AnMBR Membrane Housing Design Sustainable Treatment of Domestic Wastewater

Final Report

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ME 450 SECTION #6 Group #27

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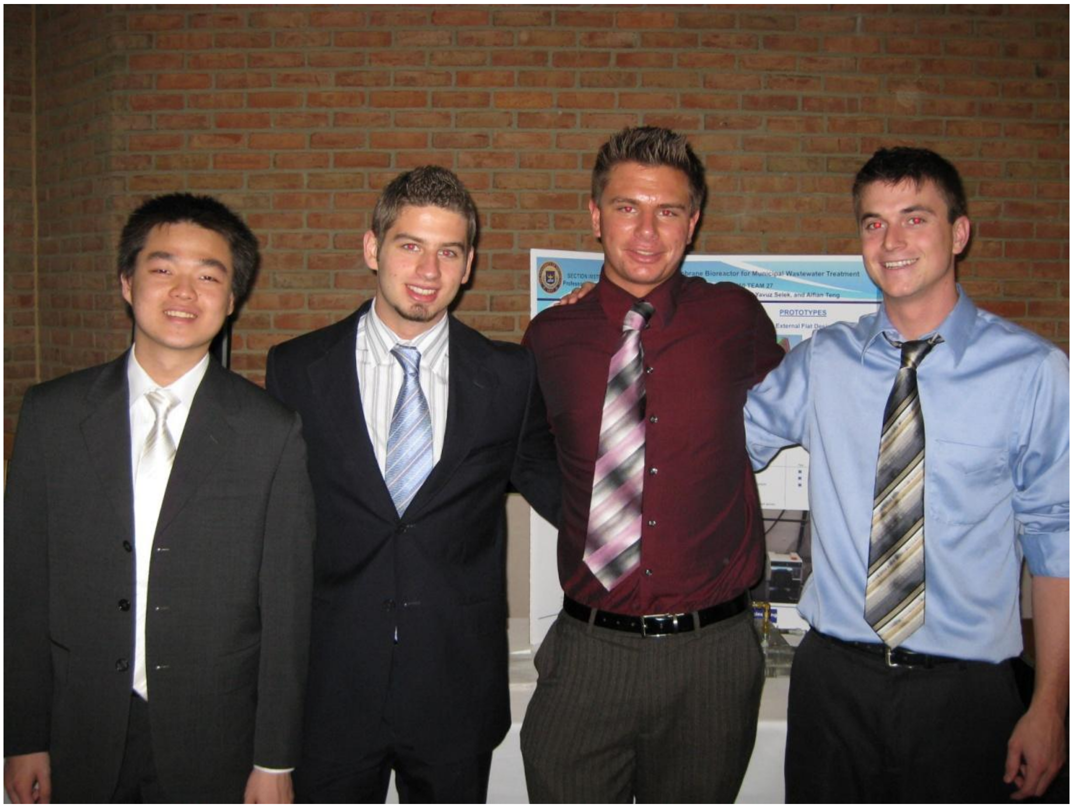

Executive Summary

Our sponsors presented us with the task of designing and building three membrane systems to be installed into the existing anaerobic membrane bioreactor (anMBR) at the University of Michigan. The three systems - an internal-submerged membrane, an external tubular membrane and an external flat membrane were to be compared based on effectiveness against fouling, energy usage, and effluent output. We were asked to design these systems to incorporate sparging. It was important that the sparging runs along the entire surface of the membrane for all three designs through the use of a nitrogen gas tank. Throughout this experiment, we strived to answer some vital questions: does sparging contribute significantly to fouling reduction? Would the external system or internal system configuration be better against fouling reduction and reduced energy consumption? Is a flat design with a dead-end flow or tubular design with cross-flow better in terms of fouling reduction and reduction in energy use? The systems all have similar surface areas ($0.04m^2$) to preserve the validity of the experiment. Initially, we came up with several concepts for each system. In order to decide on the most effective concept we ranked the concepts based on cost, time required for assembly, ability to meet engineering requirements and the feasibility of concept functionality. The numbers of designs were limited for the external concepts because we found that it would be appropriate to retrofit the existing systems. For the external flat system, nozzles have been retrofitted at the front plate for sparging and the sparging gas will be removed through the re-circulation tubes. With the external tubular system, we chose to retrofit the existing design because sparging could easily be introduced through a tube and removed without any major changes in the membrane system. The only challenge will be to ensure that all of the sparging gas is removed from the system without causing a pressure buildup. Finally, for the internal membrane system it was required that we limit the total volume of the system less than 1 L. We decided to use circular sparging plates (diffusers) that could sparge around the whole membrane effectively. The final challenge that is still to be determined will be to ensure that the membranes are stable inside the bioreactor, which we hope to accomplish through rigid tubes connected to the head plate and by gluing the bottoms of the caps to the sparging plate. Almost all the parts that we require have arrived and have been assembled. We are still missing most notably, a new external tubular membrane as the existing external tubular system needed to be kept running without interruption. Therefore, we still did not have the opportunity to test the external tubular system. The external flat system is mostly assembled and has exhibited a promising performance with the ability to prevent dead zones and create turbulence inside the system that should keep fouling to a minimum. Meanwhile, for the internal system, we are still waiting for the diffuser so that it can be tested. Once this part arrives we believe that the internal system will be ready to be implemented into the system.

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INTRODUCTION

The anaerobic membrane bioreactor (anMBR) project is sponsored by Professor Lutgarde Raskin, Mrs. Tanna Borrell and the University of Michigan. They have been working to create an effective and efficient domestic anMBR that will provide wastewater treatment on a smaller scale for local re-circulation. This would greatly reduce the energy used to pump water over vast distances to the large waste water treatment plants that exist today. Additionally, the energy use in anMBR wastewater treatment is approximately ten times less than the comparable energy use in existing mainstream aerobic wastewater treatment. The anMBR at the University of Michigan is currently facing problems due to fouling at the surface of the membrane which results in low flux. Our goal was to alleviate this problem by incorporating sparging and research on ways to improve the process of treating wastewater in an anMBR. This was accomplished by building three types of membrane assemblies - external systems of flat and tubular configurations and internal-submerged tubular configuration. The ultimate goal will be to determine the best possible combination that will minimize fouling and energy use. This may provide crucial information on the direction for future anMBRs.

INFORMATION SOURCES

As the population grows the demand for water increases there is an increasing push towards new technology for water reclamation. Anaerobic membrane bioreactors are at the forefront of these new systems because they offer clean reusable water and at lower energy costs. These facilities can handle larger amounts of wastewater as well as more concentrated industrial waste [1]. With the development of domestic anMBRs, wastewater can be sent to smaller anMBR facilities instead of large scale treatment plants. This would reduce expenditure on transporting reusable water to and from the plant [2]. The first application of anaerobic treatment of wastewater took place in the 1950s, and has come a long way in becoming an attractive method of waste treatment. It can be seen that anMBRs present a huge potential for wastewater treatment, but there are still a number of challenges to be faced.

Anaerobic Membrane Bioreactor (anMBR)

Anaerobic membrane bioreactor combines biological processes with membrane filtration. In such unit, the sedimentation is replaced by a membrane, which serves for the liquid/solid separation. It features a compact volume and high biomass concentration which breaks down the wastewater, releasing methane in the process which can be utilized as energy usage. The wastewater then filters through the membrane and leaves as clean water. Steady operation of membrane requires careful management of membrane fouling.

Fouling

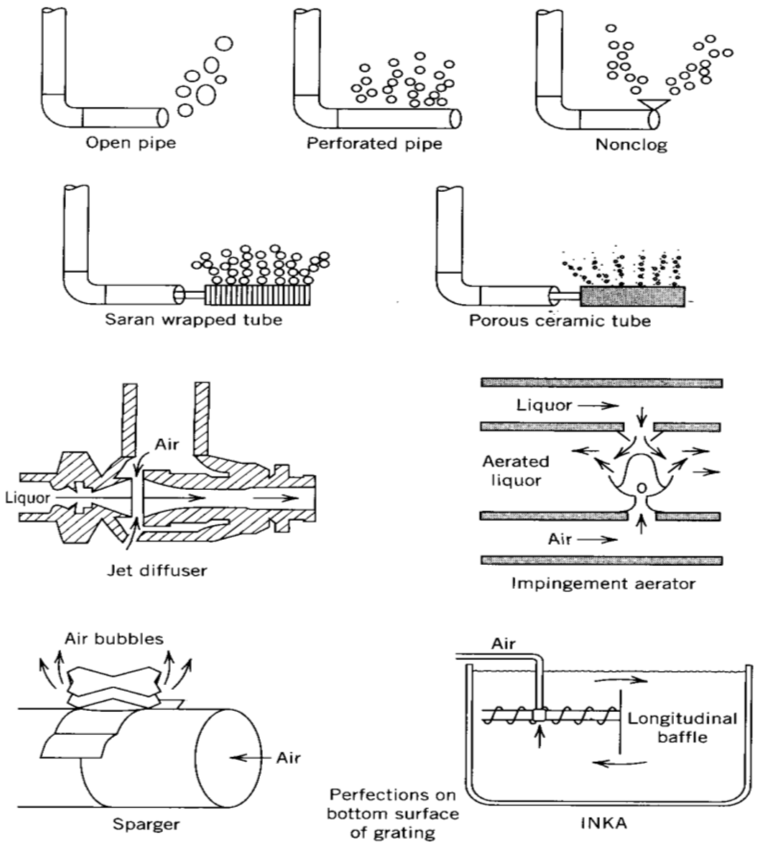
Fouling is the undesirable accumulation of microorganisms on the membrane. It causes lower efficiency and higher operating costs because the flux of treated water gradually decreases as more microorganisms accumulate on the membrane and block the flow. Membrane fouling limits the widespread use of membrane separation technology for wastewater treatment due to the increase in operating costs associated with routine membrane cleaning and environmental hazards related to this membrane cleaning. Therefore, minimization in fouling is of utmost priority.

Water Turbulence

Various means have been employed to induce turbulence in water to shake off the fouling that occurs on the membrane and prevents further accumulation. The most common methods are sparging and high-velocity flow. Sparging and high-velocity flow are incorporated in all three systems while high-velocity flow will be used the external systems.

Sparging

Sparging triggers vibration on the membrane that can clear the biomass buildup and disrupt the single-directional flow to prevent further accumulation on the membrane. The word “sparging” is used interchangeably with “bubbling”. There are a number of sparging systems including gravity, spray and diffused spargers. Diffused sparging is probably the most common and basic device for producing bubbles. This is because it is easily implemented into the membrane system in terms of space and flexibility. The diffuser can simply consist of a tube or if space permits, a panel to ensure uniform sparging for a horizontal flat sheet membrane. There exists some difficulty in sparging a tubular membrane using a simple nozzle or tube, because not all parts of the circumferential area would get sparged effectively. This is where sparging panel may be useful. Different types of sparging mechanisms in schematic and real-life form are shown on Fig. 1, pg. 8-9.



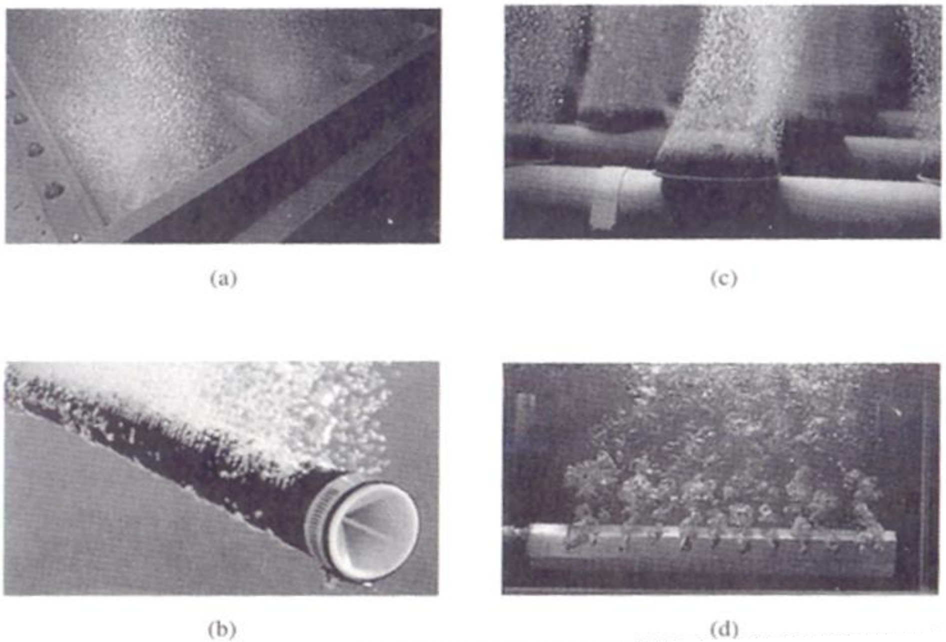


Figure 1. Schematic (On top) and Real-life Pictures of Various Diffusers (a) sparging panel, (b) fine bubble, (c) flexible tube (Wyss Flex-A-Tube), (d) coarse bubble. Courtesy of Parkson Group [6].

Generally, spargers may also suffer fouling, the very own enemy that they are trying to contain, thus reducing their performance. Note that sparging typically consumes between 40-60% of total energy needs, and therefore should be highly optimized. They have to be cleaned through cost-effective maintenance procedures regularly. Unfortunately, some of the maintenance procedures are process interruptive because they have to be taken out from the sparging tank to be cleaned. Some cleaning techniques used are acid/alkaline washing, gas injection and high pressure water jetting [4]. After an optimal air flow rate has been identified, further increase in sparging rate has no effect on fouling removal. Therefore, determining the optimal sparging rate is a key parameter in anMBR design.

Sparging can be implemented parallel with the flow of water (co-current) or in counter-current sense. In a counter-current sparging system, the bubbles are “pressed” by the opposing flow of water which impedes their motion. This will lead to longer duration of the bubbles being in contact with the surface of the membrane, resulting in more effective fouling reduction along the membrane. It also leads to lesser fouling on the sparger. However, this would mean counter-current sparger requires more energy input due to the need for higher pressure gas because some energy is wasted to counter the flow of water. The schematics are shown in Fig. 2, pg .10.

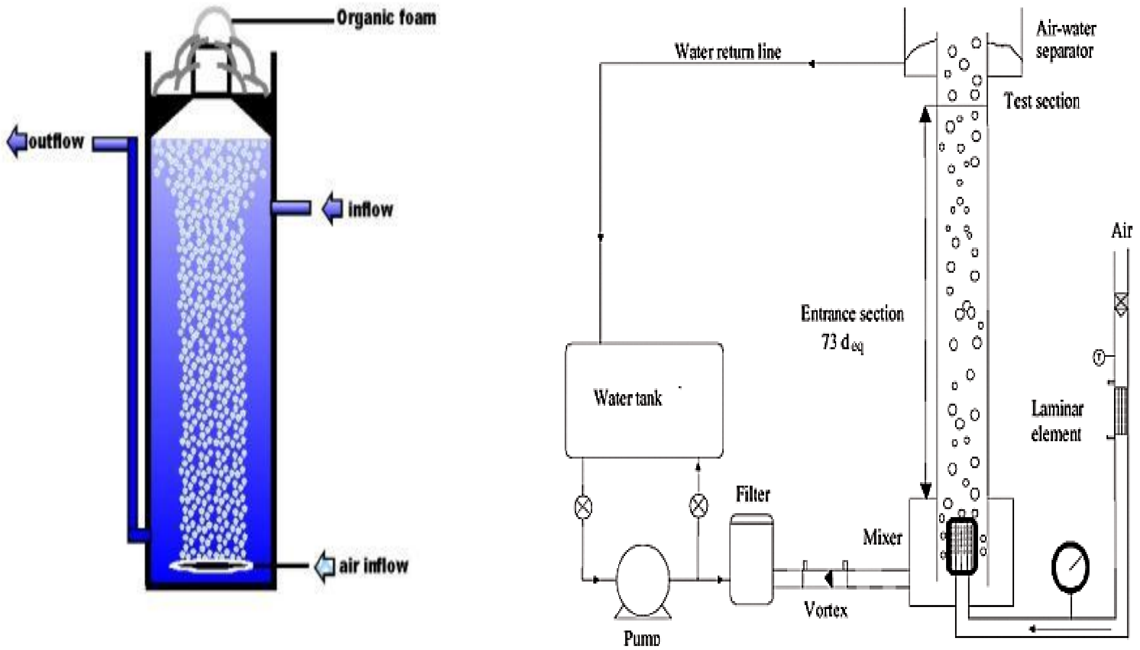


Figure 2. Schematics of counter-current (left) and co-current (right) sparging systems.

In some anMBRs, PLC (programmable logic controller) has been employed for cyclic sparging process (Fig. 3). The PLC shuts off the sparging process during times of low flux, and has been proven to reducing fouling equally as effective as continuous sparging and can save up to 50% of the energy cost. The City of Pooler, GA Wastewater Treatment Plant (WWTP) incorporates a PLC and in this configuration, a single blower scaled to sparge results in a 50% reduction in air required. This translates into a 21% reduction in energy usage and an 8.5% decrease in lifecycle cost [5]. This proves advantageous because continuous sparging is shown to be an unnecessary process.

Figure 3. Employing PLC for cyclic aeration cycle [5].

High-velocity Flow

External membrane systems operate at constant high flow velocity to create a turbulent flow, resulting in disturbance of fouling layer for minimization of membrane fouling. The strong shear force of the flow “flushes” out the biomass accumulated on the membrane surface. Despite the higher energy cost, it is more effective in reducing fouling than simply using sparging, which is typically found in submerged membrane system. The high velocity flow is accomplished by using a blower to pump the water to the membrane, typically in a cross-flow manner.

Factors that Affect Fouling

Many factors affect fouling, however, more studies need to be realized in order to find out the magnitude of impact they have on anMBR. The two major factors are the bioreactor configurations and the membrane configuration. The bioreactor configuration which is another main theme of our project consists of either the internal-submerged or the external membrane system, while the membrane configuration relies on the types of membranes and the types of flow they produce. These factors can determine the best possible combination to achieve minimal fouling depending on the type of application and the cost inherited.

Bioreactor Configuration - Submerged and External AnMBR

In the submerged membrane system the membrane is found inside the bioreactor, while in the external membrane system the membrane is located external to the bioreactor and the water is pump driven to the membrane for continuous filtration. Generally, the external anMBR tends to experience less fouling but uses more energy in comparison to the submerged system. This is because there is extra energy required for the wastewater to be pumped to the membrane for filtration compared to the internal system which has the system already submerged in the bioreactor where the wastewater is found. The energy demand on the submerged system can be up to two orders of magnitude less than the external system. However, submerged systems operate at a lower flux, thus they necessitate an increase in membrane area. The bioreactor configurations are illustrated in Fig. 4.

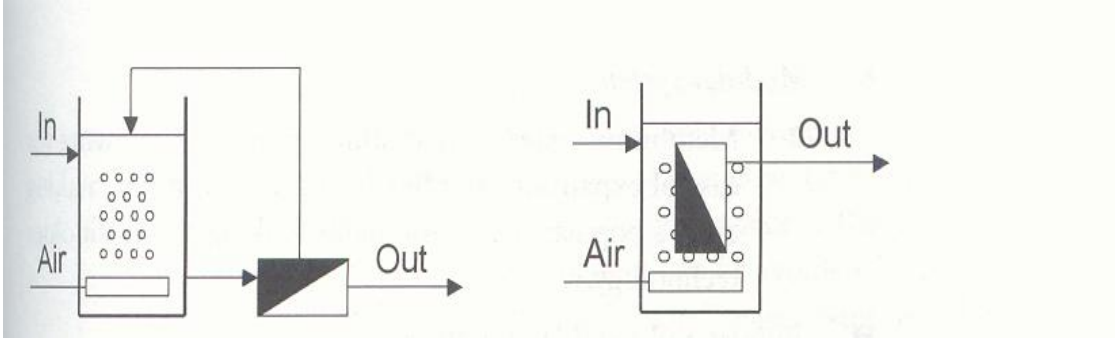


Figure 4. Left picture shows the external membrane system, while the right picture shows the internal membrane system [2].

