toyota). I believe that it comes from a strong sense of urgency to give back to Ghana and those in other developing countries, and the realization that I've been blessed with a lot, and the opportunity to put my engineering knowledge to good use. I also believe that it also comes from my innate urge to solve problems and come up with simple but hopefully smart ideas that can improve the lives of others. This interest of mine led me to the Optimal Design Lab last summer where I focused on "Designing for Developing Countries" as well as other side projects with a group that hopes to develop a multipurpose community pavilion in Ghana. Some of the designs included research on the feasibility of wind energy in Ghana for use in domestic applications. So when December graduation comes, there will be big decisions to make but until then I try to stay sane  by dancing (Congolese dance currently), playing soccer, taking pictures, drawing, reading and other creative-ish projects when there is time.

# APPENDIX A: GANTT CHART

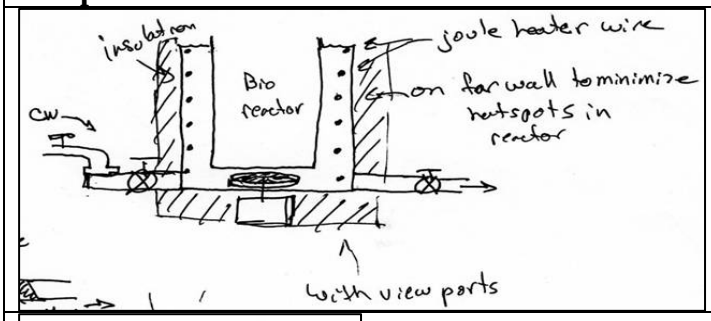
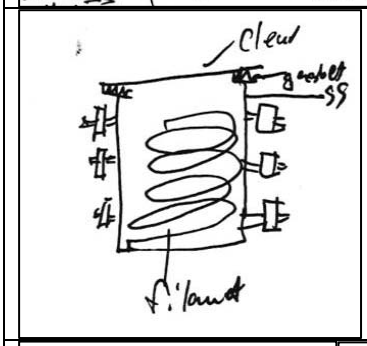
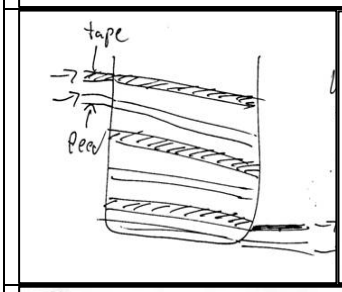
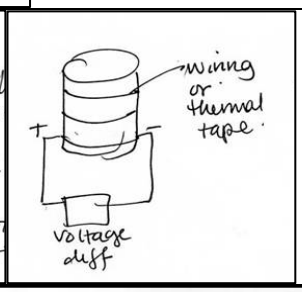
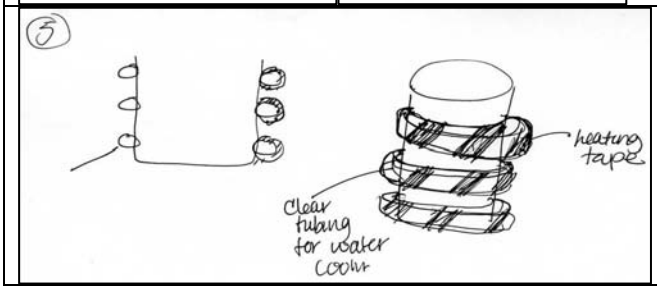
| ID | Task Name |
|---|---|
| 1 | Meet with Sponsor |
| 2 | Define Customer and Engineering Specs |
| 3 | Research Technology |
| 4 | Benchmarking |
| 5 | Create Presentation |
| 6 | Write Report |
| 7 | Design review 1 |
| 8 | Dimensional Constraints Determined |
| 9 | Assign and Research Subsystems |
| 10 | Generate Concepts |
| 11 | Select Concept based on design requirements |
| 12 | Match engineering specs to subsystems; research unknown |
| 13 | Concept Design Freeze (no further changes to system) |
| 14 | Design Review 2 |
| 15 | Research Materials and External Sources |
| 16 | Produce Detailed Designs for Alpha Prototype |
| 17 | Internal DR of Complete Detailed Drawings |
| 18 | Order External Components for Alpha System |
| 19 | Detailed Design Freeze for Alpha Prototype (nc changes in detailed drawings) |
| 20 | Meet with Bob Coury for manufacturing approval |
| 21 | Acquire All External Materials |
| 22 | Design Review 3 |
| 23 | Manufacture Prototypes |
| 24 | Assemble Prototype |
| 25 | Dry test run with H20 |
| 26 | Debug Prototype |
| 27 | Analysis of experiment results |
| 28 | Post-Construction Internal Design Review |
| 29 | Meet with Sponsor and Instructor |
| 30 | Design Review 4 |
| 31 | Produce Final detailed designs |
| 32 | Order materials for final design |
| 33 | Order Components for Final Design |
| 34 | All Materials and Components in-hand for Final Design |
| 35 | Create Final Prototype |
| 36 | All machining complete |
| 37 | Purchase Materials for Design Expo Poster |
| 38 | Create Design Expo Presentation |
| 39 | Design Expo |
| 40 | Write Subsections of Final Report |
| 41 | Final Report Draft Complete |

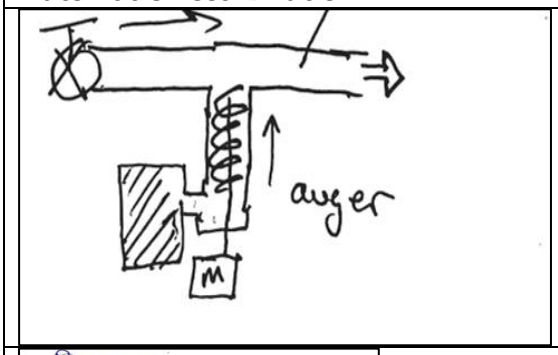
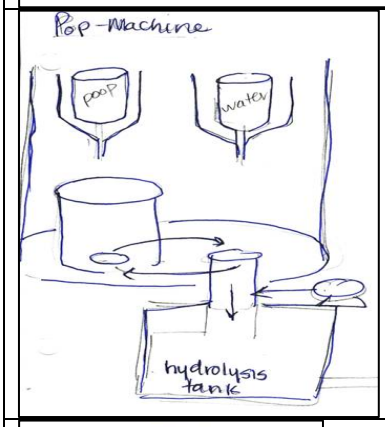
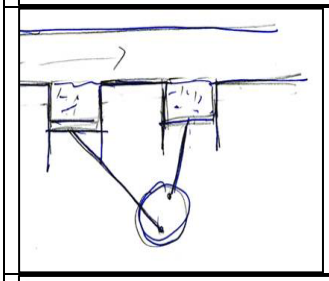
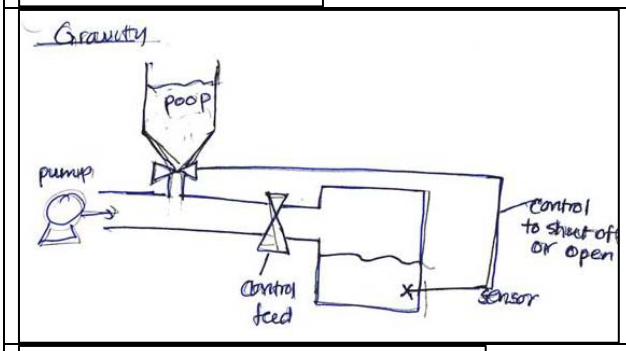
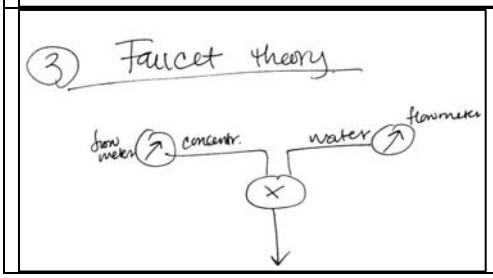