Membrane Configurations - Membrane Types and Flow Configurations

Various types of membrane are used for anMBR, and their implications are discussed below. The common types of membranes used are the tubular and the flat-sheet, while the flow configurations range from cross flow to dead-end. These are summarized in Fig. 5 and 6, pg. 12.

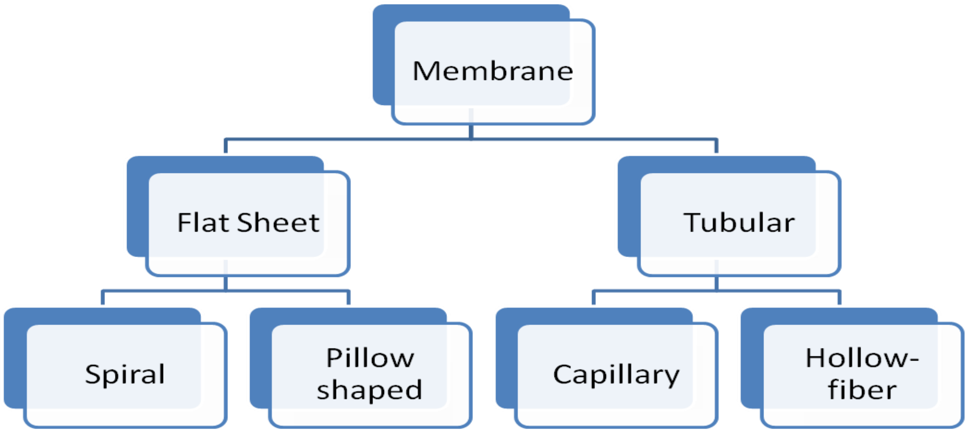


Figure 5. Various Membrane Types [2].

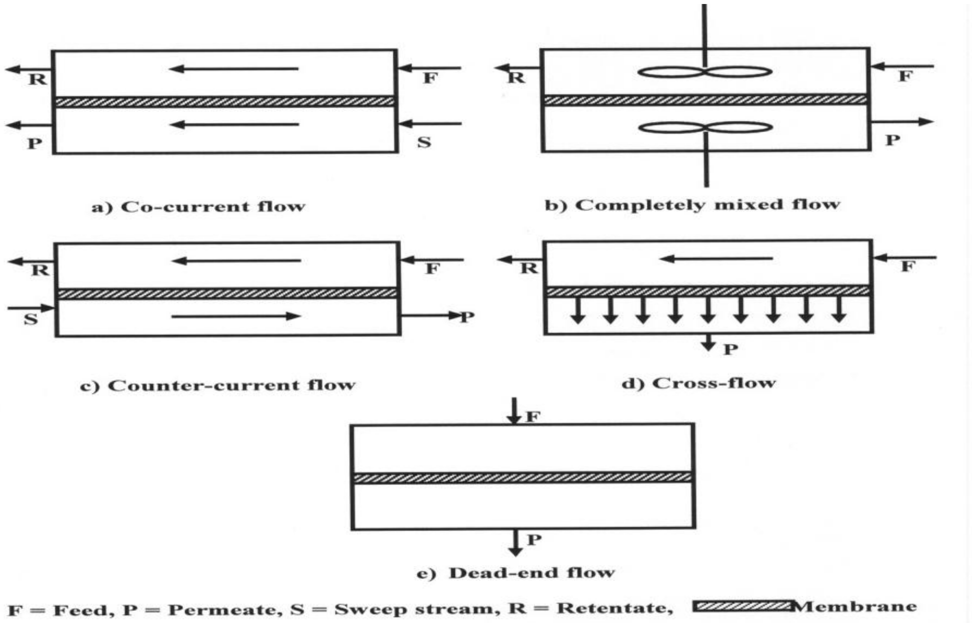


Figure 6. Various Flow Configurations [2].

Flat sheet membranes are comprised of a series of flat membrane sheets and support plates. The flow is filtered as it flows between and parallel to the membrane (Fig. 7, pg. 13). The flat sheet membranes are typically used in submerged system in anMBRs. Rotating flat plate membranes have been used to some degree to alleviate fouling [2].

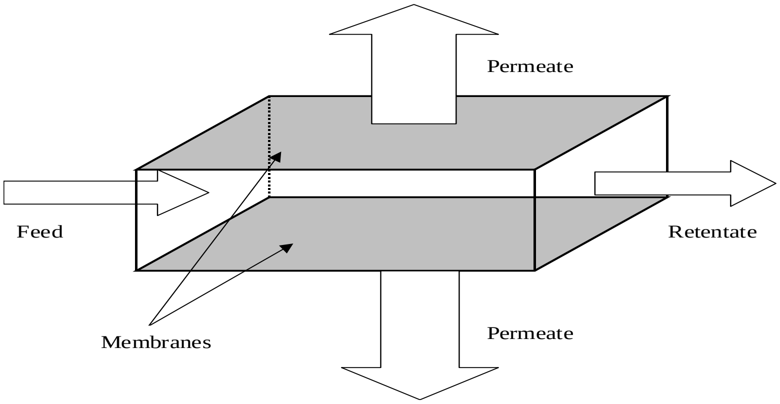


Figure 7. Flat Plate Membrane Schematic [2]

Tubular membranes are cylindrical in shape and have long been known to be a superior membrane configuration due to their rugged, reinforced construction (Fig. 8). However, their use in anMBR applications has been limited in the past due to the high energy cost of the pumping required to sustain the velocities needed for proper cross-flow and pressure gradients [3]. The difference between the tubular and the hollow-fiber membranes is that the hollow fiber membranes have finer pore sizes (1-2mm vs. 25mm). Nevertheless, human hairs tend to clog up the hollow-fiber membranes and fouling generally increases with smaller pore size [1]. Yet, the low life-cycle cost has made hollow-fiber membranes the most popular configuration for large municipal facilities [2].

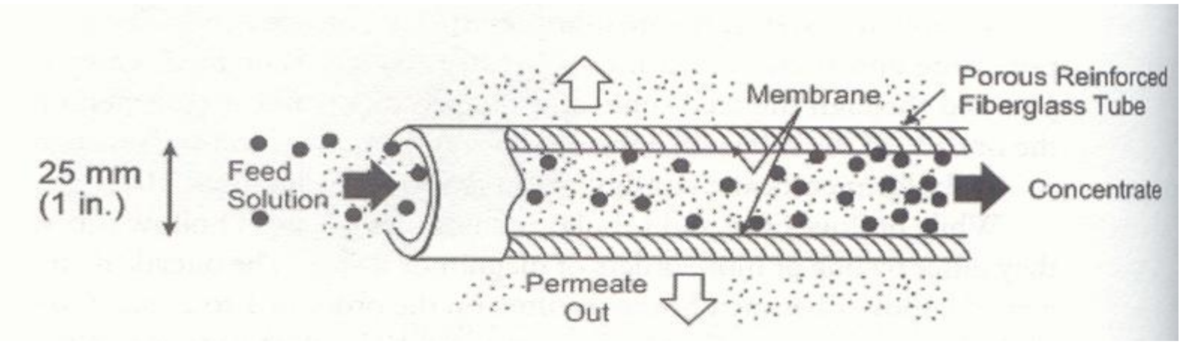


Figure 8. Tubular membrane schematic [2].

The differences between the tubular and flat sheet configurations are that the flat sheet is easily dismantled and cleaned but the tubular one has a higher hold-up volume and mass transfer coefficient. This signifies that there is a larger diffusion rate relating the mass transfer, transfer area and concentration gradient which has proven to diminish fouling. However, the flat sheet membrane is sparged much easier across its surface because of its geometry.

Meanwhile, cross-flow is most commonly used in tubular membrane system, while the dead-end flow is mostly used in the flat-sheet membrane. Cross-flow is the flow of water at high velocity tangential to the surface of a membrane to maintain contaminants in suspension. Dead-end configuration has only one feed stream and one effluent stream and has been proven to be generally insufficient in countering fouling. For counter-current flow, it has the advantage of a concentration gradient and is beneficial if reverse-osmosis is used.

Energy Usage

Another challenge facing anMBR is the energy usage associated. Previously discussed fouling issues are intertwined with energy usage because the various ways to reduce fouling will most likely consume energy. Unfortunately, there are trade-offs between performance and energy usage.

Generally, the net energy cost of anMBR is equal to the thermal energy required by the process plus other operational energy cost minus the energy gained from the methane produced, which may be reused to offset the energy requirement. The thermal energy is the sum of the energy required to heat the wastewater up to the digester operating temperature and the energy needed to replace reactor heat losses to the environment. These heat losses account for less than 10% of total energy requirements. Other sources of operational energy cost include the pumps and blowers for sparging, backflow or other cleaning processes [6]. The breakdown of energy use in anMBR is shown in Fig. 9. As can be seen, the biggest energy cost is the thermal energy, but the operational energy cost is also significant. An important aspect of the project is the energy cost associated with these operations, and this table further highlights the importance of the study.

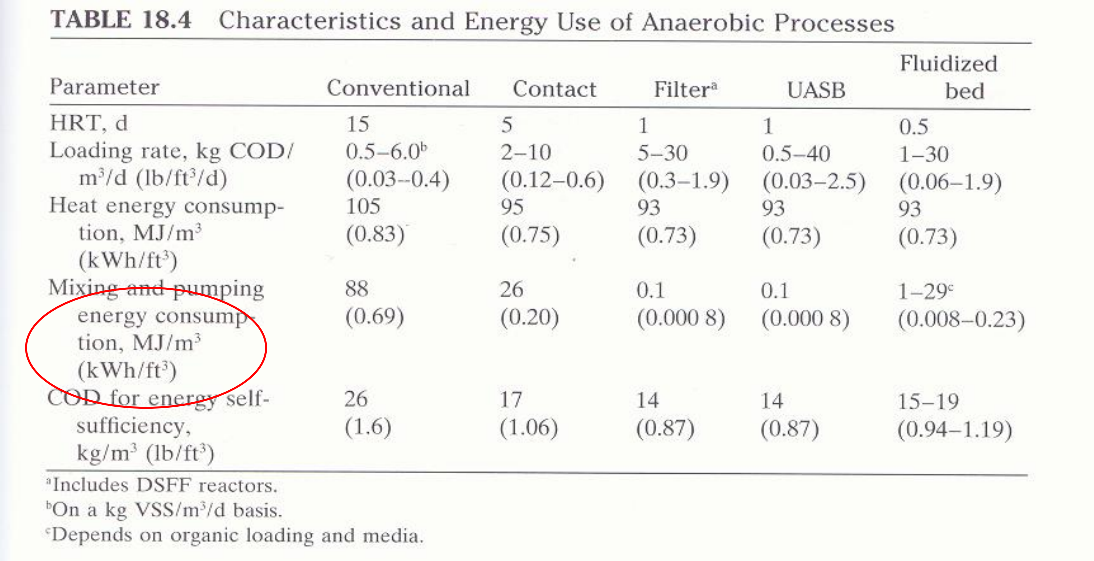


TABLE 18.4 Characteristics and Energy Use of Anaerobic Processes

Parameter	Conventional	Contact	Filter[a]	UASB	Fluidized bed
HRT, d	15	5	1	1	0.5
Loading rate, kg COD/ m^3/d (lb/ft^3/d)	0.5–6.0[b] (0.03–0.4)	2–10 (0.12–0.6)	5–30 (0.3–1.9)	0.5–40 (0.03–2.5)	1–30 (0.06–1.9)
Heat energy consumption, MJ/m^3 (kWh/ft^3)	105 (0.83)	95 (0.75)	93 (0.73)	93 (0.73)	93 (0.73)
Mixing and pumping energy consumption, MJ/m^3 (kWh/ft^3)	88 (0.69)	26 (0.20)	0.1 (0.000 8)	0.1 (0.000 8)	1–29[c] (0.008–0.23)
COD for energy self-sufficiency, kg/m^3 (lb/ft^3)	26 (1.6)	17 (1.06)	14 (0.87)	14 (0.87)	15–19 (0.94–1.19)

[a] Includes DSFF reactors.
[b] On a kg VSS/m^3/d basis.
[c] Depends on organic loading and media.

Figure 9. Energy Use of Anaerobic Processes [6].

Fig. 10, pg. 15 illustrates the energy breakdown of a typical submerged anMBR. It utilizes the aeration (sparging) process as a mean to reduce fouling on the membrane. As can be seen, sparging on the membrane consumes about 38% of the total energy requirement, which is a significant proportion. However, this process is able to reduce fouling significantly and improve membrane performance. It is once again a delicate balance between cost and performance. The scope of this project is to find out more about this balance and to maximize performance and minimize energy cost.

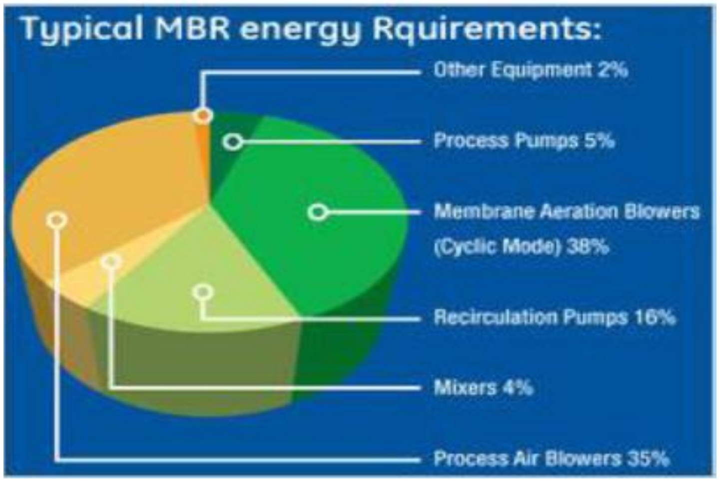


Figure 10. Typical submerged MBR energy requirement [7].

Previously, it was mentioned that typically, external anMBR consumes more energy than submerged membrane. The majority of the power consumption is due to the blower which produces a very high pressure (50-100psig) for the flow into the membrane. However, progress has been made to drastically reduce energy consumption in an external anMBR. An example is given in Figs. 11 and 12, pgs. 15-16. Dynalift technology uses two-phase flow to eliminate the high energy cost associated with conventional cross-flow filtration. A small amount of air sparged into the bottom of the vertically oriented membrane module which provides both an airlift effect to reduce the pumping energy required, and excellent membrane surface scouring. This simple innovation eliminates more than 75% of the energy needed in conventional cross-flow designs [7].

Overall, if we can optimize or find a good replacement for the process of sparging in a submerged system and cross-flow in an external system, we would reduce the energy use substantially without compromising membrane performance. Lastly, the sparging process can also be implemented in an external system to reduce fouling, but it would require more energy input.

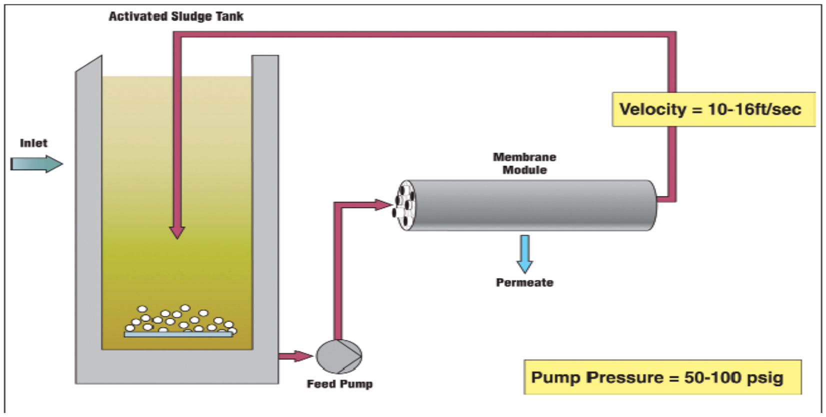


Figure 11. Generic cross-flow membrane anMBR operation [7].

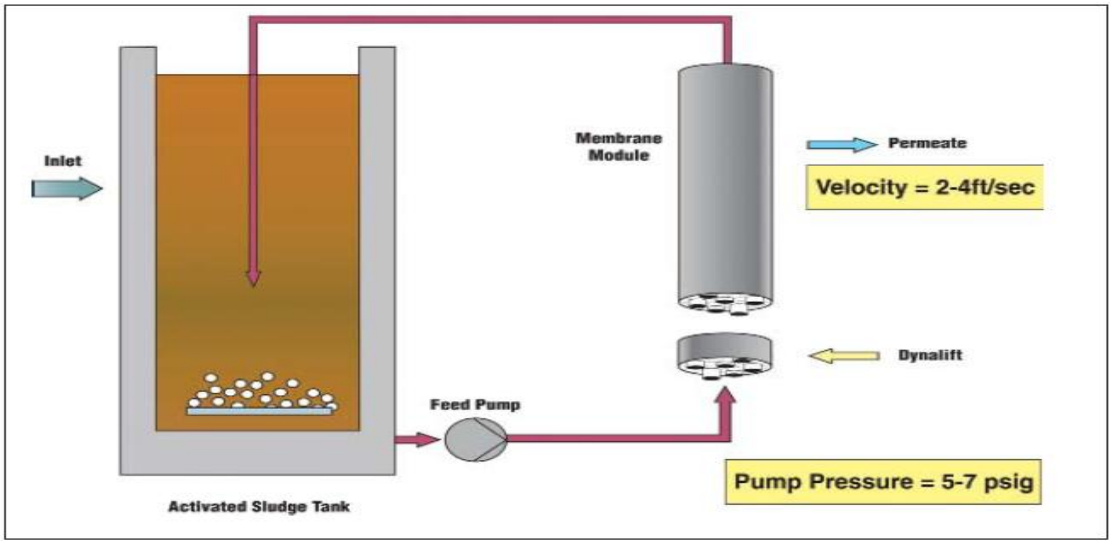


Figure 12. Dynalift external membrane anMBR operation [7].

ENGINEERING SPECIFICATIONS

Sponsor Requirements

The general requirements from our sponsor are listed below:

- To introduce sparging gas and remove it from system
- To increase the flux by reducing fouling
- That sparging runs along entire membrane surface
- That all designs have equal membrane surface area
- The flat external system minimizes dead zones
- That they install into existing systems easily
- Power consumption must be reduced

One of the main goals of this project was to see how sparging affects the flux of a system compared to a system without it. However, it was also important that we remove the gas or the pressure will build up in the system and likely to cause rupture in the bioreactor. Sparging is used to decrease fouling, thus it was important that our designs have increased flux since it was directly correlated with the amount of fouling. Another main goal was that our sparging mechanisms were designed so that the gas ran along the entire surface of the membrane for maximum fouling prevention. The surface areas had to stay consistent in all of the designs since we wanted an even comparison. Installing into the existing system was desired but not necessary because we could set up our own if needed.

From the list above we came up with quantitative targets that our designs needed to accomplish. Though controlling the amount of sparging is somewhat straightforward, measuring it is not, thus the amount of sparging desired has not been determined numerically. However, this will be explained in more detail in the validation section. The clean water (effluent) that is removed from the existing system has fluctuated constantly and has dropped to 4 L/day. The ideal rate that this can perform is 40 L/day. Because complete elimination of fouling is unrealistic, we strived to minimize fouling as much as possible. A trans-membrane pressure gradient of 80 kPa would be ideal for all three systems for the sake of consistency versus the existing system. However this was unfeasible due to the design constraints. For instance, the geometry of the external flat system would deem a pressure gradient of 80 kPa not possible because the system may fail by rupture. The surface areas perpendicular to the pressure gradient would be maintained at 0.04 m^2 for all three. Although reducing energy consumption was at the bottom of the list for the scope of this project, operating at a low power input is always desirable in real world scenarios.

The current external tubular membrane housing supports a 0.012 m diameter membrane that is 1 m long. The pressure gradient is 80 kPa across the membrane, 180 kPa on the inside and atmospheric pressure (≈ 101 kPa) on the outside. The cross flow velocity of the influent is 0.05 m/s across the membrane. The system uses two pumps; one for the influent (untreated wastewater) from the bioreactor tank and one to pump the dirty water through the membrane and create the pressure gradient.

Our design for the tubular system needed all of these attributes. Additionally, sparging was required to run along the entirety of the membrane to remove as much of the fouling as possible. The sparging gas needed to be removed from the system at the same flow rate of the input so pressure buildup would be avoided. In a quantitative manner, this would refer to having equal gas pressure at the inlet and outlet of the gas line. The housing had to connect to the existing system easily, so that it attached to the 3/8" diameter rubber tubing on both ends that circulate the dirty water across the membrane. This system needed to be similar to the one already in place and energy consumption will be identical because two pumps (the primary source of power usage) will be running with the same power output.

For the external flat membrane system it was specifically important that we did not have dead zones in the housing as the previous study group had. It was also important that sparging flowed across the whole membrane to minimize fouling. This gas needed to be extracted without removing any water or reducing the pressure inside the system. The dirty water had to re-circulate throughout the system to avoid stagnation which would lead to fouling. This system necessitated having the same surface area as the tubular system for the sake of validity in any comparison between the two. The power consumption will be slightly less than the existing tubular system since the same number of pumps is necessary with no obligation to overcome a height difference.

Regarding the submerged system, we wanted to install it into the existing bioreactor easily; which constrained us due to the operating volume of the current bioreactor. Therefore, this led to the conclusion that the total volume that the membrane system could occupy in the tank would be no larger than 1 L to accommodate the 5 L operating volume of dirty water (influent) in the 6 L tank. The diameter of the mouth of the tank is 0.215 m and is 0.27 m deep. The whole system also had to fit easily within these dimensions and not interfere with the impeller in the tank. The cap for the tank can be seen in Appendix A which shows the different locations and diameters of inlets at the head plate. The sparging has to enter through one of these holes and travel to the bottom of the membrane from which it sparges along the length of the membrane surface. The sparging needed to cover the entire membrane surface to minimize fouling and exit with the methane produced by the decomposition of waste. The tube to retrieve the clean water must also enter through one of inlet/outlet holes and connect to all the membrane housings. We hypothesized that the internal membrane system would use less energy than the external systems because it does not require influent to be pumped to the membrane to provide filtration. A vacuum pump is required in the internal system to remove the effluent from the tank.

CONCEPT GENERATION

Our concepts generation centered around three distinct designs, an internal/submerged membrane, an external flat membrane and an external tubular membrane. In order to generate the two external systems we had to look at the existing designs of the two systems. Each of the two systems did not incorporate sparging. For the concepts we generated for the external designs, we based our designs to mimic the existing membranes with sparging retrofitted. For the internal system we had to come up with a system that had certain limitations on it - it had to take up minimal space in the bioreactor (1 L or less) and had to fit around the impeller within the bioreactor tank. The goal was to make the membrane area size equivalent to the membrane area of the two external systems so that no extrapolations would be necessary to compare the systems. In order to come up with the final concepts, we held brainstorming sessions in which we went through and decomposed the possible configurations of each system and then drew designs that fit into these possible configurations (Appendix B). We then did a functional decomposition of the basic anaerobic membrane system including sparging (Appendix C). We did not eliminate any design right away no matter how implausible so that we might build on any interesting concepts that came out of the multitude of concepts.

External Tubular Membrane Concept #1

In coming up with a concept for the external tubular membrane we saw that very little modification would be needed to introduce sparging into the membrane. The existing tubular membrane qualities were well known and there was little leeway in the ability to get creative in designing the housing. The two key challenges were encountered when coming up with a way to introduce the sparging into the membrane and in figuring out how to remove the sparging gas as it exits the membrane. Our final chosen design has the influent entering from the top, with an air-water separator connected to the top tube and a T-shaped connector at the bottom of the membrane where the effluent exits and the sparging enters the membrane simultaneously (Fig. 13, pg. 22).

External Tubular Concept #2

In this concept, the membrane is inside out, with the support material placed on the inside of the membrane. The influent would flow from the outer part of the tube and the effluent would flow out from the middle. This influent can either flow from the bottom to the top or from the top to the bottom. The sparging would also be introduced by a T-connector at the bottom and there would be an air gas separator at the top. The T-connector would connect to a nitrogen tank which would provide the sparging (Appendix D).

External Flat Membrane #1

In our design process for the external flat membrane, our goal was to use the existing system to cut down on material use, manufacturing time and time spent waiting for ordered parts. We also thought that if the existing system was not feasible, we would at least use the concept of the existing design. We looked at the fallacies in the original membrane and saw that they could easily be fixed through some slight changes. The original membrane had dead zones where water did not circulate. It also fouled up to the point that there was no flux within 48 hours of its first use. Our concept assumed that with flow in all four corners and the introduction sparging would prevent the membrane from fouling. A sparging tube would be introduced at the bottom of the membrane with the gas flowing upwards along the membrane and then at the top of the membrane we would introduce an air-water separator that would remove all of the sparging gas. The downside of this design was that it was difficult to put the membrane back together because the bolting system allows for little leeway in reintroducing the bolts into the holes and there is very little space in which to introduce a tube on the inside of the system (Fig. 14, p. 23).

External Flat Membrane #2

The second concept we came up with was almost identical to the concept we came up with in the first design. From our studies and Tanna´s suggestions, a rectangular membrane is preferred versus a square membrane because it reduces the dead zones and thus is more efficient than using a square membrane. The only drawback is the increased cost due to the necessity of building a whole new system. The final area of the membrane would be equal to the square design and the casing would be bolted down in a more efficient manner where the holes on one side would be a little larger than the bolt so that there would be some leeway when replacing the bolts into the holes, making it easier to disassemble (Appendix E).

External Flat Membrane #3

The last concept we came up with looks similar to a bucket with the membrane placed at an angle in the tank and the influent flowing in at the top left and re-circulating from the bottom right. Below the membrane we would either just allow gravity to pull the influent down or we would introduce a vacuum pump to create the pressure gradient across the membrane. The sparging would be introduced by a sparging “grate” that would go across the surface of the membrane. Finally, the gas would escape through the top using either a pressure release valve or an air-water separator (Appendix F).

Internal Membrane #1

The most difficult system to design was the internal membrane because we did not have a previous system that we could analyze to use as a model for our internal design. However, because of the size restrictions and the minimal changes that can be made to the way the membranes are sparged internally based on our previous research relating to sparging mechanisms, we were limited in what we could design. Our final design concept includes multiple membranes that are held up by the vacuum tubes that pull the effluent out of the membrane. There would be a sparging tube that split into two parts so that there can be sparging on both membranes starting from the bottom. The sparging tube may also be used to hold the membranes from rotating inside the bioreactor. In one design the membranes would be flat, and the sparging tube would run across the bottom of the membranes. They would be capped on the sides to prevent the influent from getting in and allowing for the pressure to be maintained inside the membrane. The difficulty with this is that we have little benchmarking for lab scale flat internal membranes. The other design would use tubular membranes held up by a support material and capped at the bottom with a sparging tube bent and rounded off into a circular configuration at the bottom of the membrane so that the membrane could be held up by the tube and the tube could sparge all of the way up and around the membrane (Fig. 15, pg. 24).

Internal Membrane #2

In another of our designs we came up with a system where the vacuum tubes were built into a false bottom that the membranes would be permanently attached to. The top of the membranes would be sealed and the sparging tubes would run around all the sides of the membranes, the sparging gas would come out from all points along the sides (Appendix G).

Internal Membrane #3

In this design we came up with something similar to the previous except that the vacuum tubes would be attached to the top of the membranes and the sparging tubes would be built into the false bottom. The sparging gas would come up from the bottom only and the membranes would be fixed into the false bottom (Appendix H).

CONCEPT SELECTION PROCESS

To select our final concept for each design, we used some criteria we deemed to be the most important including cost, ease of assembly, ability to meet engineering requirements, effectiveness of sparging the membrane and time required to order the parts. The criteria below were ranked from lowest to highest with the lowest number being the most desirable.

External Tubular Membrane

In this membrane system we came up with two main concepts that had some spin offs to them. The main variance to these concepts was whether the influent came in from the bottom or the top; we will not judge this criterion here because we can test the tube either way once our system is setup. We found that using a new external tubular membrane that mimics the existing one would be the most preferential in introducing sparging into the membrane. There is little variation allowed for the tubular membranes because there are only so many ways they can be setup, either inside out or outside in. We chose the inside out concept because the assembly in this process will be much simpler (Table 1).

Parameters	**Weight (1-5)**	**#1**	**#2**
Cost	1	1	1
Ease of assembly	1	1	2
Engineering reqs	5	5	10
Sparging satisfied	4	4	8
Time to order	3	6	3
Total		**17**	24

Table 1. External tubular membrane concept selection scoring matrix.

External Flat Membrane

We came up with three viable concepts for the external flat membrane and then ranked them based on the criteria listed in Table 2, pg. 21. The first design concept proved to be the most effective in meeting all of our goals because it is already made and only requires a retrofit and already satisfies many of the engineering requirements that we have set forth. Building a totally new flat membrane would prove costly and require much more time to put into use. Additionally, because we were already prodded into using the existing membrane, the impetus for using the existing system is quite apparent.

Parameters	**Weight (1-5)**	**#1**	**#2**	**#3**
Cost	1	1	3	2
Ease of assembly	1	2	2	3
Engineering Reqs	4	8	4	12
Sparging satisfied	4	8	8	12
Time to order	3	3	6	6
Total		**22**	23	35

Table 2. External flat membrane concept selection scoring matrix.

Internal Membrane

The internal membrane system was the most difficult system to come up with a way to determine which design would be the most effective at achieving all of the requirements that we wanted to fulfill. In addition to all of the previous design criteria we added in amount of space taken up by the system. We ended up choosing design #1 because the cost of the system would be low and it would be the easiest to assemble. We found that introducing a false bottom would take up too much space and be difficult to implement due to the bottleneck feature of the bioreactor tank. In the end, we also chose tubular membranes because we solved the issue of sparging around a tubular membrane, which was the main difficulty in choosing between the flat and tubular shapes (Table 3).

Parameters	**Weight (1-6)**	**#1**	**#2**	**#3**
Cost	1	1	2	3
Ease of assembly	1	1	3	2
Engineering reqs	4	1	12	4
Sparging satisfied	4	1	12	8
Time to order	3	3	3	3
Volume used	4	4	8	8
Total		**11**	40	28

Table 3. Internal membrane concept selection scoring matrix.

SELECTED CONCEPT DESIGNS (ALPHA CONCEPTS)

External Tubular Membrane

In the final concept for the external tubular membrane, we used a replica of the existing tubular membrane that is currently in use with the bioreactor. The membrane section is prefabricated in South Africa. Our job will be to connect tubes to both ends that introduce and remove the sparging gas (Fig. 13). There will be a T-tube connected at the bottom with the influent re-circulating through the bottom as shown and the other connection will connect to a nitrogen gas tank that will introduce the sparging gas. At the top there will be another T-tube connection where the influent comes in from the side and the top is connected to an air-gas separator. The effluent flows out of the membrane and flows down before exiting through a separate tube. A counter-current flow (description in Information Sources, pg. 15) was chosen because it is better against fouling reduction than co-current flow.

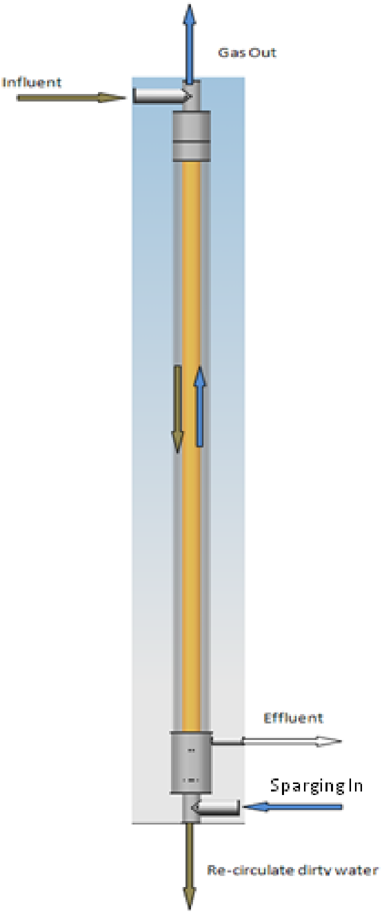


Figure 13. External tubular membrane CAD concept rendering.

External Flat Membrane

In the external flat membrane alpha concept, we decided to use the existing membrane built by the previous ME450 team. We were going to take the system apart and machine a hole to introduce a sparging tube at the bottom. The sparging tube would have had holes throughout so that the sparging would cover the entire surface. The top two holes were to be used to introduce the influent while the bottom two would re-circulate the influent back into the membrane. On the left side the exit hole is the exit of the effluent water. At the top of the flat membrane there would be a hole to introduce an air-water separator in order to remove the sparged gas without removing any of the influent. The bolts running around the outside of the membranes would be used to keep the membrane system leak free (Fig. 14).

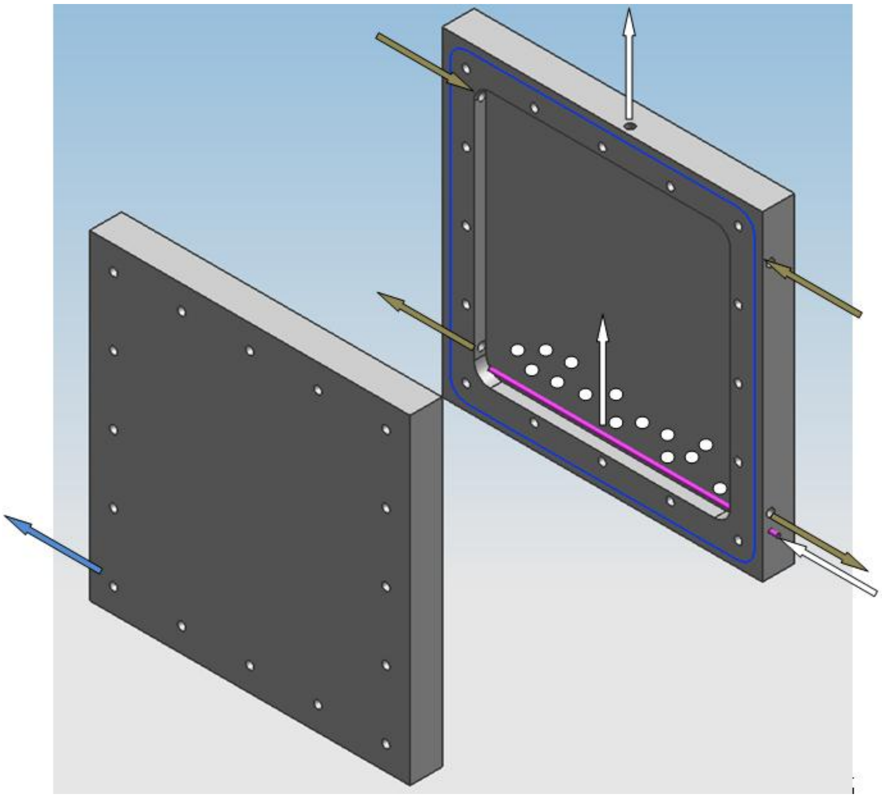


Figure 14. External flat membrane CAD concept rendering, membrane not shown.

Internal Membrane

We came up with what we believed to be our final workable concept for the internal submerged membranes (Fig. 15, pg. 24). It would consist of two tubular membranes connected at the top to rigid vacuum tubes that come from the head plate and connected to a pump. The sparging tube that comes in from the head plate would be retrofitted with a bent tube with two sparging "platforms" welded to the sparging tube. These platforms would have holes around the circumference allowing for sparging to hit all sides of the membranes. The tubular membranes would have an internal support material and would be capped at both the top and bottom, with a hole at the top to connect to the rigid vacuum tubes. The influent would surround the membranes inside the bioreactor and the pressure gradient created by the vacuum pump should cause the influent to pass through the membrane while the sparging gas prevents fouling on the membrane.

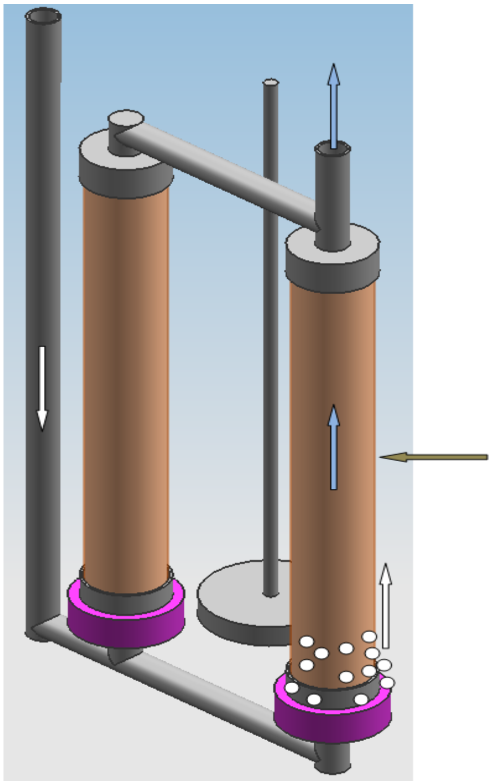


Figure 15. Internal Submerged membrane CAD rendering.

PARAMETER ANALYSIS

In terms of parameters that we have to come up with, the pressures inside of the systems are our main concern along with numerical explanations for dimensioned designs. However, testing our membrane systems will be a much better way of finding the pressures within the system because of the difficulty in calculating them numerically. Detailed calculations explaining the dimensions and the pressure that the system needs to withstand can be found in Appendix I.

External Tubular Membrane

For the tubular system, very little could be quantified numerically because we were using the existing system that had already been analyzed. The system is pre-built and our changes to the system do not alter the configuration of the tubular membrane. We are introducing sparging gas through the bottom of the tube and removing the gas at the top. In order to ensure that this occurs and that there is no excess pressure build-up in the system we plan to place a pressure transducer at the outlet (top) of the membrane housing**.**

External Flat Membrane

In our final design, we decided to use with nozzles as our sparging mechanism because it ensured one-directional flow to prevent backflow of water into the gas line. We predicted that four nozzles would be sufficient to sparge through the entire surface of the membrane. Due to geometry constraints, we used the shortest connectors that we could find and we ended up with the number four that would fit adequately. The nozzles had to fit into these four 0.3125” holes drilled into the casing. We hypothesized that the high cost of additional nozzles would offset the benefit that these additions may bring. Very little analysis on the width of the sparging area of the nozzles was done due to insufficient data, however through testing we were able to verify that sparging did reach the whole membrane area (see video attached on TeamCenter).