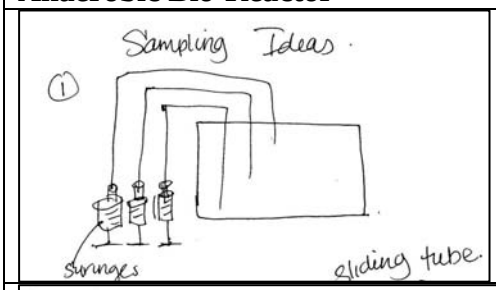
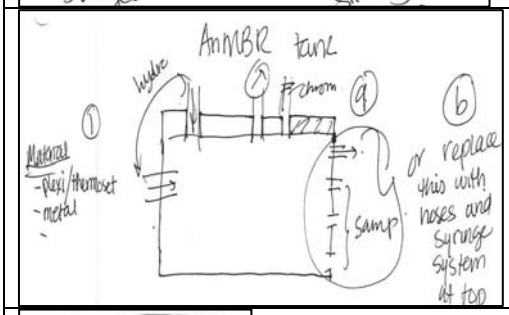
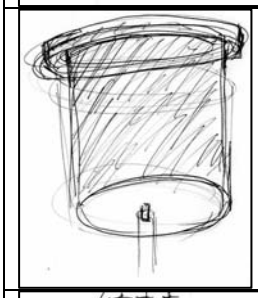
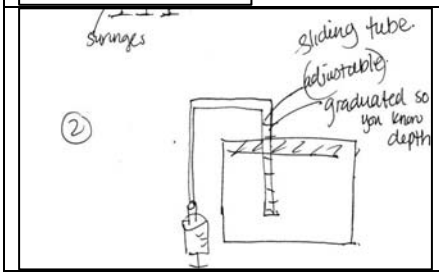
# APPENDIX B: CUSTOMER REQUIREMENTS AND RELATIVE IMPORTANCE

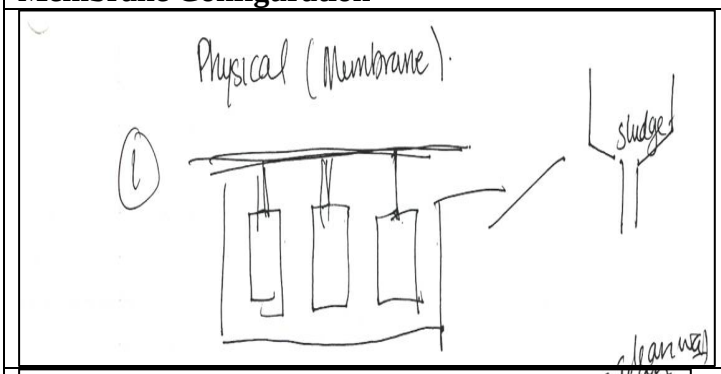
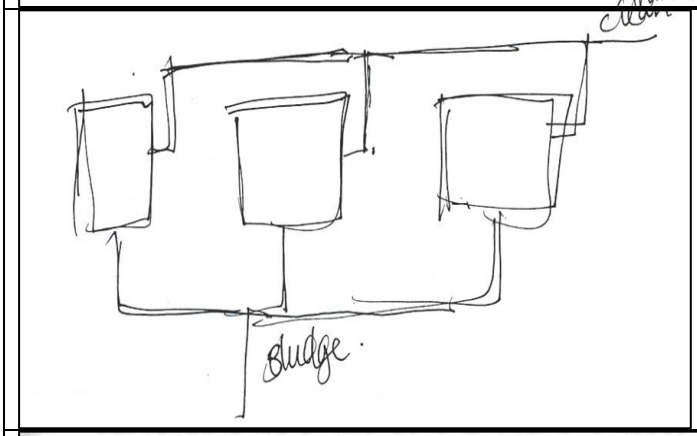
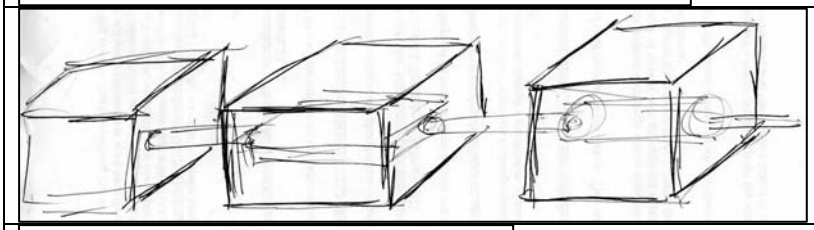
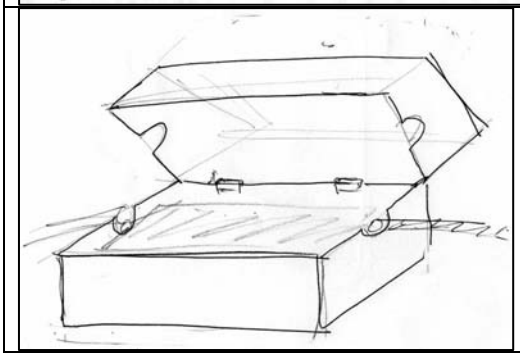
| Customer Requirement | Relative Importance |
|---|---|
| Reactor size | 1.0 |
| Components provide necessary environment for Anaerobic chamber | 1.0 |
| Precise and Accurate Temperature Control System | 1.0 |
| Easy access gas gauge so that flow rate(from loading rate) is readable/visible | 0.3 |
| Gastight Seals | 1.0 |
| Biogas Collection | 1.0 |
| Automatic feed dilution and addition | 1.0 |
| Easy access for sampling of effluent and biomass | 0.6 |
| Useable with membranes from manufacturer with minimal modification | 0.9 |
| Option of installing membranes internally or externally. Ability to change the order. | 0.2 |
| Easy access to membrane for removal/examination | 0.8 |
| Adaptability to different types of membranes | 1.0 |
| Ability to run for lengthy experimental times | 1.0 |
| Option of running w/ or w/o hydrolysis phase | 0.7 |
| Option of running w/ or w/o fouling prevention measures | 0.9 |
| Option of running w/ ion exchange or other nutrient removal systems | 0.9 |
| Durable | 0.8 |
| Visually Pleasing | 0.2 |
| Inexpensive | 0.7 |
| Safe to Use | 1.0 |
| Visibility of Reactions | 0.4 |
| Easy to operate | 0.5 |
| System or ability to remove nitrogen and phosphorous | 0.8 |