Internal Membrane

The most complicated part of the internal system was designing the sparging mechanism which needed to prevent backflow while providing enough pressure to overcome internal surrounding pressure. We did this by finding diffuser from EnviroQuip Corporation called Snap-Cap Plus 5 diffuser. It can withstand 689 kPa which is well over anything that will be seen in our system. We decided against making our own sparging mechanism simply because of the benefits that the Snap-Cap Plus 5 diffuser already provided. It has an internal diaphragm that has a dual function of preventing backflow and fouling. These essential functions may not be present had we made our own sparging mechanism due to the complexity of designing a diaphragm itself. This decision of incorporating a diffuser limited our internal membranes to be 0.0508 m in diameter. Due to this requirement we increased the height of the membrane to preserve the original area requirement of $0.04 m^2$ and ensured that the membranes still fit into the system. In order to keep this total surface area the same between all three membranes, each membrane needed to be 0.1484 m tall which included the 0.0127 m caps on both ends. Due to size constraint of the bioreactor (0.21 m diameter), only two diffusers (0.08 m in diameter each) could be used. These calculations can be seen in Appendix I.

The support material also must be able to withstand the 80 kPa of pressure difference creating a force of 1600 N. Because the support material had to withstand such a large force we chose PVC tubing with 0.25” diameter holes along the surface, wrapped with stainless steel to prevent collapse of the membrane.

PROTOYPE DESCRIPTION

External Tubular Membrane

The external tubular membrane will be a replica of the existing system in place at the University of Michigan, purchased from a company in South Africa. The system will work by creating a pressure difference (trans-membrane pressure) between the inside and outside of the membrane. The water that does not go through the membrane will be re-circulated into the system. The sparging bubbles will aid in reducing any bio-fouling on the membranes. Finally, the gas will outlet through an air-water separator and the process will repeat. The outer tube will have an exit point where the clean water will leave the system. At the top there will be an air release valve at the highest point in order to ensure all the sparging gas is removed. At the bottom there will be a Y-connector where the top will connect to the tubular membrane in order to re-circulate the effluent, the bottom part will be connected to the re-circulation system and finally the other connector will be connected to the nitrogen tank to provide the sparging into the system. The housing for the tubular housing ordered can be seen in Fig. 16 on page 26. There will also be a check valve in the sparging tube to ensure that no water backflows into the nitrogen tank.

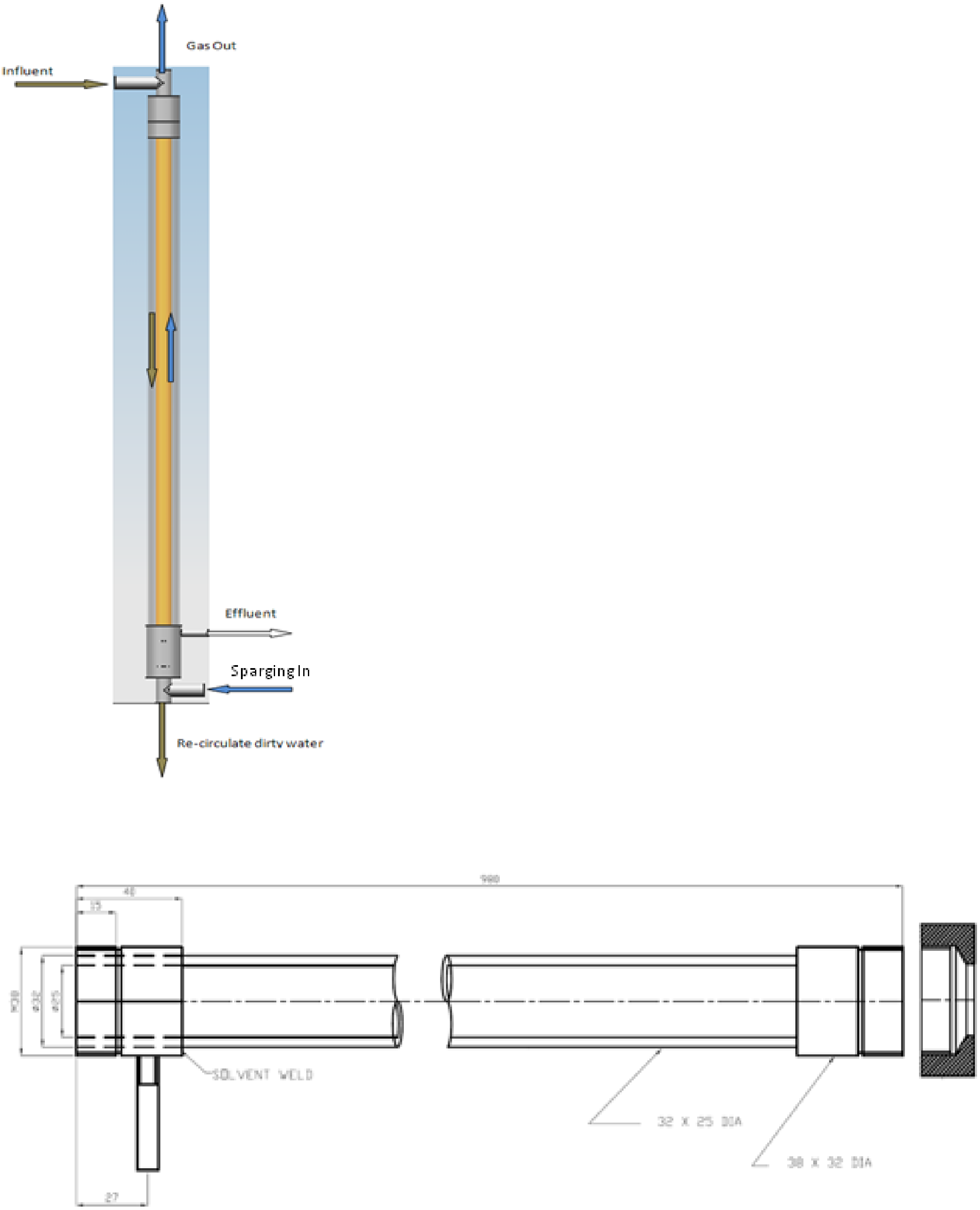


Figure 16. External tubular housing drawings

External Flat Membrane

The external flat membrane was retrofitted from the existing system with a sparging mechanism. Four holes were drilled into the influent side of the membrane and four small nozzles (Fig. 18, pg. 28) were inserted and sealed. The nozzles were connected by a piping system (Fig. 17, pg. 27) that will connect to a nitrogen tank. The top tubes on the membrane will be connected to the re-circulating exiting effluent and the bottom tubes will be connected to the incoming effluent.

The membrane system was sealed by bolting the housing around the membrane and placing gaskets in between the two pieces. The process will work by introducing the influent at the bottom tubes and a pump produces a pressure gradient that forces some of this influent to pass through the membrane and exit out of the clean water tube (on the bottom right) on the opposite side of the membrane. The rest of the influent will re-circulate through the top two tubes. The sparging gas will then collect at the top and it will pass through the re-circulating tubes at the top where an air release valve will remove the gas from the system. This system should improve on the existing membrane setup because in the previous system there was nothing implemented that reduced the bio-fouling and it will help to relieve the dead zones due to the turbulent flow of the water caused by the sparging.

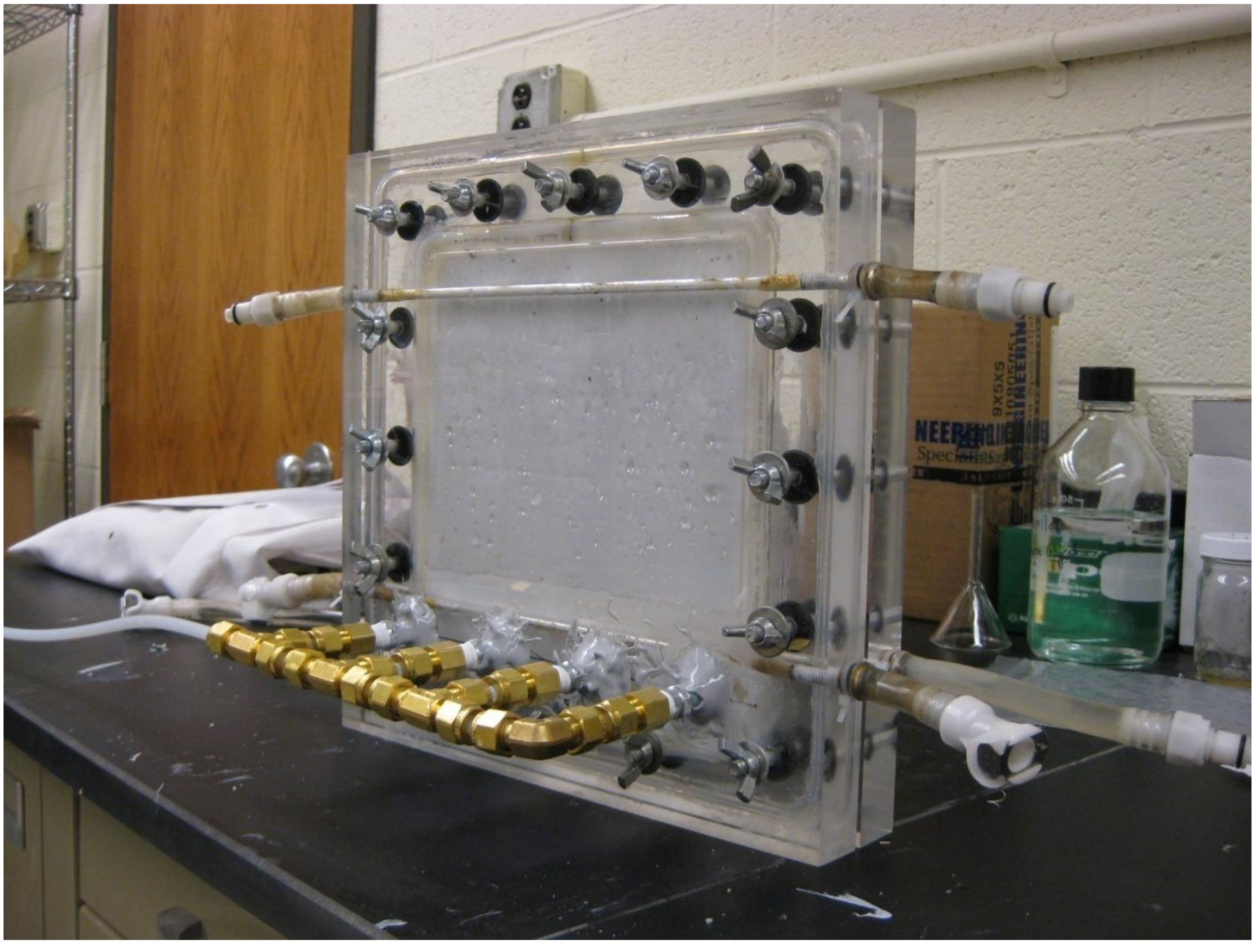


Figure 17. External Flat Membrane Prototype.

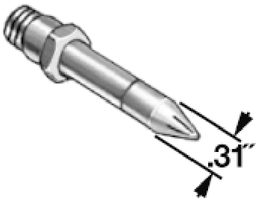


Figure 18. Nozzle to be installed in external flat membrane system.

Internal Membrane

In the internal membrane there are two tubular membranes placed within the bioreactor. They will be held up by rigid tubes connected to the head plate and glued into the cap at the top of the membrane. The membrane is supported from the inside by a stainless steel mesh and capped at the top and bottom. To ensure a water tight system and that only filtered water indeed flows across the membrane, we used aquarium glue to wrap the membrane onto the supporting material, supported by an aluminum strip at the wrap end which were then capped at the top and bottom using flexible vinyl caps. This is seen in our prototypes in Fig. 19, pg. 29, for better understanding. The sparging system runs along the bottom of the tank and through the use of elbows and tees, connects to a diffuser (Fig. 20, pg. 29) which holds up the membranes at the bottom. The way this system will work is that there will be a pressure gradient created by the vacuum pump. It will pull the influent into the tubular membrane in turn filtering the wastewater by passing through the membrane; the clean water is then sucked out. The sparging mechanism will work by introducing nitrogen gas from a tank that will be connected to the sparging rod in the head plate, the sparging gas will run through our piping set up and into the diffuser where the gas will be is released and because it also has an internal diaphragm, no fouling and backflow will occur. The gas will act to knock the bio-fouling off the membranes and keep the flow rate through the membrane at a near constant level. The gas will be removed in the same manner that the methane gas produced by the influent is removed. A dimensioned drawing can be seen in Appendix J.

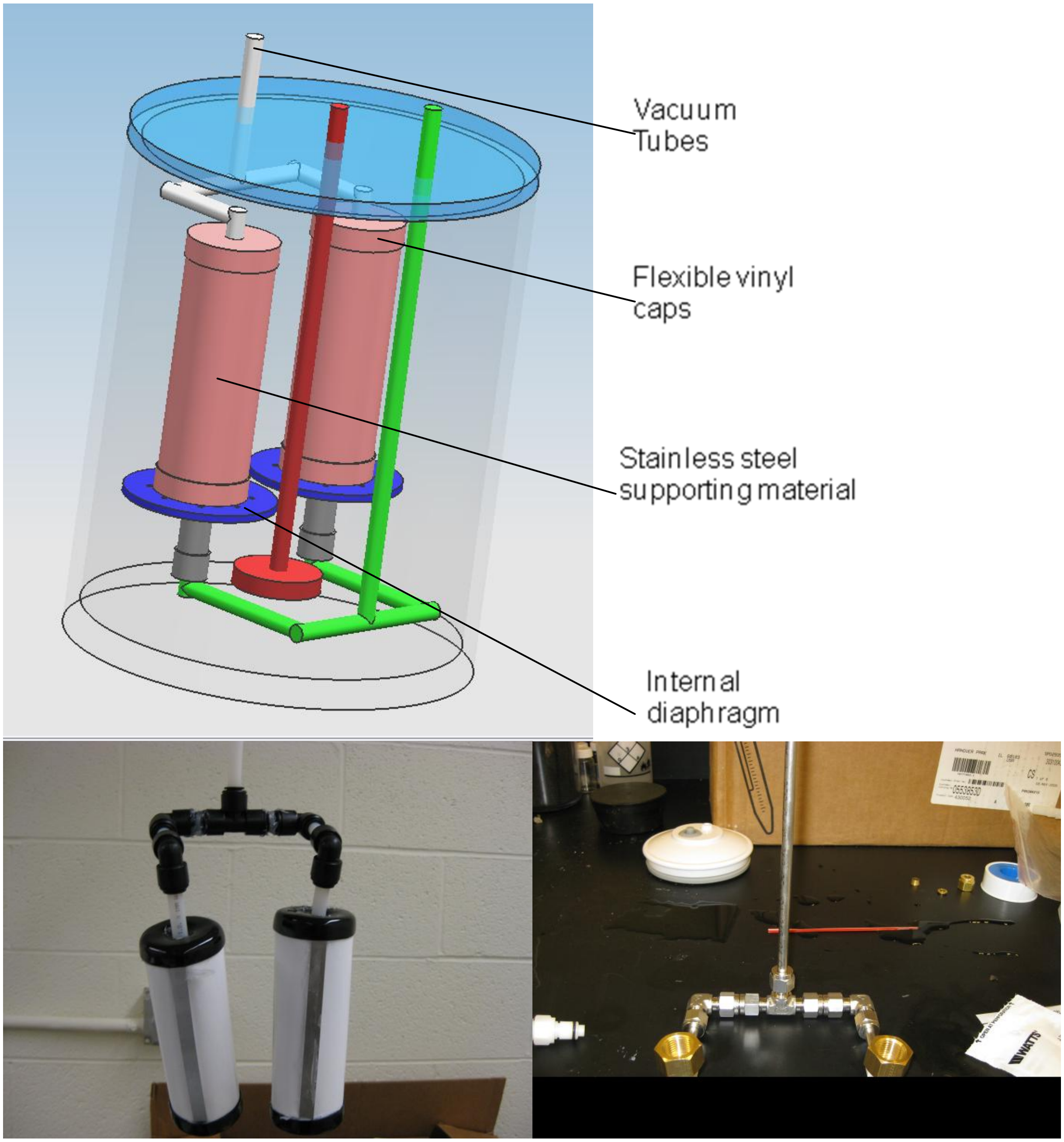


Figure 19. Internal membrane system mock up and prototypes (membrane and vacuum system on right, sparging on left).

Figure 20. Diffuser

FABRICATION PROCESS

External Tubular Membrane Process

The external tubular membrane has been ordered from South Africa but has not yet arrived. Once it arrives, it will be necessary to seal up a few connections that leaked on the first system that was ordered from the same company. Once that is complete, we will need to incorporate the sparging mechanism. This will be done using a T-connector on the bottom - one end for the water recirculation and the other end for the sparging tube. The ¼" sparging tube will be connected to a ¼ " barb to a ¼" NPT to a check valve which will be connected to the nitrogen tank with ¼" tubing. At the top of the system, an air release valve will be installed at the highest point to remove the sparging gas. Then the housing will be installed into the existing system of tubing and pumps.

Parts List: (Numbers are from macmastercarr.com)

1 Y-connecter ¼"	2808K131
¼" Check Valve	8549T15
Barb-NPT ¼"	2808K28
1/8" Air release valve	47225K83

External Flat Membrane Process

To retrofit the housing with sparging, we used the process:

- Drill four holes - 0.3125" in diameter (Dimensioned drawing is in Appendix K)
- Place nozzles 0.015 m deep into holes and seal with epoxy (allowed to cure)
- Wrap pipe tape on threads of nozzles
- Screw on 1/8" NPT to ¼ " tubing converter to each nozzle
- Cut four 0.03 m long pieces of ¼" tubing and tighten swage locks
- Cut three 0.035 m long pieces of ¼" tubing and connect elbow and three tees
- Attach elbow and tee assembly to the nozzle assembly
- Epoxy around nozzles to create a more rigid fitting
- The nitrogen tank is then directly connected to the system using ¼" tubing

Parts List: (Numbers are from macmastercarr.com)

4 nozzles 1/8" NPT	31875K11
1/8" NPT to ¼" tubing converter	5272K281
¼" plastic tubing	
3 ¼" brass tees	5272K251
1 ¼" brass elbow	5272K241

Internal Membrane Process

The internal membrane housing was assembled as follows:

- Drill ¼" holes in into 7/8" diameter PVC (Dimensioned drawings in Appendix L)
- Cut PVC to 0.1484 m in length
- Cut metal mesh to 0.148 m by 0.168 m
- Wrap around PVC and rubber band the ends
- Cut sheet metal to 0.148 m by 0.01 m

- Cut membrane to 0.148 m by 0.178 m
- Wrap membrane and seal with aquarium glue
- Place sheet metal strip on overlapping membrane seal
- Drill 0.005 m hole into top of vinyl cap
- Insert 0.15 m vacuum tube into vinyl cap and seal with aquarium glue
- Put aquarium glue on edges of both vinyl caps (one with hole and tube and one plain)
- Place on top and bottom of housing
- Allow glue to cure and repeat for second housing

The internal sparging system was assembled as follows:

- Cut ¼” tubing to 0.025 m (x2)
- Insert tubing into both sides of tee and tighten swage locks
- Attach elbows parallel to bottom of tee to tubing in the tee and tighten
- Cut tubing to 0.058 m (x2)
- Insert tubing into elbows and tighten swage locks
- Connect ¼ “ tubing to 3/8 “ NPT elbow converter to other end of 0.058 m tubing
- Screw in the sparging plates
- Attach tubing from tank lid to top of tee

The internal vacuum system was assembled as follows:

- Cut 0.010 m diameter plastic tubing to 0.03 m (x2)
- Push to connect to bottom of tee (on both sides)
- Push to connect the elbows to other side of the tubing
- Cut 0.010 m tubing to 0.06 m (x2)
- Connect tubing to the other side of elbows
- Connect the other elbows such that they point down
- Connect 0.15 m of tubing from the membrane housing to the elbow
- Attach tubing from tank lid to the top of the tee

Attach bottom of membrane housing to the sparging plates using aquarium glue.

Parts List: (Numbers are from macmastercarr.com)

PVC 1 7/8” outer diameter 2’ long
Stainless steel mesh 0.3 m by 0.4 m
2” inner diameter vinyl caps 9753K91
¼” Stainless steel tubing 2’ long 89895K221
1 Stainless steel tee for ¼” tubing 5182K434
2 Stainless steel elbows for ¼” tubing 5182K414
2 Push to connect ¼” tubing to 3/8” female NPT converter 5111K387
2 Snap Cap 5 diffusers with 3/8” male NPT
1 Polyurethane tubing 0.010 m diameter 4’ long 9355T42
1 Push to connect tee for 0.01 m diameter tubing 5449K135
4 Push to connect elbows for 0.01 m diameter tubing 5449K165

PROBLEM ANALYSIS

We did analysis and inspection on the three systems, and hypothesized on the possible problems that may arise. In turn, we devised some measures that can minimize the possibility of failure in the systems and make them more robust overall.

External Tubular Membrane

One thing that we are concerned about is the fouling that may occur at the Y-connector that connects the gas line and the influent at the bottom of the membrane. There is a possibility that the fouling may clog the gas line and reduce the gas flow rate over time. If we cannot hear air coming from the air release valve we know this is the case. As a result, the effect of sparging will deteriorate over time and this should be prevented or minimized. One way to reduce this risk would be to incorporate a nozzle in line with the sparging tube near the Y. This would help in minimizing fouling in the area. Pressure build-up is another problem that may arise due to the fouling. If the air-water separator at the top cannot release the gas fast enough compared to the gas into the system, then pressure build-up will occur and may cause rupture. The pressure transducer inside the system must be closely monitored to ensure this does not occur (Figure 21).

Loose fittings are another problem to be concerned. Since the system is subjected to continuous high pressure flow (sparging gas and cross-flow), there is bound to be fatigue in the fittings and leaks may occur. Periodic inspection and maintenance will be essential.

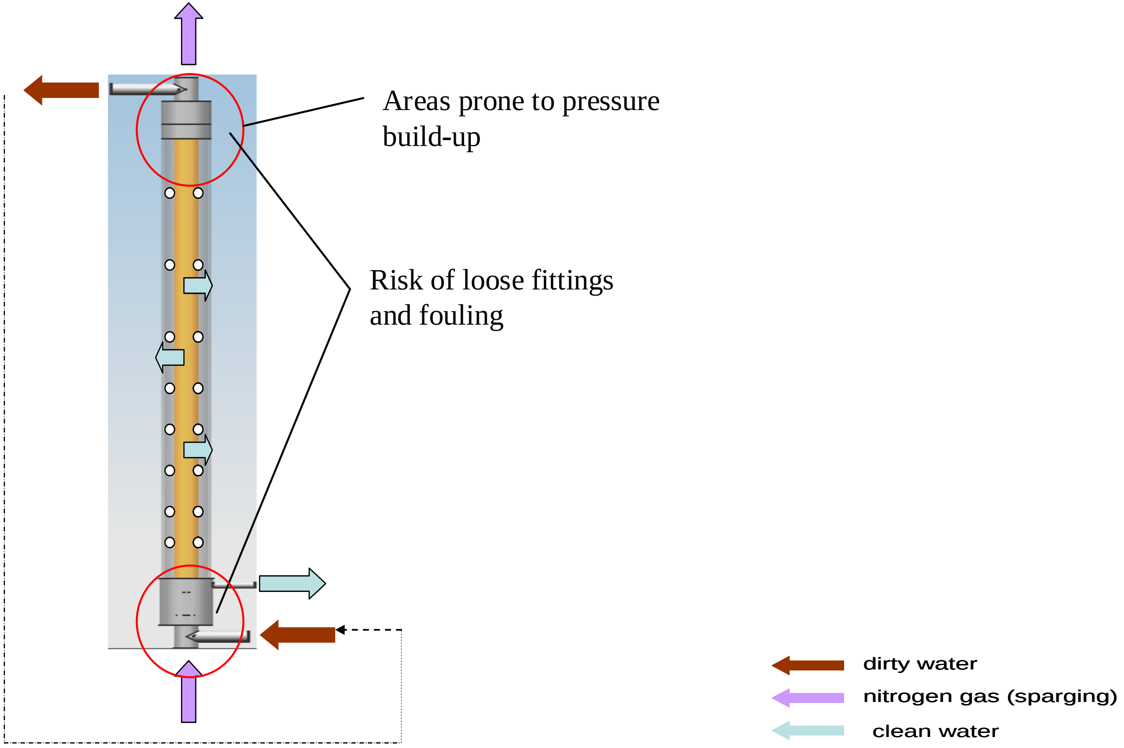


Figure 21. High risk areas for external tubular membrane system.

External Flat Membrane

We are especially concerned about the pressure buildup that may come about in this system. In our design, there are only two outlets where the gas can escape through air-water separators. However, we have four inlets for the nozzles that will allow gas into the system. There is a possibility that the amount of gas out of the system will be less than the gas into the system per unit time. The effect may be catastrophic as the system may leak or even rupture. Careful monitoring of the level of gas in the housing is necessary to ensure that there is a balance between gas in and gas out via the air release valve (Figure 22).

Loose fittings may occur also over time due to the high pressure flow. Again, periodic inspection and maintenance is required. The gas line is the highest priority, especially where the nozzle meets the housing. Another problem region can be found in examining the bolts along the sides of the system where the system secures tightly. Due to the high internal pressure, which creates a situation similar to a pressure vessel on the inside where the membrane is situated, there is a danger that the bolts may loosen and the system may begin to leak.

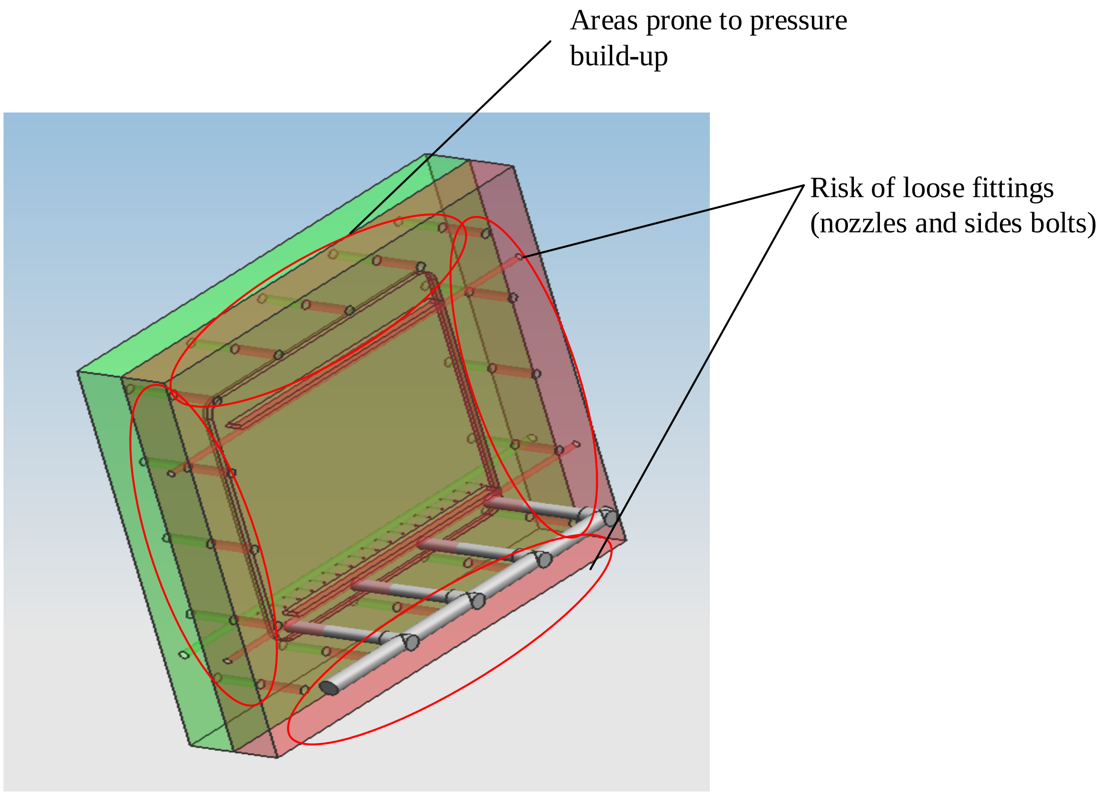


Figure 22. High risk areas for external flat membrane system.

Internal Membrane System

The only potential problem we are concerned with in this system is leaking in the system. Using aquarium adhesive between the supporting material and the membrane has its limitation, and it may not fully seal. In this case, we might require other adhesive method such as melting the membrane to the caps and the support material to ensure water tight seals. The pressure created by the vacuum may also cause the system to become unstable from unwanted vibration or movements. However, this problem can be easily solved by using a dampening cushion at the bottom much like a sponge (Figure 23).

Loose fittings at the gas line are a problem due to the high pressure sparging gas. The risk is further magnified by the suction from vacuum pressure. Therefore, the outlet gas line may be particularly problematic and has to be monitored and inspected periodically.

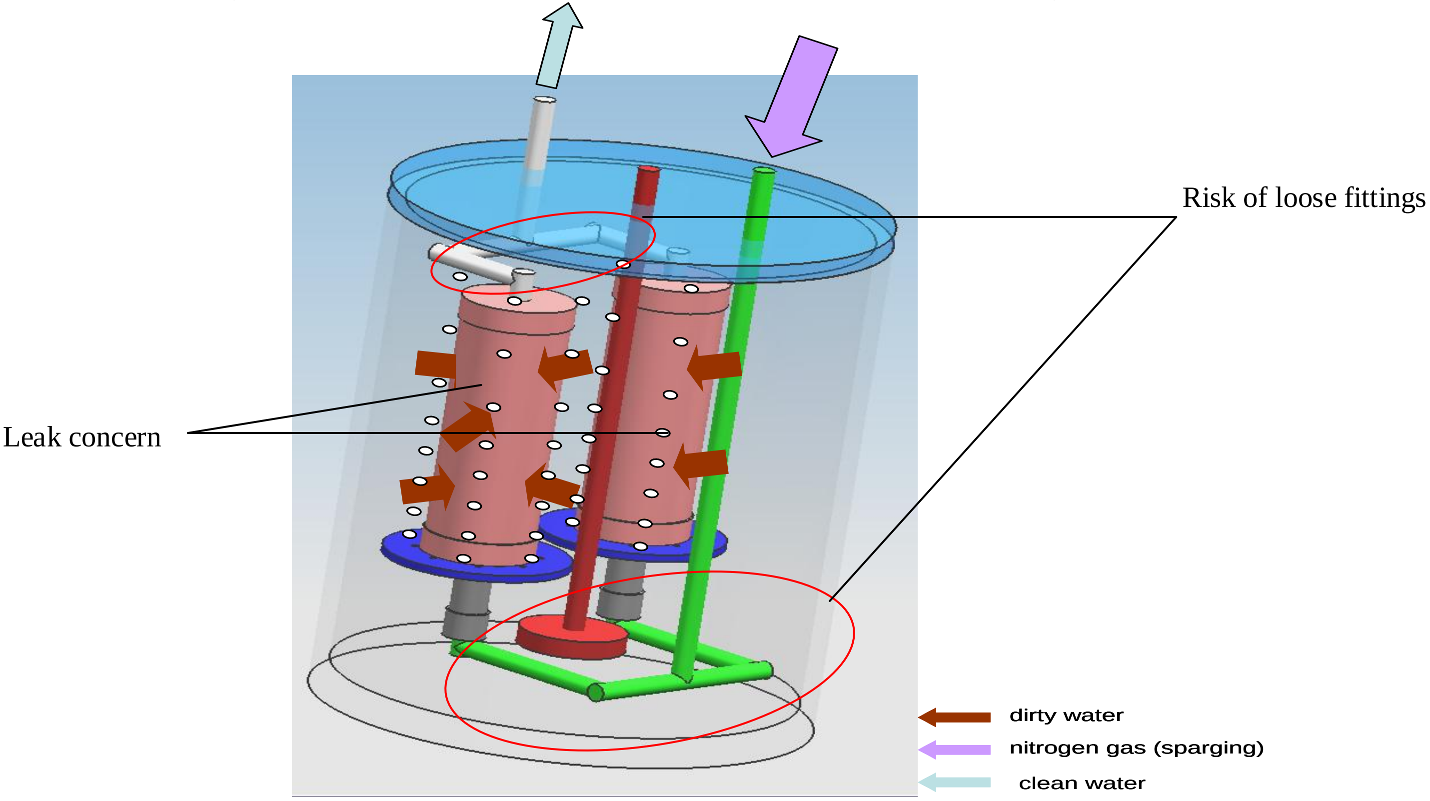


Figure 23. High risk areas for internal membrane system.

MATERIAL SELECTION ASSIGNMENT

To determine the most appropriate material selection, we used CES software to carry out the material analysis. However, since only the internal system was built from scratch, while the external systems were already built previously with additions merely made in the sparging sectors; the analysis was focused on the internal system. We focused on the diffuser and the supporting material which were the fundamental parts of the internal system. We had a choice of stainless steel or Celcon plastic for our diffusers based on the manufacturer's specifications. Our analysis is as follows:

Supporting Material (Hollow tube)

The function of the supporting material was to hold the membrane rigid vertically and to serve as a collecting medium for the clean water. It required multiple holes drilled on its surface to allow for water to flow in from all sides after undergoing filtration. We were concerned with cracks during the drilling process; therefore maximized fracture toughness was one of our objectives that go along with minimized cost and density. The constraints were non-corrosive and non-biodegradable since we did not want any rusting due to the wastewater environment. In a typical anMBR, a slightly acidic solution is maintained for minimized fouling, thus we also wanted durability against weak acid and alkali (biomass breakdown releases alkali) in our constraint. Finally, dealing with flammable methane which is produced during the process, we needed to choose a non-reactive material that will not react with methane to cause a fire (self-sustained burning).

Our final choices were between stainless steel and PVDC. In the end, PVDC was chosen due to its higher density. Both were comparable in the pricing, durability and reactivity properties. However, since we wanted to minimize the stress on the diffuser which will support the load of the supporting material, we chose PVDC which has lower density. In our actual prototype, we chose PVC instead of PVDC because of the availability in the local dealer where PVC is more common and it retains the common important material property of PVDC. Other possible choices were metal alloys and alumina, but they were more expensive materials. A complete analysis is shown in Appendix M.

Diffuser

The function of the diffuser is to act as a sparging mechanism by releasing bubbles along the surface of the membrane to combat fouling. It also has the function of supporting the mainframe of the whole system – it is where the supporting material and membrane sit on. We located a suitable diffuser with the correct size and function. Due to the manufacturer's specifications, we were given a choice of either stainless steel or Celcon plastic. Our objective was to maximize compressive load without buckling, and to minimize density so that the diffusers would not put too much stress on the fittings underneath it where they were connected to. The constraints that we have for the diffuser were that it had to be non-corrosive and non-biodegradable, strong against acid and alkali, and that we had to choose between stainless steel and Celcon plastic based on the manufacturer's specifications.

POM (Celcon plastic) was chosen as our material choice because it exhibits better performance than stainless steel in terms of maximized compressive strength and minimized density based on our material indices which can be seen in the Appendix M. The price and the durability of the POM and stainless steel are comparable. However stainless steel is heavy, thus we eliminated it.

A brief analysis on the material types for the fittings and connections has also been done. For the internal system, we have a metal based fitting on the bottom where the high pressure sparging gas comes in from, while plastic based fittings were used for the upper part that consists of the vacuum section. The reason for this selection was that we wanted to avoid placing a huge stress on the lower part of the assembly, while at the same time; we wanted an overall stable system where it would settle on the tank floor without floating.

For the external system, we used metal based connections to fit the nozzle for an overall sturdier and more stable system. This is justified by the higher density and strength values for metal than plastic.

DESIGN FOR ASSEMBLY

We conducted Design for Assembly to minimize and optimize our parts so that assembly time and cost can be reduced, making the systems ideal. The DFA charts associated with assembly are not applicable since we were dealing with lab scale and not a full size prototype

Internal Sparging System

Dealing with the constraints of time and space we were limited on what we could build and how big the system could be. The fact that we needed to sparge from the bottom but come in from the top forced us to use a tubing systems with tees and elbows. The internal sparging system consisted of

- 2 diffusers
- 2 elbow converters
- 2 elbows
- 1 tee
- 5 tubes of various length
- 1 tubing size converter

Assembling this system involved cutting the tubing to size with a tube cutter and connecting the tees and elbows which meant tightening 7 nuts on the swage lock systems with a wrench. It was also necessary to make sure that there were only 90 degree angles between any and all pieces. On top of that we needed to screw in the sparging plates to each of the converters. With all the measurements and tools right in front of you one could assemble this system in 30 minutes.
If this was to go into production on a large scale it would be ideal to design the tank with two inlets at the bottom with the correct sized female NPT fit and assembly would take a mere 30 seconds to just screw in the sparging plates, instead of 30 minutes. This would also reduce the number of pieces from 13 to 2; 4 if you count the inlets embedded in the tank. This could now be an automated process and no human hours would be needed.

Internal Membranes Housing

The membrane housings that we made for our design were problematic since we needed a small specific size which we could not find for purchase. Most tubular membranes go from the inside-out, but ours needed to go from outside-in. This forced us to wrap a flat sheet around the housing and seal it with aquarium glue. The system we designed consisted of:

- 2 permeated PVC pipes
- 2 sheets of stainless steel mesh
- 2 sheets of membrane
- 2 vinyl caps on bottom
- 2 vinyl caps on top with holes for vacuum tubes
- 2 strips of sheet metal
- 4 rubber bands

Holes were drilled into the PVC pipe using a mill and took about two hours to complete. The steel mesh was cut with scissors and the membranes with an Exacto knife. The mesh was

wrapped around the PVC and rubber banded at both ends. The membrane was then wrapped around the mesh and sealed with aquarium glue and then the sheet metal was placed along the seal so as to keep the membrane tight on the support material. Then the caps were placed on the top and bottom and sealed. The whole process took approximately four hours to complete.
This system could be reduced in parts and assembly time by designing and manufacturing for large production numbers. We could use injection molding of a strong plastic that is the correct size and has holes in the mold. Then an automated system could wrap the membrane then melt the ends together for a seal. The caps would ideally be more rigid and with a pre-inserted tube for the connecting the vacuum system. This could be a completely automated system and take a maximum of an hour, most of the time owing to the hardening process of the injection mold.

Internal Vacuum System

Again dealing with the tank lid and limited input holes it was necessary to have a series of tees and elbows to connect the vacuum tubing to the lid. This system consisted of:

- 4 elbows
- 1 tee
- 7 pieces of tubing of varying lengths

Assembly took about 15 minutes to cut the tubes to size with a utility knife and insert them in the elbows and tee and align them so that all angles were 90 degrees.
Again with a large production number it would be beneficial to design the tank lid with two holes directly above the two sparging inlets. Incorporating the vacuum tube in the membrane assembly, this system would then have no parts and take no time for assembly.

External Flat Sparging System

The decision to use the existing housing limited our design of the sparging system. The fact that we could not purchase piping that teed and elbowed in the right places forced us to use a system of swage lock tees and elbows. The system consisted of:

- 4 nozzles
- 4 tube to NPT converters
- 7 pieces of tubing of varying lengths
- 3 tees
- 1 elbow

There is not much here that we could realistically improve. It is likely we could design and manufacture a tube that has the necessary tees and elbows but unlikely that we could directly incorporate the nozzles this would result in a 9 part system instead of the 19 part system which is still a large improvement. This would rid us of having to tighten each bolt on the swage lock with a wrench and reduce the time of assembly as well.