# APPENDIX C: CONCEPT GENERATION

| **Temperature Control** | |
|---|---|
|  | • **Cold water from tap in to cool**<br>• **Heating wires inside water jacket**<br>• **Stirrer at bottom**<br>• **Insulation** |
|  | • **Coiled heating element inside actual tank**<br>• **Room for sample ports** |
|  <br>  | • **Heating tape is outside bioreactor**<br>• **Easy to service**<br>• **Isolates electrical and wet components** |
|  | • **Heating tape wrapped around tubing that holds the water for temp. control**<br>• **Can heat or cool** |

| Automatic Feed Dilution | |
|---|---|
|  | • **Auger spin rate determines mass flow rate**<br>• **Valve for incoming DI water** |
|  | • **Precise measurement of water and concentrate**<br>• **Accurate dilution**<br>• **Pop-machine parts** |
|  | • **Double piston mechanism uses one motor**<br>• **Accurate and repeatable volume dispension** |
|  | • **Gravity Feed saves use of 1 pump**<br>• **Fewer moving parts** |
|  | • **Use 1 lever to control mass flow rates of water and concentrate like a faucet**<br>• **Easy to buy** |

| **Anaerobic Bio-Reactor** | |
|---|---|
|  | • **Defined depths of sample ports to keep strata from mixing**<br>• **Easy use of disposable syringes for sampling** |
|  | • **Non-brittle Plexiglas**<br>• **Side sample ports**<br>• **Room for gas collection at the top** |
|  | • **Sampling Port on Reactor Bottom** |
|  | • **Sliding sample port for sampling any depth in tank**<br>• **Graduated for precise depth measurements** |

| Membrane Configuration | |
|---|---|
|  | • **Submerged Membrane** |
|  | • **Membranes in Parallel** |
|  | • **Membranes in Series** |
|  | • **Membrane Housing that can accommodate multiple membrane forms** |

# APPENDIX D: HRT CALCULATIONS BY TANNA ALFORD-BORRELL

| V (L) | HRT (hrs) | Q (L/day) | refill (d) | load (mg/Lday) |
|---|---|---|---|---|
| 3 | *2* | *36.00* | *0.44* | *6000.00* |
| | *4* | *18.00* | *0.89* | *3000.00* |
| | 6 | 12.00 | 1.33 | 2000.00 |
| | 8 | 9.00 | 1.78 | 1500.00 |
| | 10 | 7.20 | 2.22 | 1200.00 |
| | 12 | 6.00 | 2.67 | 1000.00 |
| | **14** | **5.14** | **3.11** | **857.14** |
| | **16** | **4.50** | **3.56** | **750.00** |
| | **18** | **4.00** | **4.00** | **666.67** |
| | **20** | **3.60** | **4.44** | **600.00** |
| | **22** | **3.27** | **4.89** | **545.45** |
| | **24** | **3.00** | **5.33** | **500.00** |

| V (L) | HRT (hrs) | Q (L/day) | refill (d) | load (mg/Lday) |
|---|---|---|---|---|
| 5 | *2* | *60.00* | *0.27* | *6000.00* |
| | *4* | *30.00* | *0.53* | *3000.00* |
| | *6* | *20.00* | *0.80* | *2000.00* |
| | 8 | 15.00 | 1.07 | 1500.00 |
| | 10 | 12.00 | 1.33 | 1200.00 |
| | 12 | 10.00 | 1.60 | 1000.00 |
| | 14 | 8.57 | 1.87 | 857.14 |
| | 16 | 7.50 | 2.13 | 750.00 |
| | 18 | 6.67 | 2.40 | 666.67 |
| | 20 | 6.00 | 2.67 | 600.00 |
| | **22** | **5.45** | **2.93** | **545.45** |
| | **24** | **5.00** | **3.20** | **500.00** |

| V (L) | HRT (hrs) | Q (L/day) | refill (d) | load (mg/Lday) |
|---|---|---|---|---|
| 4 | *2* | *48.00* | *0.33* | *6000.00* |
| | *4* | *24.00* | *0.67* | *3000.00* |
| | 6 | 16.00 | 1.00 | 2000.00 |
| | 8 | 12.00 | 1.33 | 1500.00 |
| | 10 | 9.60 | 1.67 | 1200.00 |
| | 12 | 8.00 | 2.00 | 1000.00 |
| | 14 | 6.86 | 2.33 | 857.14 |
| | 16 | 6.00 | 2.67 | 750.00 |
| | **18** | **5.33** | **3.00** | **666.67** |
| | **20** | **4.80** | **3.33** | **600.00** |
| | **22** | **4.36** | **3.67** | **545.45** |
| | **24** | **4.00** | **4.00** | **500.00** |

| V (L) | HRT (hrs) | Q (L/day) | refill (d) | load (mg/Lday) |
|---|---|---|---|---|
| 6 | *2* | *72.00* | *0.22* | *6000.00* |
| | *4* | *36.00* | *0.44* | *3000.00* |
| | *6* | *24.00* | *0.67* | *2000.00* |
| | *8* | *18.00* | *0.89* | *1500.00* |
| | 10 | 14.40 | 1.11 | 1200.00 |
| | 12 | 12.00 | 1.33 | 1000.00 |
| | 14 | 10.29 | 1.56 | 857.14 |
| | 16 | 9.00 | 1.78 | 750.00 |
| | 18 | 8.00 | 2.00 | 666.67 |
| | 20 | 7.20 | 2.22 | 600.00 |
| | 22 | 6.55 | 2.44 | 545.45 |
| | 24 | 6.00 | 2.67 | 500.00 |

red text produces gas flow rates below what is accurately measureable by the meter
orange text undesireably frequent wastewater production

below minimum typical organic loading rate for anaerobic treatment
below lowest average values reported in literature (one paper went as low as 300, but that was not the norm)

# APPENDIX E: ALPHA CONCEPT ANMBR BIOREACTOR CAD MODELS

**Figure E1: Anaerobic bioreactor without insulation box**

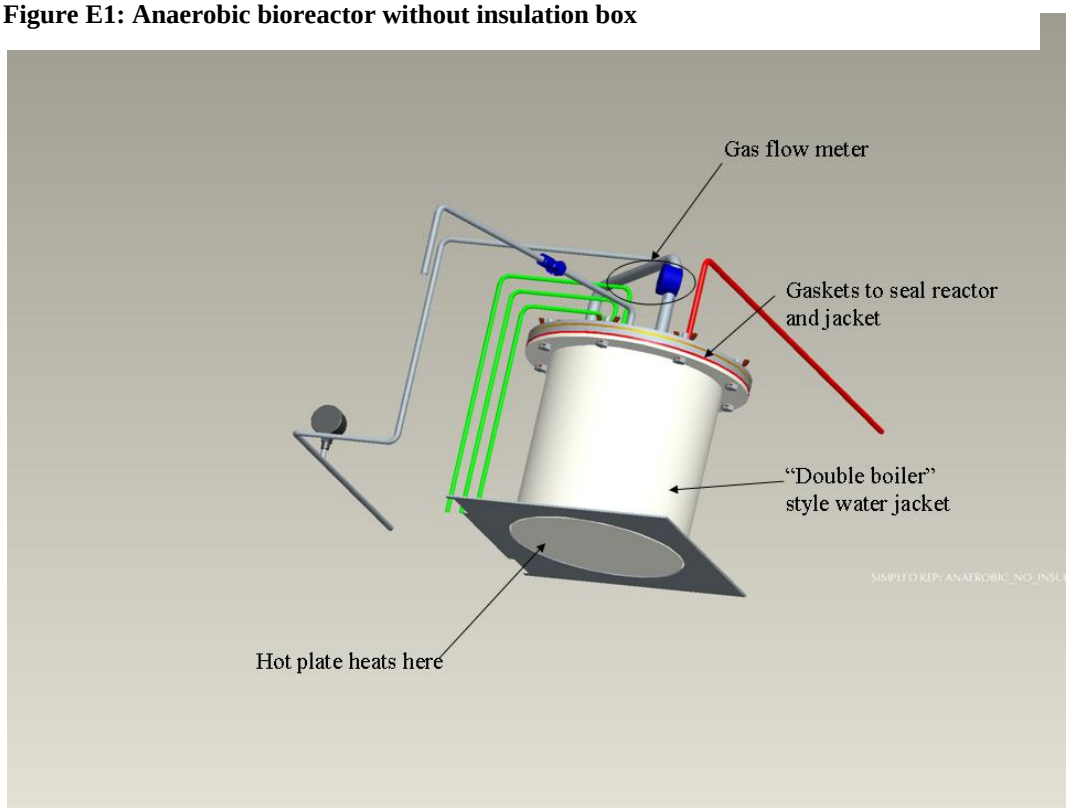
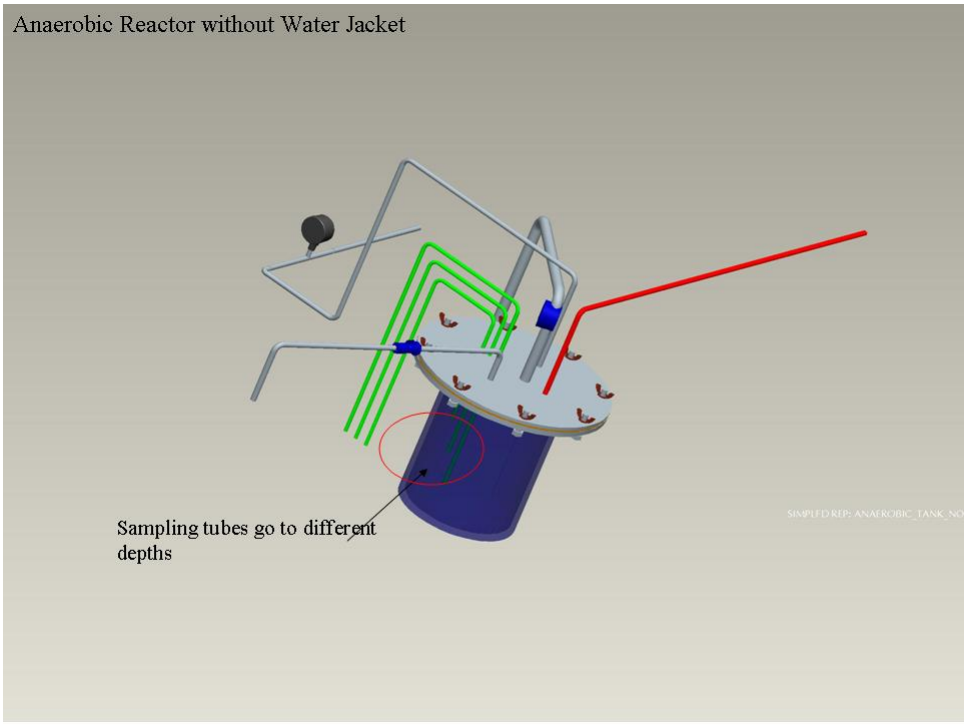
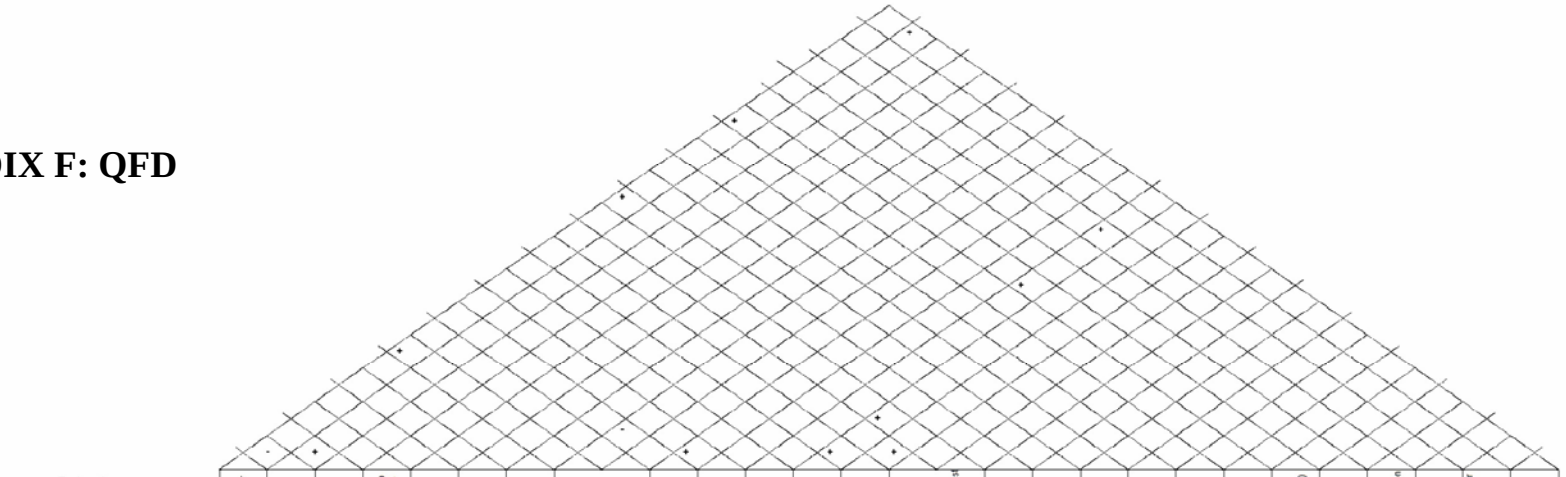