External Flat Housing

Without completely redesigning the housing we could get rid of all the bolts and wing nuts by designing a clamping system that could be one part made up of a series of pieces. This could prove to be worth it in the long run because assembly of clamping system could be automated then put on by a person. Then maintenance would be much simpler since it would be one clamp then you can pop on and off instead of having to screw and unscrew 20 bolts.

External Tubular Sparging System

This system is quite simple and a redesign would likely add to more parts. The system consists of:

- Y- connector
- Tubing
- Check valve
- Barbed to NPT converter

By using a Y-connector we can introduce sparging through a tube connected to a nitrogen tank with a check valve to keep water from going in the sparging tube. The barbed to NPT converter is used to connect the check valve to the tubing. The process takes a maximum of five minutes.

External Tubular Housing

This system comes assembled and works great so no improvements are apparent as of now because we have not yet received the housing.

DESIGN FOR ENVIRONMENTAL SUSTAINABILITY

We employed the use of SimaPro Evaluation as the analysis tool for the design for environmental sustainability. Our system is designed in a way that it will not have an adverse impact on the society. A more detailed analysis can be seen in the Appendix N.

Internal membrane supporting material: PVDC vs. Aluminum

Aluminum appears to be the more appropriate material choice based on the environmental impact in being recyclable and using less resources. However, based on the relative impacts in disaggregated damage categories, the PVDC appears to be the more appropriate material. This would mean that aluminum will do more harm to the environment when compared with PVDC. However, PVDC affects human health more negatively than aluminum. When considering the life cycle of the material which determines the overall effect on the environment, it appears the aluminum would be the proper choice due to the lower point value, however its corrosive nature and tendency to rust may prove to be problematic in implementation into the system.

Supporting material in external tubular system: X5CrNiMo18 (316) vs. Titanium

Based on this analysis, it appears that titanium would have been a better choice than the stainless steel we chose (X5CrNiMo18). Based on all of the results, titanium negatively affects the environment in less important categories than the stainless steel. Both are comparable in the relative impacts in disaggregated damage categories and substance usage. However, the stainless steel fares badly in terms of resource usage in comparison. The X5CrNiMo18 has a much higher point value according to the ecoindicator which means it will have a bigger impact when the life cycle as a whole is considered. However, when considering the scarcity of titanium and the cost of the metal it may prove inhibitive in implementing this metal into the system.

DESIGN FOR SAFETY

We carried out analysis of our system to determine the safety of our systems and ensured that the risk they carry are acceptable and reasonable. We employed the DesignSafe software for the analysis. The risk assessment produced several major risks and unexpected risks that we did not foresee prior. A more detailed analysis can be found in Appendix O.

Major risks

Since the collection of clean effluent in significant amount takes hours, we are concerned that the long duration will result in loose inspection and monitoring because of the lack of manpower to keep an eye of the set-up during the whole process. This may be deemed as a potential danger when something goes wrong and no one is present to notice the problem.

A significant amount of nitrogen gas and methane gas from sparging and end product respectively may be released to the air in the lab (or wherever the set-up is). This may lead to high concentrations of these two types or gas in the room which is not ideal, especially because methane is flammable. Proper ventilation is therefore required in the lab. A gas collection system can even be designed to collect the methane which is a source of energy.

The next major risk is the pressure build-up in our systems. Since we are incorporating sparging in all three systems, the gas used may cause pressure build-up if there is no effective gas removal design. However, we are only concerned with pressure build-up in the external systems, since the gas in the internal system is outside the “control volume.” The gas in the internal system will just float to the surface of the wastewater as bubbles where it will burst and escape.
The high pressure sparging gas may induce leaks in our connections and fittings. Since sparging gas is likely to be implemented most of the time, this is a major risk that we will likely face. Therefore, periodic inspection and maintenance needs to be done on the fittings and connections to ensure a leak-safe system.

Lastly, fatigue is another concern we have. Due to the high pressure cross-flow design and the continuous sparging, fatigue in the system will develop, especially in the fittings and connections along the gas lines. This will again cause leaks in the systems. Therefore, inspection and maintenance need to be done periodically.

Unexpected risks

There are several risks that we did not expect before. We did not foresee the problems that this slow continuous process can bring. Ergonomic factor such as limited monitoring and inspection time will be a weakness that is very difficult to solve in this continuous experimental process. Unforeseen problems like crashing of the programs running the system, leaks or even pressure build-up may go unnoticed and do harm. Another challenge that this continuous process brings is the continuous emitting of methane and nitrogen gas which have to be dealt with. Finally, fatigue is another unexpected risk that we discovered due to the addition of high pressure sparging and cross-flow.

FMEA process adds detection to the traditional considerations of likelihood and significance when assessing operating reliability. Detection is the likelihood that a risk event will not be detected in thee to prevent real damage.

Acceptable risk is the minimum tolerable level of threat in an experiment while zero risk is impossible to attain. In terms of function and safety, there needs to be a balance between the two. In other words, the function needs to be fulfilled but there needs to be a certain level of safety associated with it too. Otherwise, it will be futile if the function is accomplished with much “casualties” involved. With regards to our project, we are dealing with methane gas which can be utilized for energy usage and that is the function of the methane gas here. However, the risk associated with it is that it is very reactive and flammable. Therefore, proper ventilation or an effective mean to store the gas will reduce the risk close to zero risk. This goes the same to nitrogen gas which serves as our sparging gas (function). Proper ventilation (safety) is needed to prevent unusually high concentration (risk) in the room.

MANUFACTURING PROCESS SELECTION

The membrane housings that we have designed and built are for testing purposes and ideally our best design would be scaled up in size for use in real wastewater treatment plants. This is why when we determined a real-world production volume for our project, we considered the number of anMBR plants around the world and come up with an approximate production volume of 100 units. This number should be sufficient in our scope and taking into account current technological limitations. As this technology is new and still progressing, there might be a better design coming up in the future years, so we determined 100 as a good estimate for a current production volume.

As we are scaling our designs up to real world applications, we decided to use the flux of effluent at our rate of ratio. A typical waste water treatment center cleans 9500 m^3/day and our design will ideally produce 40L/day, so our scaling ratio is 1 to 273,500. This would mean that we will have to use 474,000 support materials for internal membrane. Since the support material is made of PVC and the production volume is very high, the best method to manufacture these components would be to use injection molding. Using injection molding, PVC support materials could be built with built-in holes and would eliminate the need for drilling. The smallest sized feature would be the holes on the support material and this could easily be achieved using injection rotational molding method shown in Fig. 24, pg. 41. There would be no heat treatment and coating needed. Using such a method for production will greatly reduce the total manufacturing cost as we are going to need a very large amount of this material. Our second component, the sparging plate was outsourced for our prototypes. Although it might be a better idea to manufacture these parts internally, coming up with a different and more efficient method of sparging may greatly reduce the cost that would be generated by this component.

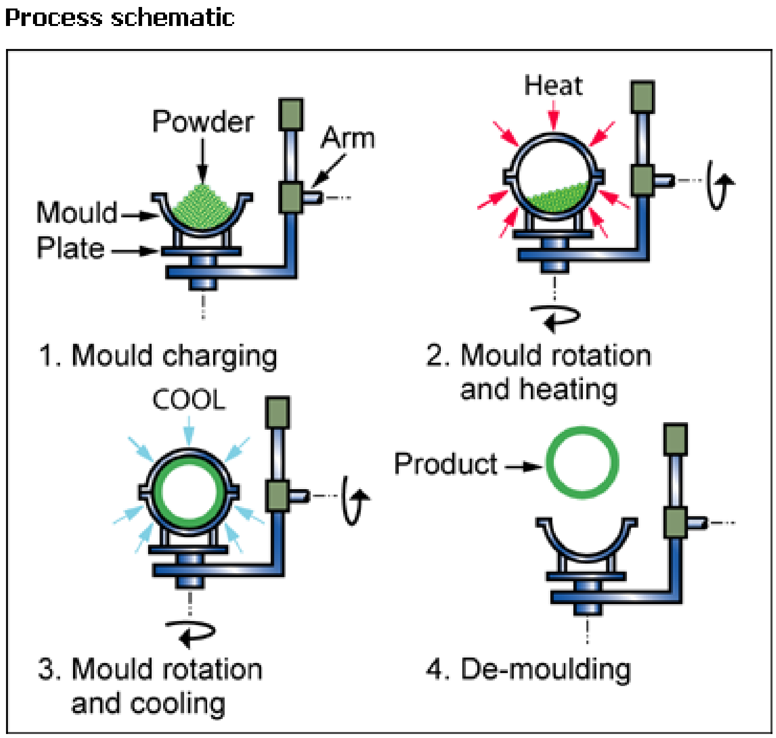


Figure 24. Process schematic for injection molding.

RESULTS

No comparisons between the systems could be made since not all parts arrived on time.

External Tubular

There is no result from the external tubular system since it has not arrived due to logistical glitch.

External Flat System

The only testing done here is has been on the sparging system since the functionality of the system was proven by the past ME 450 group. We first tested to see if the nitrogen came through all 4 nozzles which it did. Then we put together the housing with water inside to determine if the system leaked water which it did not. We then applied sparging and determined that no gas or water leaked from the system. During this same test, we also determined the dead zones would all be relieved from the sparging judging from the pattern of the flow. The video "Flat Sparging.avi" on Teamcenter documents this sparging. However, the nitrogen tank was not placed near the existing system due to space constraint and a tank clamping issue, thus, we could not implement it to determine if the sparging did in fact reduce fouling and increase flux. Table 4 summarizes the results.

No Leaks in Sparging	Yes
No Leaks in Housing	Yes
Sparging Relieves Dead Zones	Yes
Sparging Increases Flux	TBD

Table 4: Summary of important results for external flat membrane system.

Internal Membrane System

The sparging plates have not yet arrived, but the rest of the system was checked for leaks and none were found. When the plates arrive they can be screwed in and tested for leaks. The sparging system was tested by plugging all outlets and opening the nitrogen tank and looking for air escaping at the connections and no leaks were seen. The vacuum system was tested for leaks by plugging all holes and running a vacuum pump. Since no water was pulled out we determined the system did not leak. During a test to see if water could be pulled from the membrane housings, one of the seals broke and forced us to rethink about the capping system which will be described later in the following section. Because the sparging plates never arrived and the sealing is being reanalyzed, we could not run experiments to determine if the sparging indeed increased the flux. Table 5 summarizes these results.

No Leaks in Sparging	Yes, no leaks
No Leaks in Vacuum	Yes, no leaks
Membrane Housing Seals	No
Sparging Increases Flux	TBD

Table 5: Summary of important results for internal membrane system

FUTURE WORK AND VALIDATION

Our prototypes are incomplete at this point of time and therefore, our validation becomes even more important for the sake of future work when all the parts have arrived. Although it is purely theoretical and lacks the empirical basis, we feel that this can give a sense of what to expect in the future when the system is assembled.

External Tubular Membrane System

The effect of sparging in the external tubular system is determined in two ways. One will be to determine if it successfully reduces fouling and increases our effluent, and the other will be whether the sparging gas is be removed from the system effectively to prevent pressure buildup in the system causing failure.

We have several ways of validating the success of fouling reduction. Fouling reduction can be assumed to be successful when effluent flow rate is roughly consistent from the beginning to the end of the experiment. This is because fouling causes the flow rate to decrease. The way to do this will be to note the change in the effluent flow rate in intervals. This could be done at hourly, daily or even weekly intervals depending on monitoring availability. A table similar to Table 6 below may be used.

Time interval	9am-12pm	12pm-3pm	3pm-6pm
Effluent collected			
% difference			

Table 6. In-lab experiment result data.

To truly validate whether sparging is successful in fouling reduction, we do not have the quantitative mean other than basing it on the results that we obtain after tests have been conducted and comparing them with the existing system without sparging.

The next concern is the removal of sparging gas to prevent pressure buildup. Since the removal of sparging gas is through the top of the system, we have to make sure that the air bubbles are able to travel upwards until they reach the air-water separator and outlet from the system. This will also ensure that sparging runs along the entire membrane height for maximum performance, which is one of our engineering specifications. This means the pressure of the sparging has to be sufficiently high. To test whether pressure buildup exists in the system, we will compare pressure readings by installing pressure transducers at the inlet and outlet of the gas line. If there is no significant difference between the two readings, then it will be safe to assume that pressure buildup is minimal as this would mean that the gas flow rate into and out of the system are approximately equal. In determining how high the gas pressure must be, we can test this empirically. By altering the regulator at the gas tank, we can adjust the pressure of the gas until we see common readings at the inlet and outlet pressure transducers. We assume that some pressure losses will occur along the flow, and therefore, if the readings are close enough (±10% difference) we can assume that we have found the sparging pressure we want.

By incorporating sparging into our system based off the existing system, it is imperative that the sparging should not interfere by contributing any pressure. Keeping with the analysis above; by ensuring that the inlet and outlet gas pressure are effectively the same would ensure that sparging does not distort the trans-membrane pressure gradient.

We do not foresee a difference in flow rate for our system as long as the pump speed is kept the same with the existing system. However, since in our system we will be employing counter-current flow, the flow rate inside the membrane maybe slightly lower due to the opposing flow against sparging gas. Meanwhile, if a co-current flow is implemented, the flow rate will be higher instead. It depends on how high the pressure of the sparging is, and at this point of time, we have no test data available. If the pressure were low enough, then flow rate should not be affected significantly. We hypothesized that since density of water is much higher than nitrogen (sparging air), this should only minimally affect flow rate. From our design set-up, the flow of the water is largely smooth and undisturbed with the wastewater re-circulated back to the main line continuously, and therefore, we assume that the flow rate will remain constant. To achieve our flow rate target, we may be able to alter the pump speed accordingly.

Energy usage will be the same as the existing system because sparging comes merely from nitrogen tank. We also have to ensure that water and air do not mix in the line. An air-water separator is attached at the junctions where sparging and water encounter each other and we would not expect any mix-up. Furthermore, nozzle and check-valve will also be installed at the T-connector gas line inlet to prevent backflow of water. A schematic of the system can be seen in Fig. 25 on page 44.

For a more quantitative result, any water-air mixing will result in drastic change in the pressure readings of the pressure transducers. If there is no mixing, the pressure transducers should register consistent values.

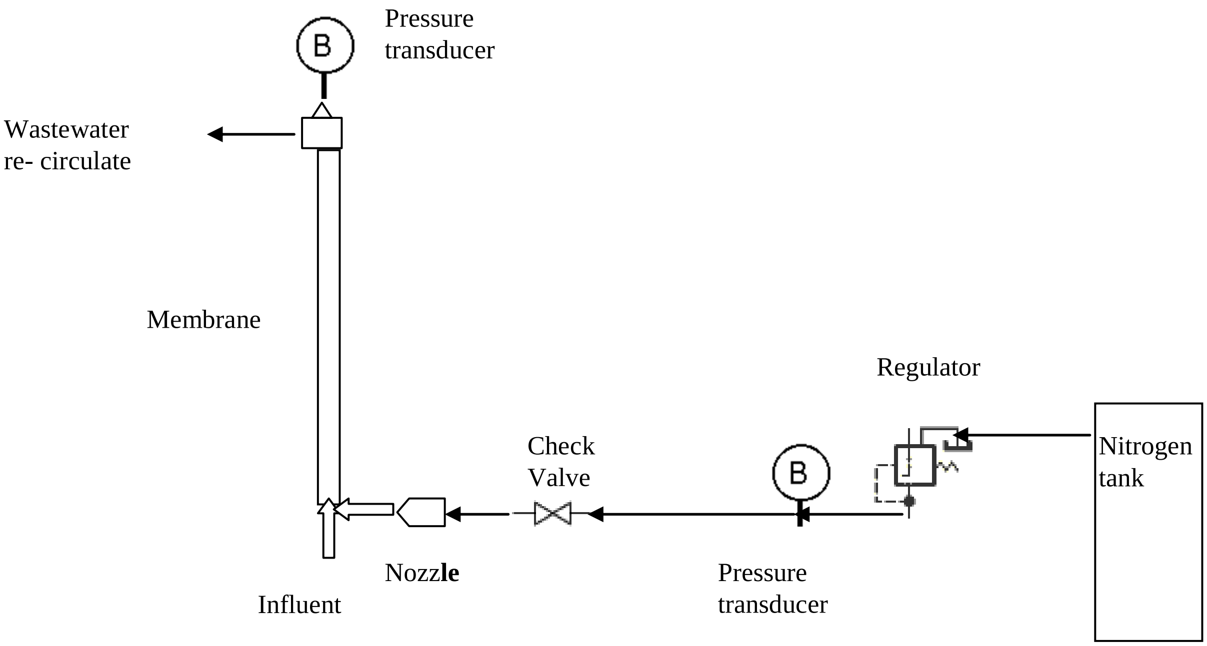


Figure 25. Schematic of external tubular system process.

External Flat Membrane System

We have determined that there are no leaks in the housing or the sparging systems. Judging from the pattern of flow under the influence of sparging, we have also rid it of any dead zones. Now all that is left to validate is whether or not the sparging truly reduces the fouling. This will be done similarly to the external tubular with a control test that has no sparging. This will help in determining if sparging works and is always necessary.

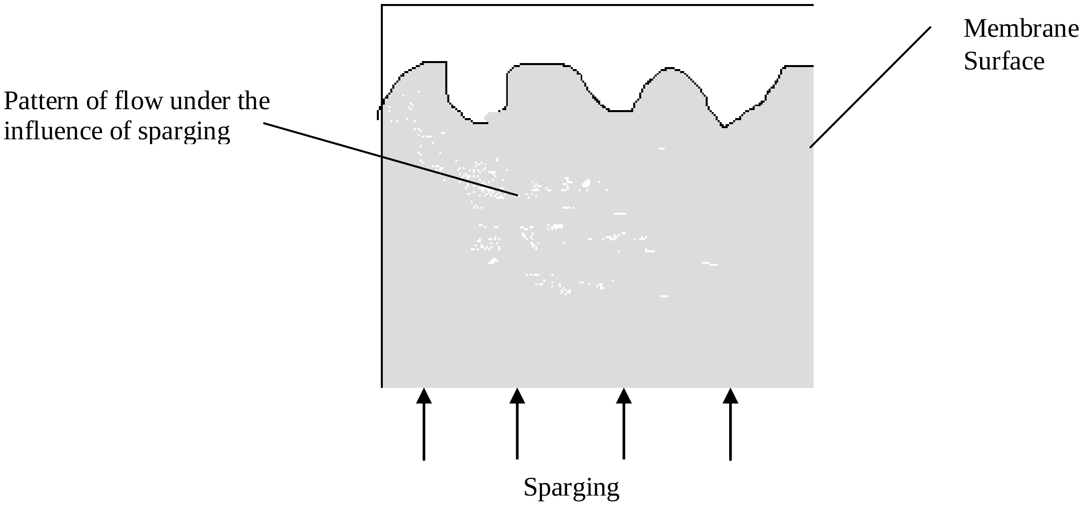


Figure 26: Sparging induces sufficient turbulence to affect almost the whole surface of membrane.

Internal Membrane System

There are no leaks in both the sparging or vacuum tubing systems but a seal was broken at the membrane housing. The seal where the vacuum tube is inserted in the caps broke because the vinyl caps are too flexible and deform in the vacuum which causes the seal compromise. To fix this we plan to order new, hard PVC end caps and drill a hole to insert the vacuum tube and then test the seal again to see if it holds. This will be done by attaching the membrane and vacuum system to the vacuum pump and dying the water with a special dye that will not enter the inside of the membrane if there are no leaks. If the water comes out clean then we know there are no leaks and the seals are all holding. Once the sparging plates come in we can attach them to the rest of the sparging system and then begin testing the sparging effects. This will be done by using the same experiments as the external systems.