**Figure E2: Anaerobic bioreactor without water jacket. Note the different depths of the sampling tubes**



# APPENDIX F: QFD



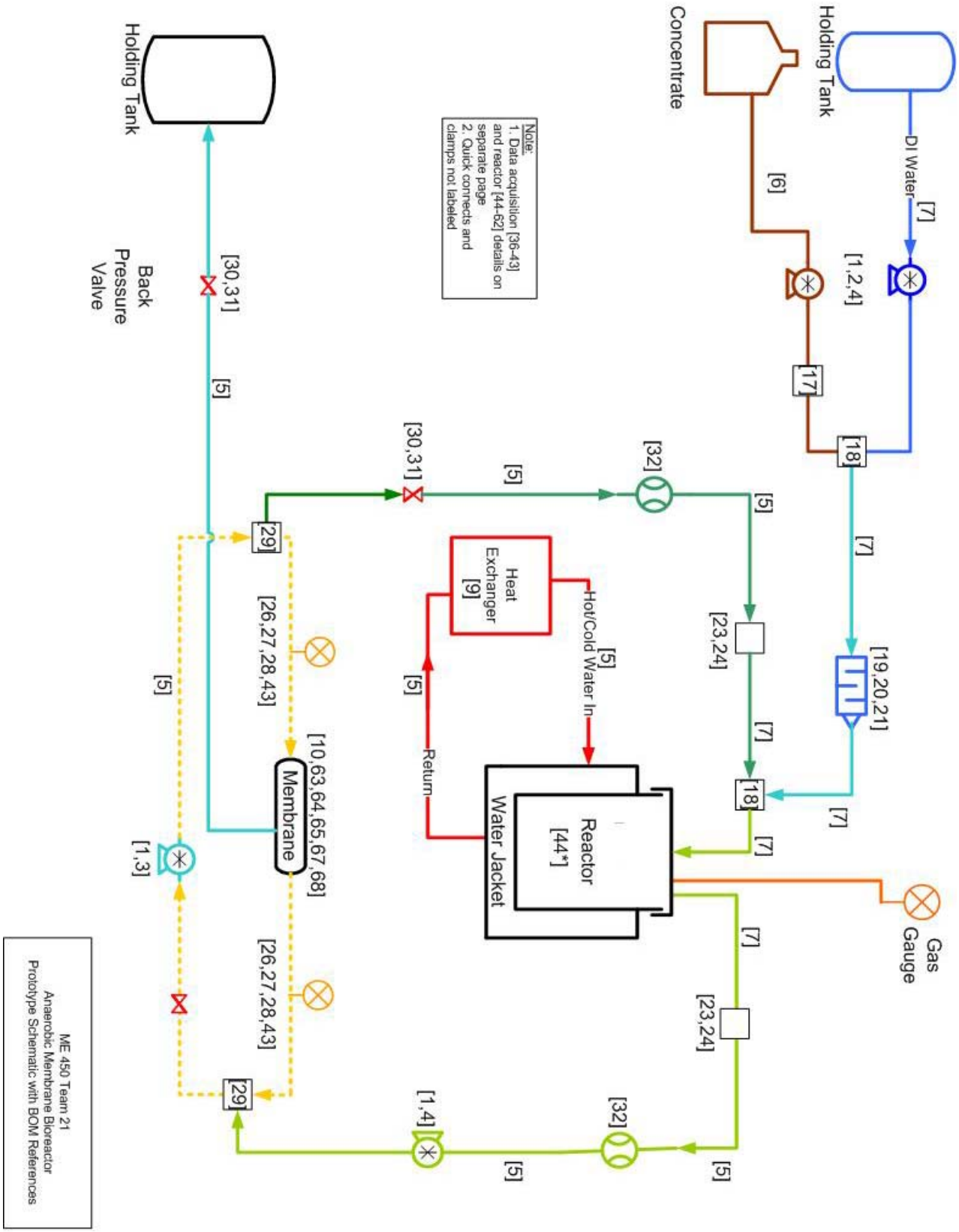
| Engineering Characteristics / Customer Attribute | Importance | Volume of container | Total power input required | Temperature of Reactor | maximum # steps to access components | Pressure loss of anaerobic compartment to surroundings | % of unvalved gas collected | % Visible Area (of Anaerobic compartment) | Size of membranes accomodated (dimensions) | total # membranes accomodated (flat, tubular, spiral | time install experimental components | # of tools to install | WW Pump power usage | back pressure tolerance of WW pump | Running time | WW Pump duty cycle (service time) | # of experimental test cells | Mass | # pinch points | # potential trip hazards | Distance between Hydraulic and Electrical Components | # of Possible Experimental Permutations | Cost | Range of crossflow flowrates (velocities) | Possibility of Backflushing | Possibility of intermittent operation | Time to install membranes | Time between major service (cell removal, pump replacement | WW flow rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reactor size | 1.0 | 9 | 3 | 3 | 1 | | | 1 | 3 | 1 | | | 9 | 3 | 1 | | | 9 | 1 | | 2 | | 3 | 1 | | | 1 | | 9 |
| Components provide necessary environment for Anaerobic chamber | 1.0 | 3 | 9 | 9 | | 9 | | | | | | | 3 | 3 | | 3 | | | | | | | | 3 | 3 | | | | 3 |
| Precise and Accurate Temperature Control System | 1.0 | 9 | 9 | 9 | 1 | | | 3 | | 1 | 3 | 1 | | | 9 | | | 3 | | 3 | 3 | | 9 | | | | | | 1 |
| Easy access gas gauge so that flow rate(from sparging rate) is readable/visable | 0.3 | 3 | 9 | | 9 | | | | | | | | | | 1 | | | | | | 1 | | 1 | | | 3 | | | |
| GasTight Seals | 1.0 | | 3 | 3 | 3 | 9 | 9 | | | | 3 | 3 | 1 | 1 | 9 | | | | | | | | 3 | | | | | | |
| Biogas Collection | 1.0 | 9 | 3 | 1 | 1 | 3 | 9 | | 1 | | 3 | 3 | 1 | | 1 | | 3 | 3 | | | | | 9 | | | | | | |
| Automatic feed dilution and addition | 1.0 | | | | | | | | | | | | | | 9 | | | | | | 1 | | 9 | | | | | | 1 |
| Easy access for sampling of effluent and biomass | 0.6 | | | | 3 | | | | | | | | | | | | | | | | | | | | | 3 | | | |
| Useable with membranes from manufacturer with minimal modification | 0.9 | 3 | | | | | | | 9 | 9 | 3 | 3 | | | | | 1 | | | | | | 3 | | | | 3 | | 3 |
| Option of installing membranes internally or externally. Ability to fit single like under. | 0.2 | 3 | | | 9 | | | | 3 | 3 | 1 | 1 | | | | | 3 | | | | | | 3 | | 3 | | | | |
| Easy access to membrane for removal/examination | 0.8 | 9 | | | 9 | | | 3 | | | 9 | 9 | | | | | | | 1 | | | | | | | 9 | 9 | | |
| Adaptability to different types of membranes | 1.0 | 3 | 3 | | 1 | | | 1 | 9 | 9 | 1 | 1 | 9 | 9 | 3 | 1 | 3 | | | | | | 3 | 3 | 3 | | 1 | | 3 |
| Ability to run for lengthy experimental times | 1.0 | 1 | 1 | 9 | | 3 | | 1 | | | | | 3 | | 9 | 9 | | | | | | | | 9 | 9 | 9 | | 9 | 3 |
| Option of running w/ or w/o hydrolysis phase | 0.7 | | 3 | | 1 | | | 1 | | | 1 | 1 | | 1 | 1 | | 3 | | | | 1 | 3 | 3 | | | 3 | | | |
| Option of running w/ or w/o fouling prevention measures | 0.9 | | 3 | | 1 | | | 1 | | | 1 | 1 | | 1 | 1 | | 1 | | | | 1 | 9 | 9 | 9 | 9 | 3 | | | |
| Option of running w/ ion exchange or other nutrient removal systems | 0.0 | | 3 | | 1 | | | 1 | | | 1 | 1 | | 1 | 1 | | 0 | | | | 1 | 0 | 0 | | | | | | |
| Durable | 0.8 | | | 1 | | | | | | | 1 | 1 | 3 | 3 | 3 | 9 | | | | | | | 9 | | | | | 9 | |
| Visually Pleasing | 0.2 | 1 | | | | | | 3 | | | | | | | | | | | 1 | 1 | | | 1 | | | | | | |
| Inexpensive | 0.7 | 9 | 9 | 1 | | 1 | | | 3 | 3 | | | 3 | 3 | 3 | 3 | 3 | | | | | 3 | 9 | | | | | | |
| Safe to Use | 1.0 | 3 | 3 | 1 | 1 | 9 | | | | | 1 | 1 | | | 1 | | | 3 | 9 | 9 | 9 | | | | | | 1 | | |
| Visability of Reactions | 0.4 | 1 | 3 | 3 | 1 | | | 9 | 3 | 1 | | | | | 3 | | 3 | | | | 1 | | | | | | | | |
| Easy to operate | 0.5 | 1 | | | 9 | | | 3 | | | 9 | 9 | | | 1 | | 3 | | 9 | 9 | 9 | 1 | | | | 1 | 9 | 3 | |
| System capability to remove nitrogen and phosphorous | 0.0 | | 3 | 3 | 1 | | | 1 | | | 1 | 1 | | 1 | 1 | | 9 | | | | 1 | 9 | 9 | | | | | | |
| **Units** | | L | W | C | # | kPa | % | % | m | # | minutes | # | W | kPa | days | % | # | kg | # | # | m | # | $ | m/s | | | min | days | L/hr |
| **Zheng/Abdullah Lab Systems** | | 4-6 L | | 37 | | | | | | | | | | | | | | | | | | | | 1.5-1.9 | ? | ? | | | 10 |
| **Competitor** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Target (Plan)** | | 5-10 | TBD | 10-40+/- | 3 | 0 | 100 | 20 | TBD | 3 | 10 | 2 | TBD | TBD | 730 | 100 | 5 | 150 | 0 | 0 | 0.3 | 60 | 400 | TBD | Yes | Yes | 3 min | 720 | TBA |
| **Total** | | 56 | 54 | 40 | 30 | 34 | 18 | 17 | 25 | 22 | 29 | 28 | 31 | 24 | 52 | 22 | 35 | 19 | 16 | 17 | 25 | 32 | 83 | 24 | 24 | 24 | 17 | 18 | 23 |
| **weight absolute** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **weight percent** | | 6.67 | 6.47 | 4.79 | 3.55 | 4.03 | 2.15 | 2.08 | 2.99 | 2.65 | 3.46 | 3.31 | 2.65 | 2.85 | 6.19 | 2.67 | 4.16 | 2.24 | 1.05 | 2.00 | 2.93 | 3.86 | 9.92 | 2.69 | 2.83 | 2.89 | 2.00 | 2.12 | 2.71 |

# APPENDIX G: BILL OF MATERIALS

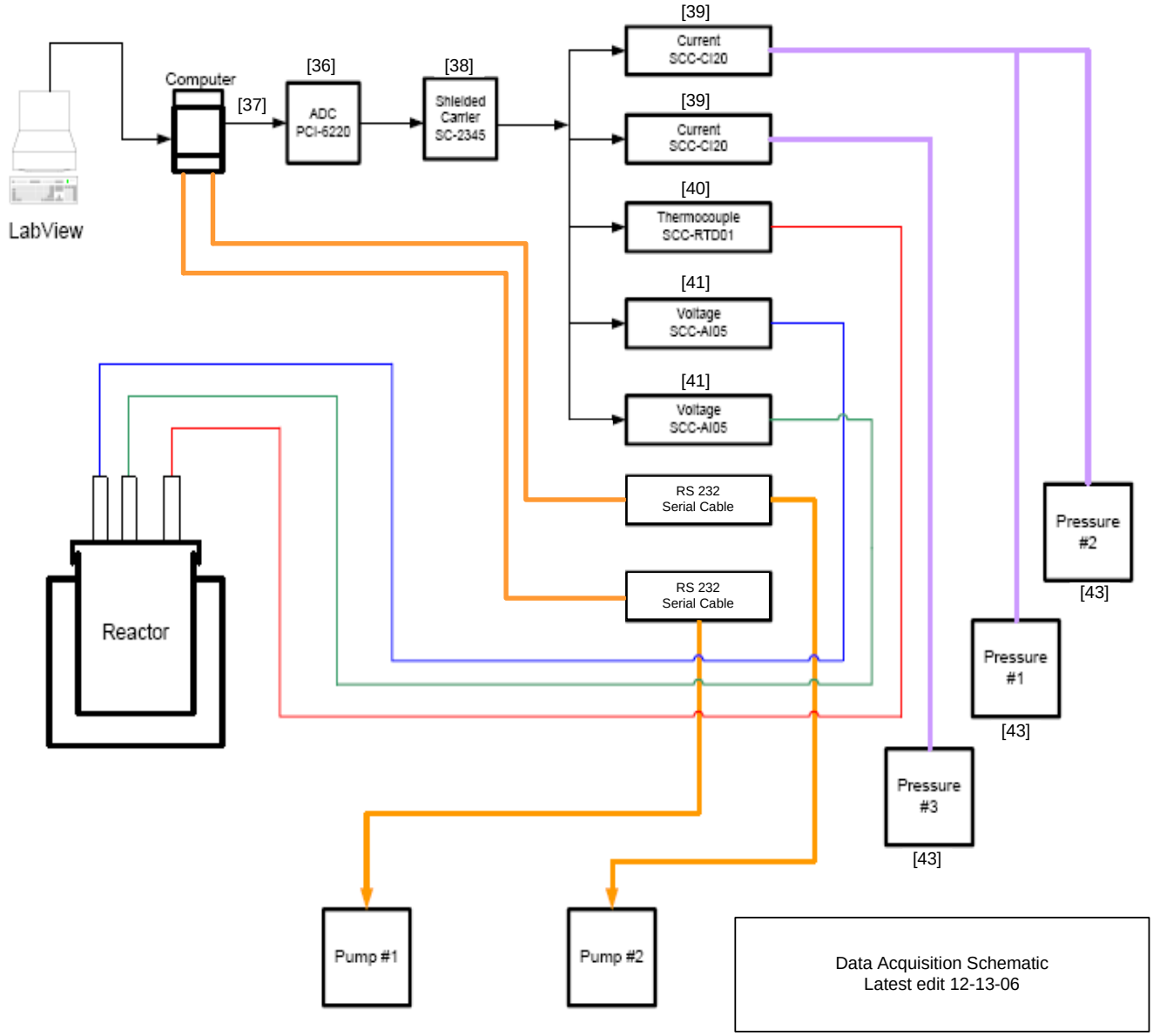
| | # | Item | Qty. | Distributor | Part # | Unit Price | Total Price |
|---|---|---|---|---|---|---|---|
| Cole-Parmer | 1 | **MasterFlex Easy Load II Pump Head** | 4 | Cole Parmer | EW-77201-60 | $255.00 | $1,020.00 |
| | 2 | **MasterFlex 2-channel mounting hardware** | 1 | Cole Parmer | EW-07013-05 | $24.00 | $24.00 |
| | 3 | **MasterFlex L/S ® Brushless Computer-Compatible/Programmable Drives** | 1 | Cole Parmer | EW-07550-30 | $1,690.00 | $1,690.00 |
| | 4 | **MasterFlex L/S ® Brushless Computer-Compatible/Programmable Drives** | 2 | Cole Parmer | EW-07550-50 | $1,690.00 | $3,380.00 |
| | 5 | **Precision Tygon LFL Tubing 25 ft** | 1 | Cole Parmer | EW-06429-18 | $92.00 | $92.00 |
| | 6 | **Precision Tygon LFL Tubing 25 ft** | 1 | Cole Parmer | EW-06429-13 | $42.00 | $42.00 |
| | 7 | **Precision Tygon LFL Tubing 25 ft** | 1 | Cole Parmer | EW-06429-16 | $64.00 | $64.00 |
| | 8 | **L/S 25 Tygon LFL Tubing** | 1 | Cole Parmer | EW-06429-25 | 71 | $71.00 |
| | 9 | **Cole-Parmer ® Polystat ® Six-Liter Refrigerated Circulating Baths** | 1 | Cole Parmer | K-12108-10 | $2,170.00 | $2,170.00 |
| McMaster | 10 | **Plexiglas** | 4 | McMaster | 8560K321 | $44.91 | $179.64 |
| | 11 | **Acetyl Quick-Connect 1/8" Plug and Barb with Shutoff Valve** | 6 | McMaster | 5012K44 | $6.16 | $36.96 |
| | 12 | **Acetyl Quick-Connect 1/8" Socket and Barb with Shutoff Valve** | 6 | McMaster | 5012K38 | $6.34 | $38.04 |
| | 13 | **Acetyl Quick-Connect 3/8" Plug and Barb with Shutoff Valve** | 10 | McMaster | 5012K86 | $6.78 | $67.80 |
| | 14 | **Acetyl Quick-Connect 3/8" Socket and Barb with Shutoff Valve** | 10 | McMaster | 5012K83 | $6.90 | $69.00 |
| | 15 | **Viton O-Ring** | 1 | McMaster | 9464K693 | $12.30 | $12.30 |
| | 16 | **Viton O-Ring** | 1 | McMaster | 9464K686 | $8.95 | $8.95 |
| | | **Feed:** | | | | | |
| | 17 | **(1/16" x 1/8") barb** | 2 | McMaster | 53055k125 | $0.69 | $1.38 |
| | 18 | **(1/8") 'Y'** | 2 | McMaster | 53055k153 | $1.49 | $2.98 |
| | 19 | **(1/8" x 1/8") barb to npt** | 3 | McMaster | 53055k207 | 1.12 | $3.36 |
| | 20 | **(1/8" x 3/8") npt female** | 2 | McMaster | 45375k343 | 38.83 | $77.66 |
| | 21 | **(3/8")npt inline mixer** | 1 | McMaster | 35385k31 | 65.83 | $65.83 |
| | 22 | **(1/8" x 3/16") barb** | 2 | McMaster | 53055k126 | 1.23 | $2.46 |
| | | **Into Reactor:** | | | | | |
| | 23 | **(1/4" x 5/16")m quick-turn coupling** | 4 | McMaster | 51465k137 | 4.19 | $16.76 |
| | 24 | **(1/8" x 3/16")f quick-turn coupling** | 4 | McMaster | 51465k115 | 4.52 | $18.08 |
| | 25 | **worm drive clamps (set of 15)** | 2 | McMaster | 5388k14 | 4.37 | $8.74 |
| | | **Pressure Measurment:** | | | | | |
| | 26 | **(1/8")npt psi/kpa stainless (0-15psi)** | 3 | McMaster | 3850k21 | 18.69 | $56.07 |
| | 27 | **(1/8")npt 304 stainless cross** | 3 | McMaster | 4464k311 | 8.19 | $24.57 |
| | 28 | **(3/8" x 1/8") tube to npt** | 7 | McMaster | 53055k212 | 1.95 | $13.65 |
| | | **Loop T:** | | | | | |
| | 29 | **(3/8") barb 'T'** | 3 | McMaster | 53055k173 | 2.35 | $7.05 |
| | | **Valves:** | | | | | |
| | 30 | **3/8" needle valve** | 2 | McMaster | 4891k73 | 29.18 | $58.36 |