CONCLUSIONS

From this project, it has become clear that the sparging mechanism is the main driver for all of our designs. We have designs with sparging incorporated in all three systems and attempted to address which system will end up with the best performance against fouling and energy usage. However, due to logistical (not all parts arriving) and technical and unforeseen glitches, we have not been able to come up with conclusive results. The external tubular system was entirely untested due to communication lag times from us to South America. The external flat membrane system has exhibited promising performance against fouling and dead zones based on the pattern of flow under the influence of sparging. However, it has yet to be installed to the existing bioreactor to be tested for fouling due to some technical issue (nitrogen tank placement in room). The internal tubular membrane systems for sparging and vacuuming have been assembled and showed no leaks. However, the capping system on the housings themselves proved to be inadequate and is being readdressed. Also the diffusers for the sparging mechanism have yet to arrive. Nevertheless, we hope that this project will be a stepping stone for answering the important question regarding which system is the best in an anaerobic membrane bioreactor. In the future when all three systems are fully assembled, they can be run and compared against one another. At the end of the day, the best combination of sparging, membrane, flow and bioreactor configurations can be determined through the best performance against fouling and energy consumption.

ACKNOWLEDGMENTS

We would like to thank Prof. Skerlos for his support and direction in getting us through the semester and encouraging us to do our best. We would also like to thank Tanna Borrell for helping us order our parts and help in deciding the best way to test our prototypes. We would also like to thank Lutgarde Raskin for financing our project and also Bob Coury and the machine shop staff for their help in building our prototypes.

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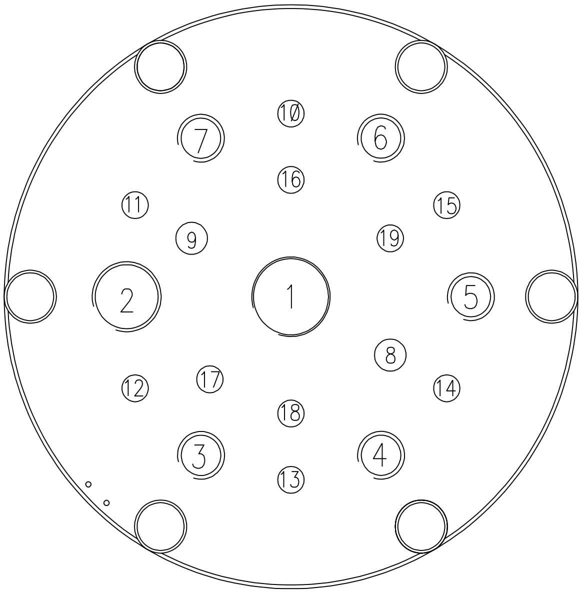
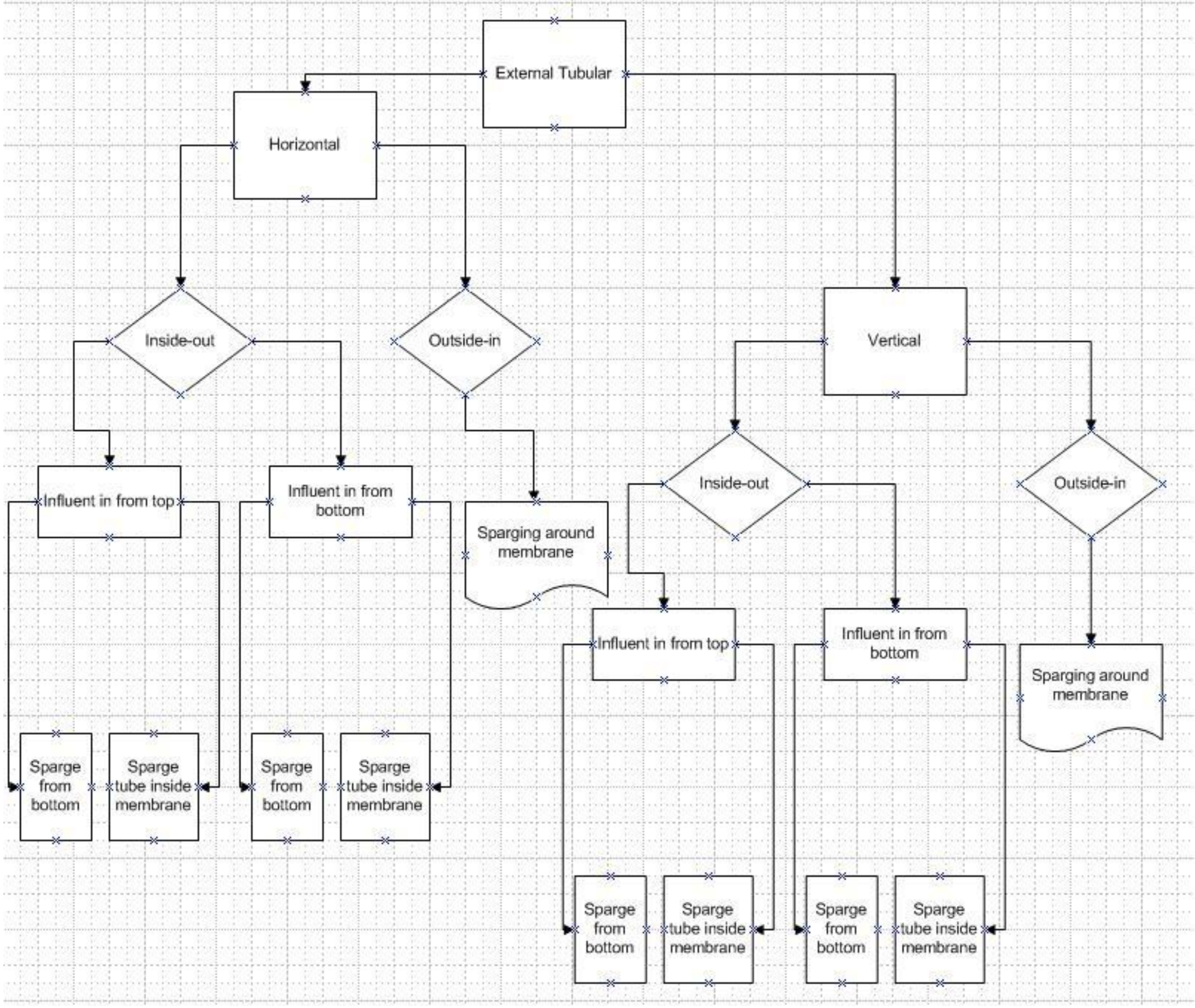
APPENDICIES

APPENDIX A: Diagram of head plate for bioreactor tank.

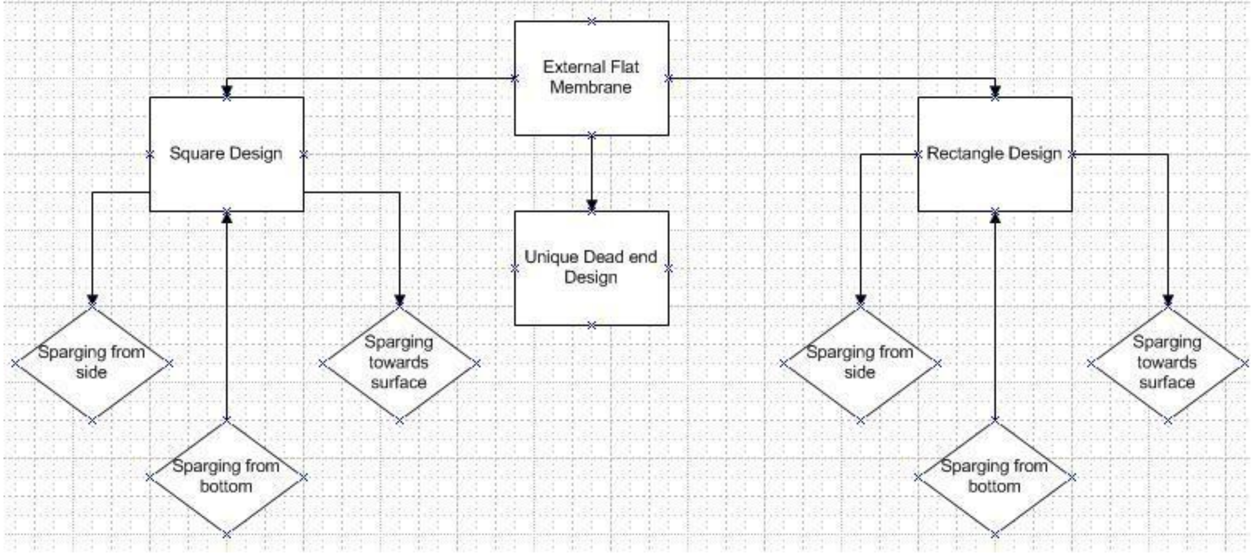


	Article number	Description		Article number	Description
	M30 x 1 port			**10 mm ports**	
1.	Z81315MG07	" STIRRER ASS. MAGNET COUPLED"	10.	Z81308LU02	"AIR OUTLET PIPE BIOREACTOR"
	G3/4" port		11.	Z81323TP07	"THERMOMETERPOCKET"
2.	Z81300N005	"NIPPLE FOR PH/MV"	12.	Z81319MB07	"SAMPLE PIPE ASSEMBLY"
	M18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

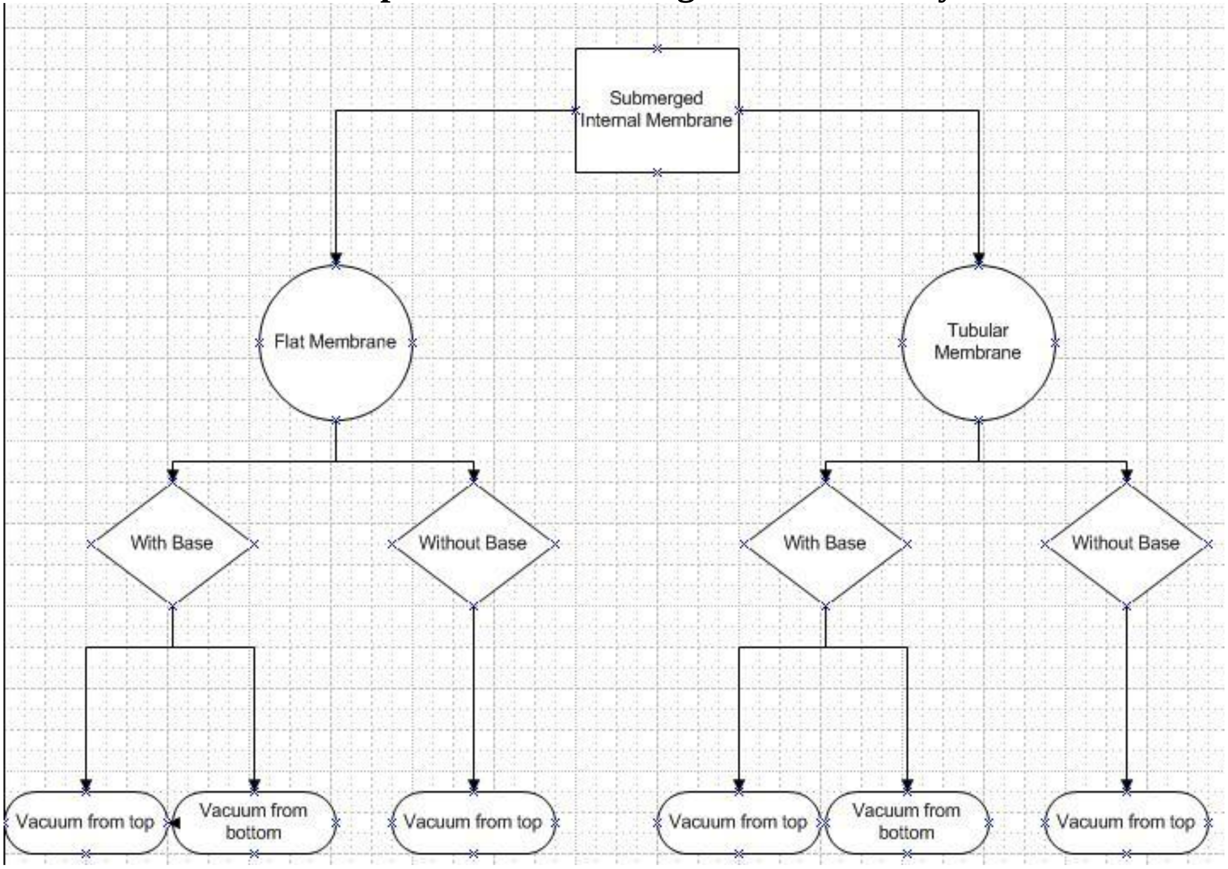
APPENDIX B1: Decomposition of external tubular membrane system.



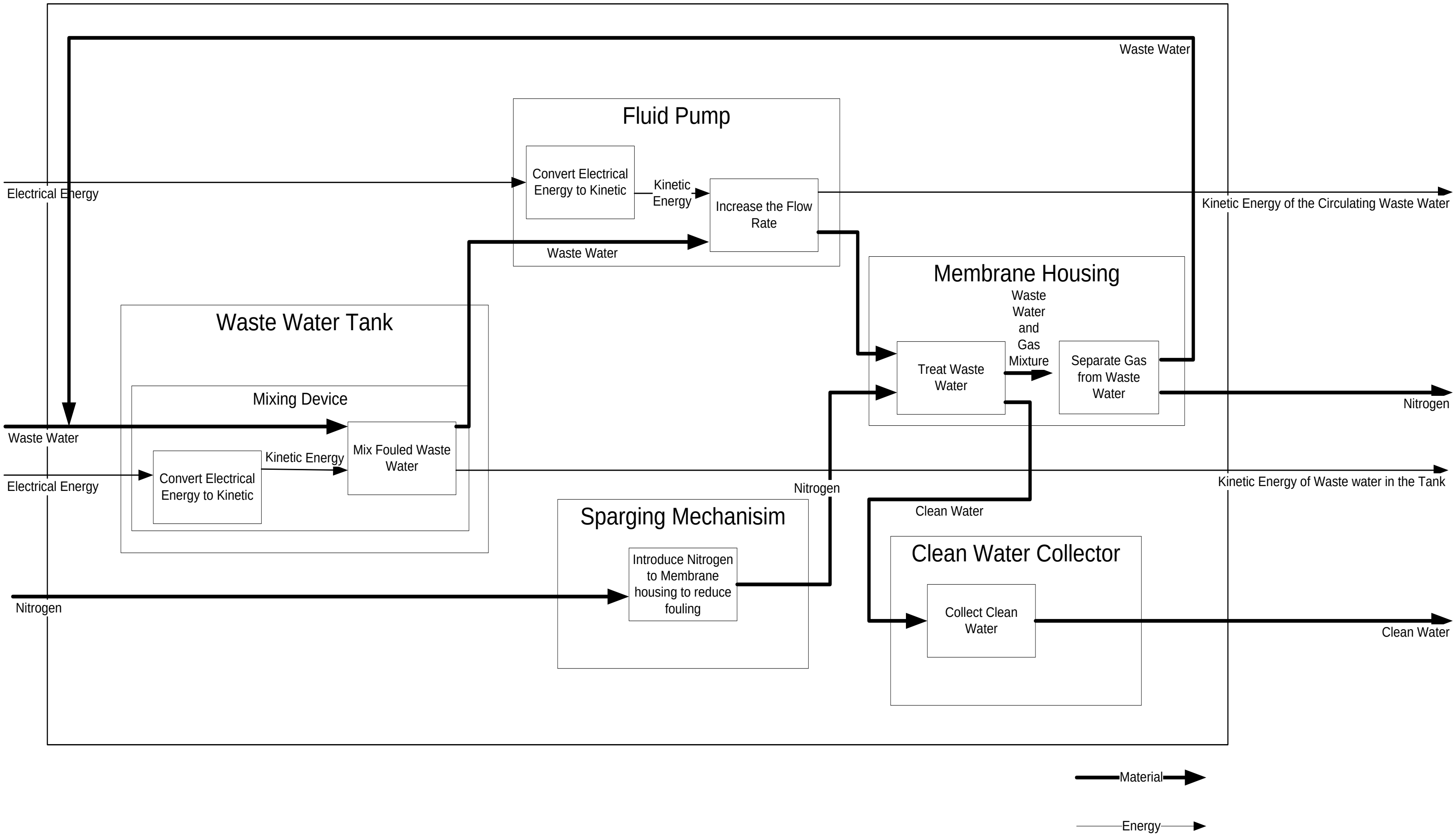
APPENDIX B2: Decomposition of external flat membrane system.



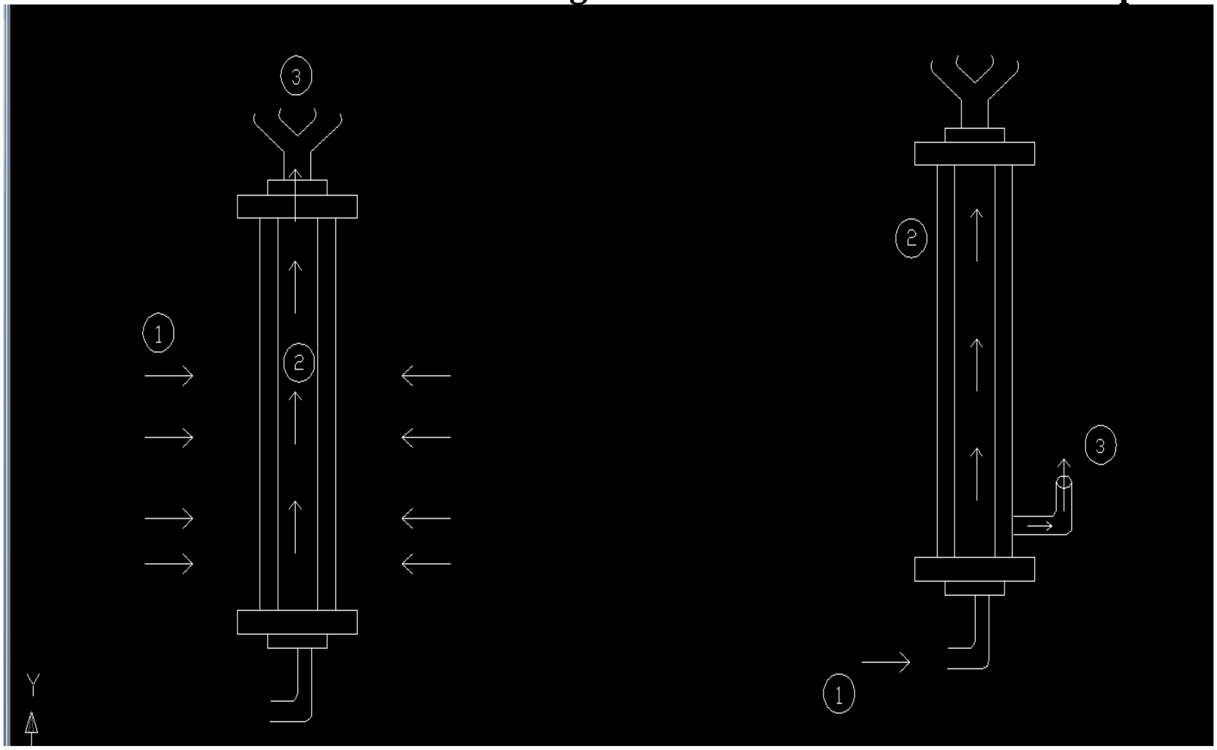
APPENDIX B3: Decomposition of submerged membrane system.