| | 31 | **3/8" barb** | 6 | McMaster | 53055k217 | 2.46 | $14.76 |
| Fisher | 32 | **Low Flow Meter (manual)** | | | | | |
| | 33 | **Hose Clamps** | 2 | Bel-Art | H40407 0075 | $172.96 | $345.92 |
| | 34 | **T-connectors (L/S 16)** | 2 | Fischer | 14-198-5A | $37.48 | $74.96 |
| | 35 | **T-connectors (L/S 18)** | 1 | Fischer | 15-319A | $15.05 | $15.05 |
| National Instruments | 36 | **M Series DAQ (w/driver software)** | 1 | NI | 779065-01 | $359.10 | $359.10 |
| | 37 | **Shielded Cable** | 1 | NI | 192061-02 | $107.10 | $107.10 |
| | 38 | **Shielded Carrier** | 1 | NI | 777458-01 | $242.10 | $242.10 |
| | 39 | **Current input module** | 2 | NI | 777459-05 | $143.10 | $286.20 |
| | 40 | **RTD Input Module** | 1 | NI | 777459-18 | $296.10 | $296.10 |
| | 41 | **2-Channel Isolated Analog Input** | 1 | NI | 777459-24 | $296.10 | $296.10 |
| | 42 | **1-Channel Current Output Module** | 2 | NI | 777459-33 | $224.10 | $448.20 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Omega | **Pressure Transmitter** | 3 | Omega | PX182B-060G | | $120.00 | $360.00 |
| 43 | | | | | | | |
| | **Basic 7 ltr round bottom jacketed bioreactor** | 1 | Applikon | Z61103CT07 | | $3,592.80 | $3,592.80 |
| | **Magnetic stirrer, 7 ltr bioreactor** | 1 | Applikon | Z81315MG07 | | $2,125.80 | $2,125.80 |
| | **pH+ sensor, gel filled, 325 mm** | 1 | Applikon | Z001032551 | | $302.40 | $302.40 |
| | **Cable for Applikon pH/DO sensor, 2 meter** | 1 | Applikon | Z100200010 | | $102.60 | $102.60 |
| | **Electrode holder/nipple (pH)** | 1 | Applikon | | ? | ? | ? |
| | **Sample pipe,adjustable** | 1 | Applikon | Z81319MB21 | | $241.00 | $241.00 |
| | **Thermometer pocket** | 1 | Applikon | Z81323TP07 | | $180.00 | $180.00 |
| | **Temperature sensor, Pt100, L=200 mm** | 1 | Applikon | Z71204T002 | | $167.40 | $167.40 |
| | **Foam/level sensor** | 1 | Applikon | Z711203001 | | $299.70 | $299.70 |
| AppliKon | **Cable for foam/level sensor** | 1 | Applikon | Z71513AF02 | | $66.60 | $66.60 |
| | **Electrode holder/nipple (level)** | 1 | Applikon | | ? | ? | ? |
| | **Air inlet pipe assembly/pipe (4mm ID)** | 1 | Applikon | Z81318L007 | | $241.00 | $241.00 |
| | **Air outlet pipe/overlay pipe** | 1 | Applikon | Z81308LU02 | | $123.00 | $123.00 |
| | **Septum holder** | 1 | Applikon | Z81302PD02 | | $125.10 | $125.10 |
| | **Marine impeller, vortexing** | 1 | Applikon | Z81314RC07 | | $195.30 | $195.30 |
| | **Blindstopper for 18 mm ports** | 3 | Applikon | Z81301BD02 | | $72.90 | $218.70 |
| | **Blindstopper for 12 mm ports** | 2 | Applikon | Z81322BP08 | | $53.10 | $106.20 |
| | **Blindstopper for 10 mm ports** | 5 | Applikon | Z81322BP03 | | $46.80 | $234.00 |
| | **Blind plug for 3/4" port** | 1 | Applikon | Z81301BD04 | | $101.70 | $101.70 |
| | **1/4" – 20 bolt, nut, washers** | 16 | | | | $0.50 | $8 |
| | **Inner Rubber O-ring** | 1 | | | | $8.95 | $8.95 |
| | **Outer Rubber O-ring** | 1 | | | | $12.30 | $12.50 |
| Hardware store | **Quick connect assemblies** | 6 | | | | $75 | $75 |
| | **3/16" grommet** | 16 | | | | $0.30 | $4.80 |
| | **Porous membrane support** | 1 | | | | $2.50 | $2.50 |
| | | | | | | Grand Total | $20,703.28 |

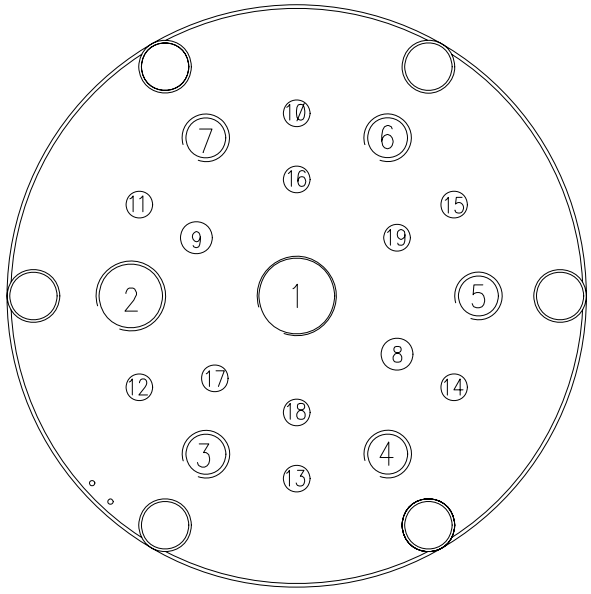
## APPENDIX H: SYSTEM SCHEMATIC



# APPENDIX I: DATA ACQUISITION SCHEMATIC



## APPENDIX J: APPLIKON HEADPLATE SCHEMATIC [44*]




| | | | |
|---|---|---|---|
| | **M30 x 1 port** | | **10 mm ports** |
| | Article number Description | 10. | Article number Description |
| 1. | Z81315MG07 " STIRRER ASS. MAGNET COUPLED" | | Z81308LU02 "AIR OUTLET PIPE BIOREACTOR" |
| | **G3/4" port** | 11. | Article number Description<br>Z81323TP07 "THERMOMETERPOCKET" |
| | Article number Description | 12. | Article number Description |
| 2. | Z81300N005 "NIPPLE FOR PH/MV" | | Z81319MB07 "SAMPLE PIPE ASSEMBLY" |
| | **M18 x 1.5 ports** | 13. | Article number Description<br>Z81319MB07 "SAMPLE PIPE ASSEMBLY" |
| | Article number Description | 14. | Article number Description |
| 3. | Z81300N002 "NIPPLE PH/MV/LE/INOC " | | Z81319MB07 "SAMPLE PIPE ASSEMBLY" |
| | Article number Description | 15. | Article number Description |
| 4. | Z81302PD02 "SEPTUM HOLDER " | | Z81322BP03 "BLIND STOPPER T=6-12MM" |
| | Article number Description | 16. | Article number Description |
| 5. | Z81301BD02 "BLIND STOPPER ASS." | | Z81322BP03 "BLIND STOPPER T=6-12MM" |
| | Article number Description | 17. | Article number Description |
| 6. | Z81301BD02 "BLIND STOPPER ASS." | | Z81322BP03 "BLIND STOPPER T=6-12MM" |
| | Article number Description | 18. | Article number Description |
| 7. | Z81301BD02 "BLIND STOPPER ASS." | | Z81322BP03 "BLIND STOPPER T=6-12MM" |
| | **12 mm ports** | 19. | Article number Description<br>Z81322BP03 "BLIND STOPPER T=6-12MM" |
| | Article number Description | | |
| 8. | Z81322BP08 "BLIND STOPPER ASS." | | |
| | Article number Description | | |
| 9. | Z81322BP08 "BLIND STOPPER ASS." | | |

**Note:**

- Stirrer Assembly must be placed in port : 1
- Sparger (Air Inlet Pipe) can be placed in port : 10, 11,12, 13, 14 or 15
- Baffle can be placed in port : 11, 13 and 15 or 10, 12, 14
- Heat Exchanger can be placed in port : 17 and 19 or 16 and 18