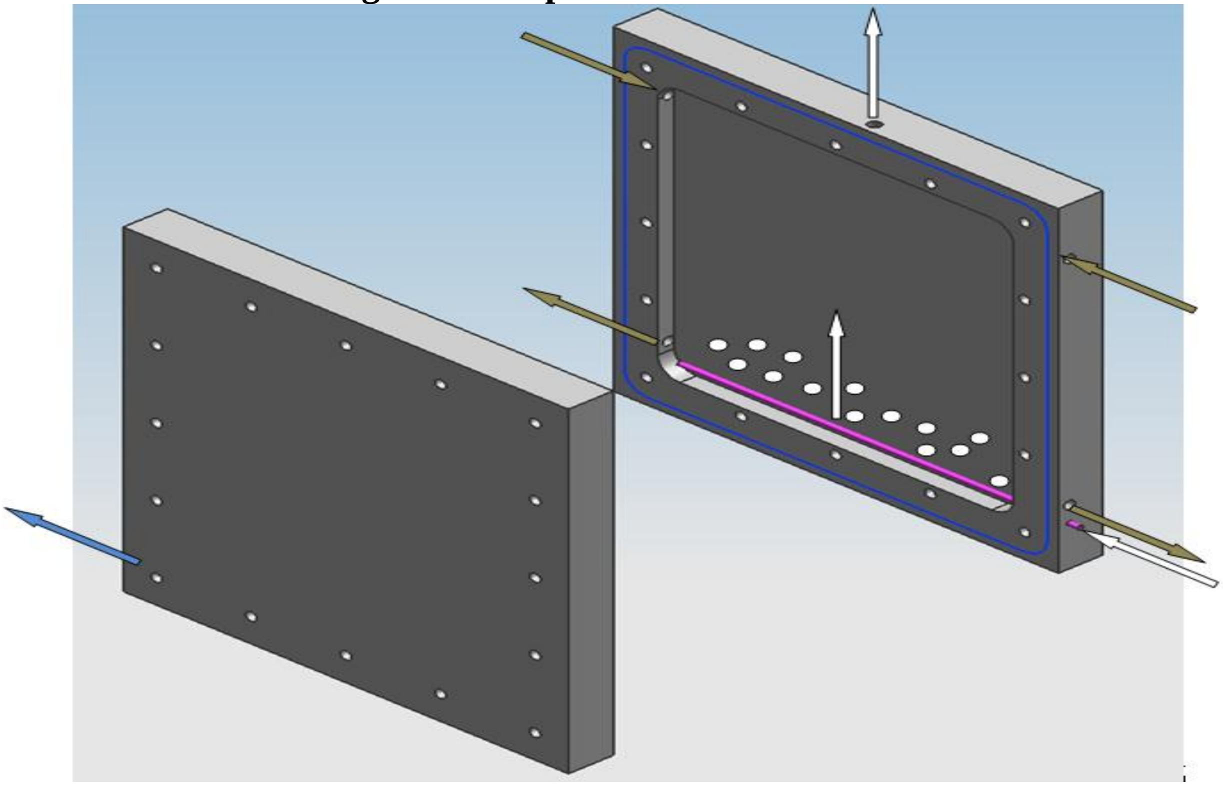
APPENDIX C: Functional decomposition of our general system.



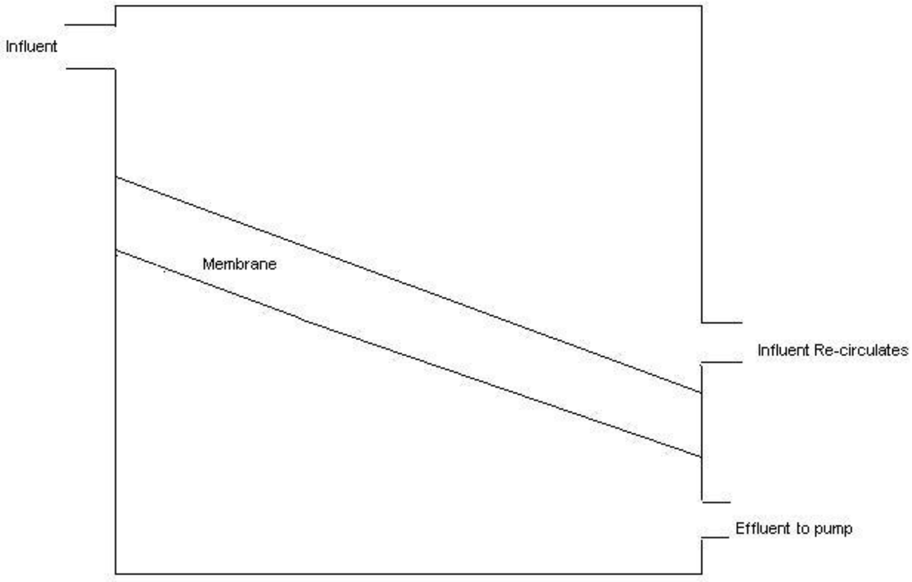
APPENDIX D: Inside-out versus regular membrane orientation concept.



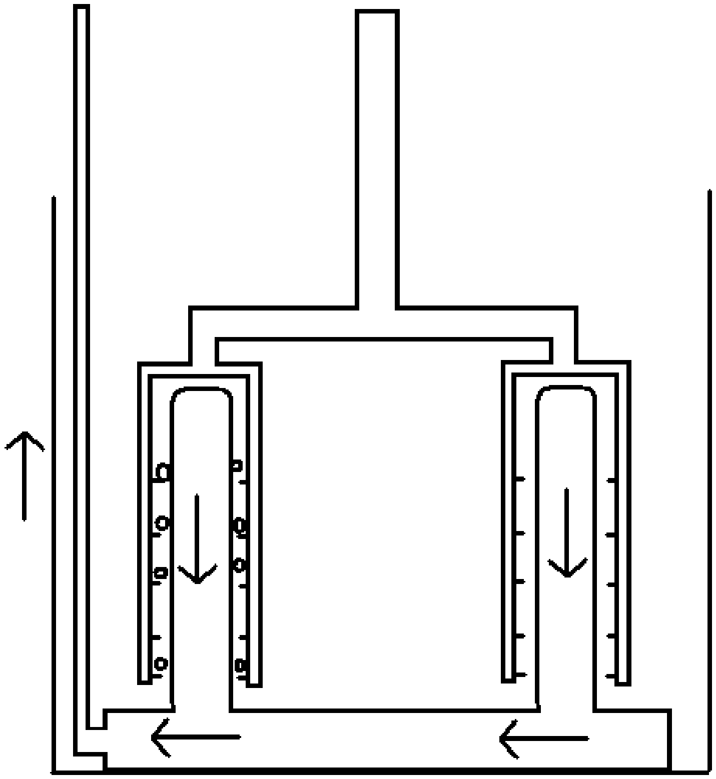
APPENDIX E: Rectangular concept for external flat membrane.



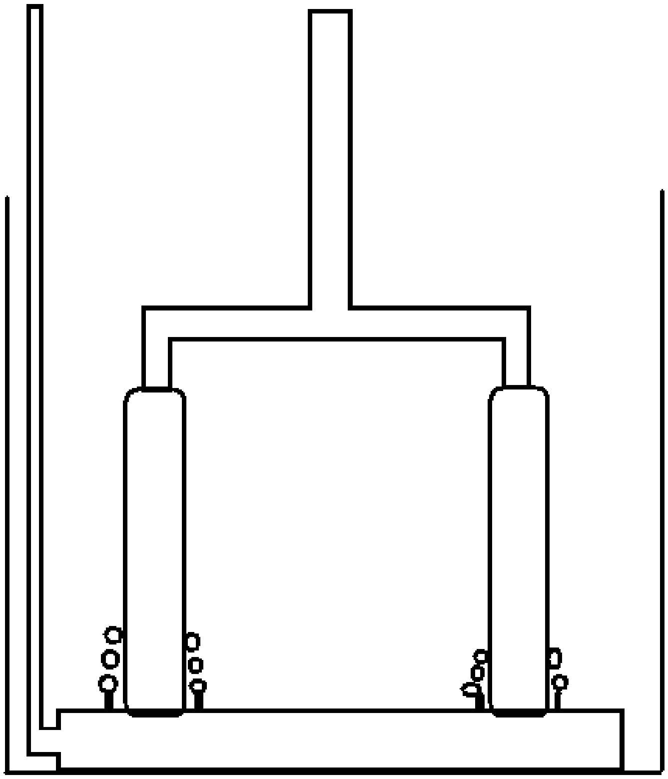
APPENDIX F: Concept of dead end flat sheet with re-ciculating capabilities.



APPENDIX G: False bottom for vacuum concept for internal system.



APPENDIX H: False bottom for sparging in internal system.



APPENDIX I: Calculations

$Surface\ Area\ = \pi DL$

$L = \frac{SA}{\pi D}$

Existing System
D = .0125 m
L = 1 m
Thus, SA= .04 m^2

Internal System
D = .0508 m
SA = 0.04 m^2
Thus, L = .246 m

Each is L/2=12.3 cm with two end caps of 1.27 cm each L_{tot}=14.84 cm

E = Pressure * Volume

$V = \pi \frac{D^2}{4} L$

L = .1484m
D = .0508 m
g= 9.8 m/s^2
ρ=1 kg/m^3
h= .27 m

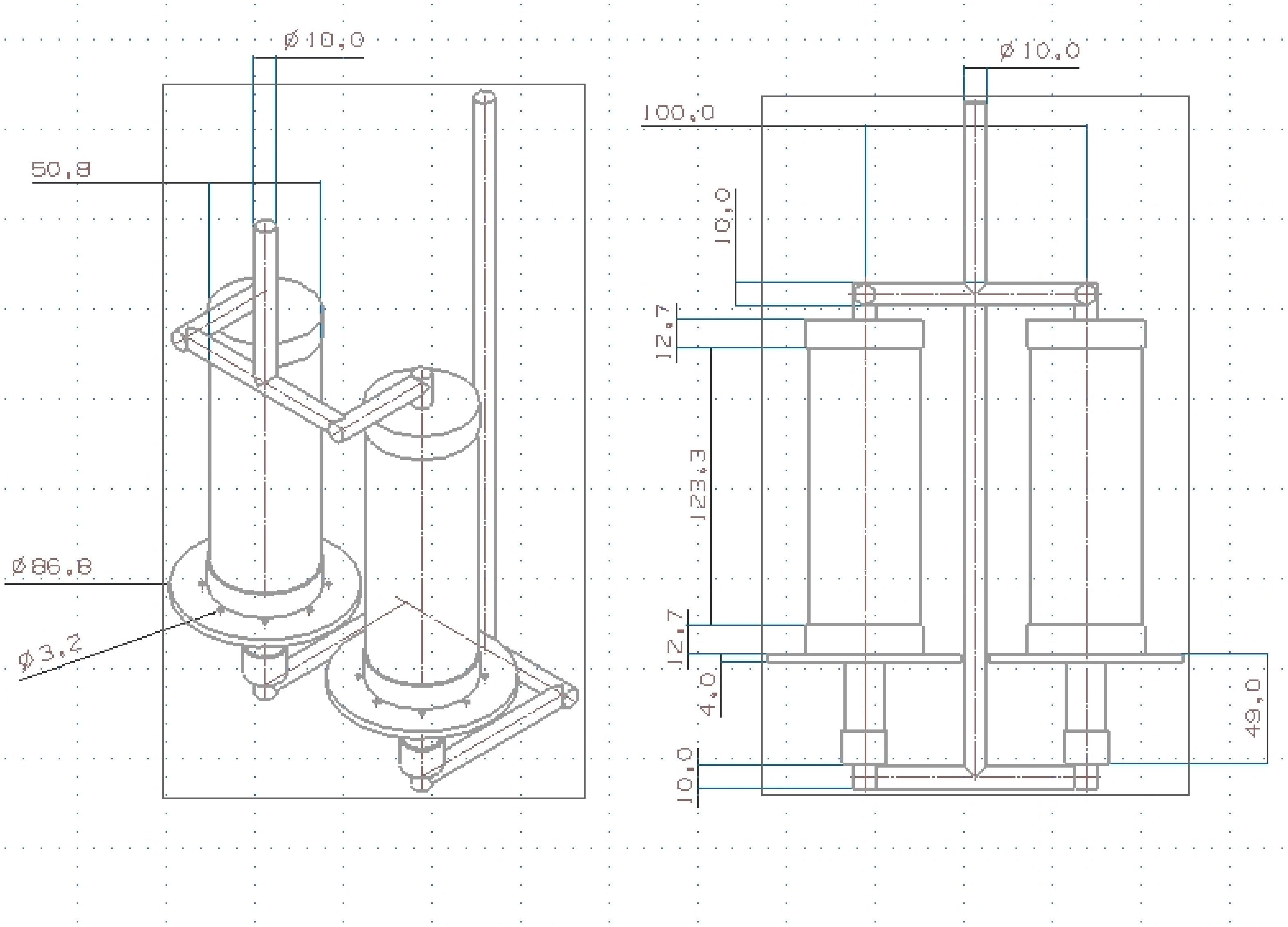
$P = \rho g h$

Thus V=.000301 m^3 and P_1=80,000 Pa and P_2=1*9.8*.27=2.646 Pa
Then E=P V= 80,000*.000301+ 2.646*.000301= 24.06 Watts/membrane
E_{tot}= 2 * E = 48.12 Watts

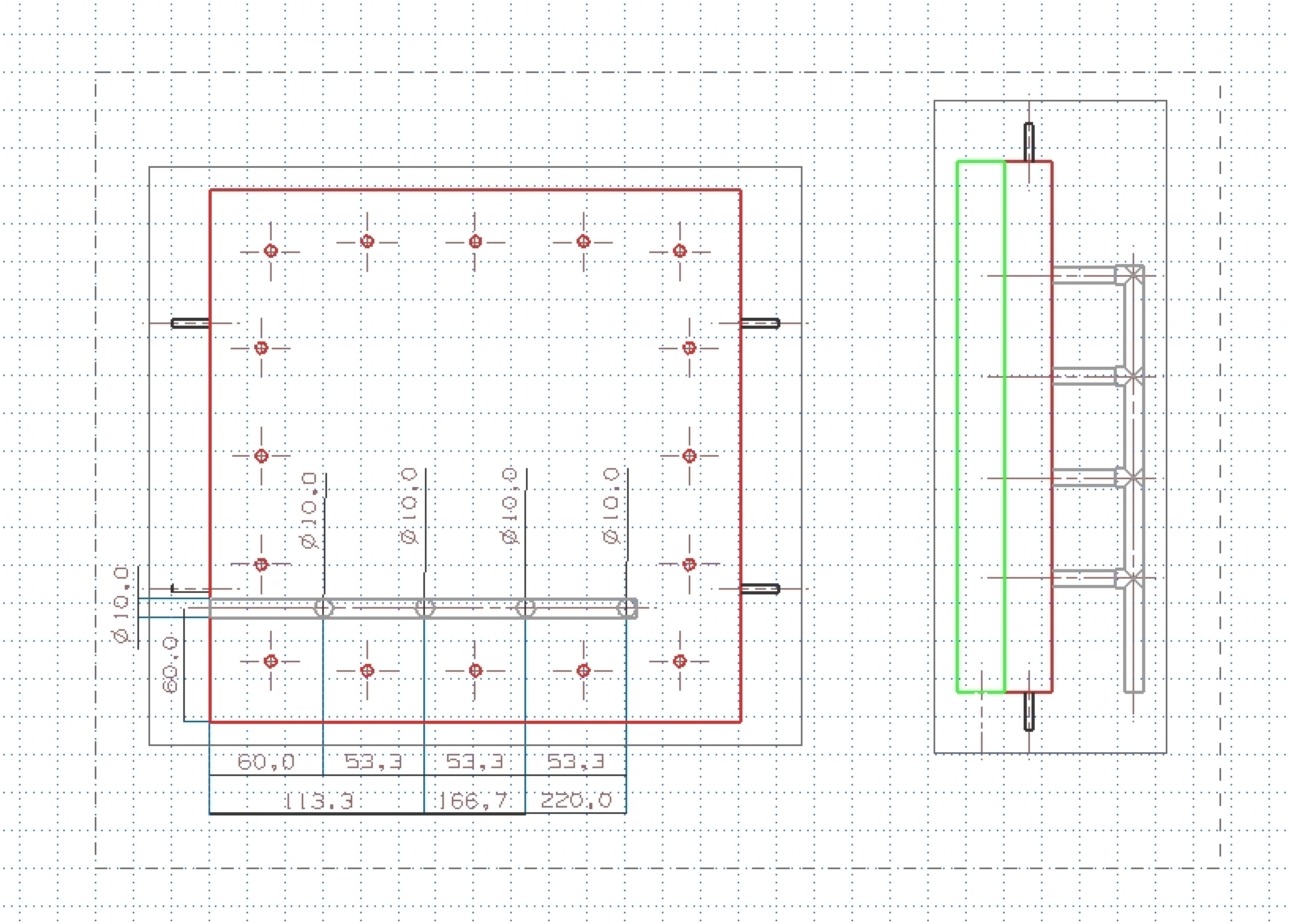
Force = Pressure * Area

P = 80,000 Pa
A= .02 m^2
Thus F= 80,000 Pa * .02 m^2 = 1600 N

APPENDIX J: Dimensioned drawing of internal system



APPENDIX K: Dimensioned drawing of drill holes for external flat



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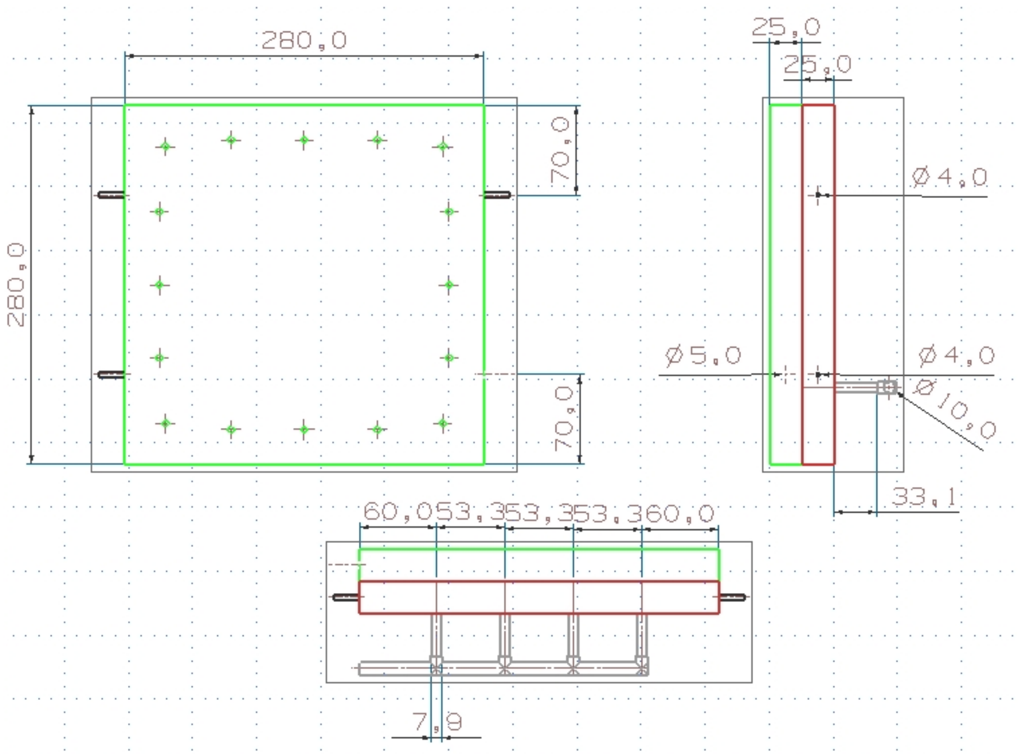
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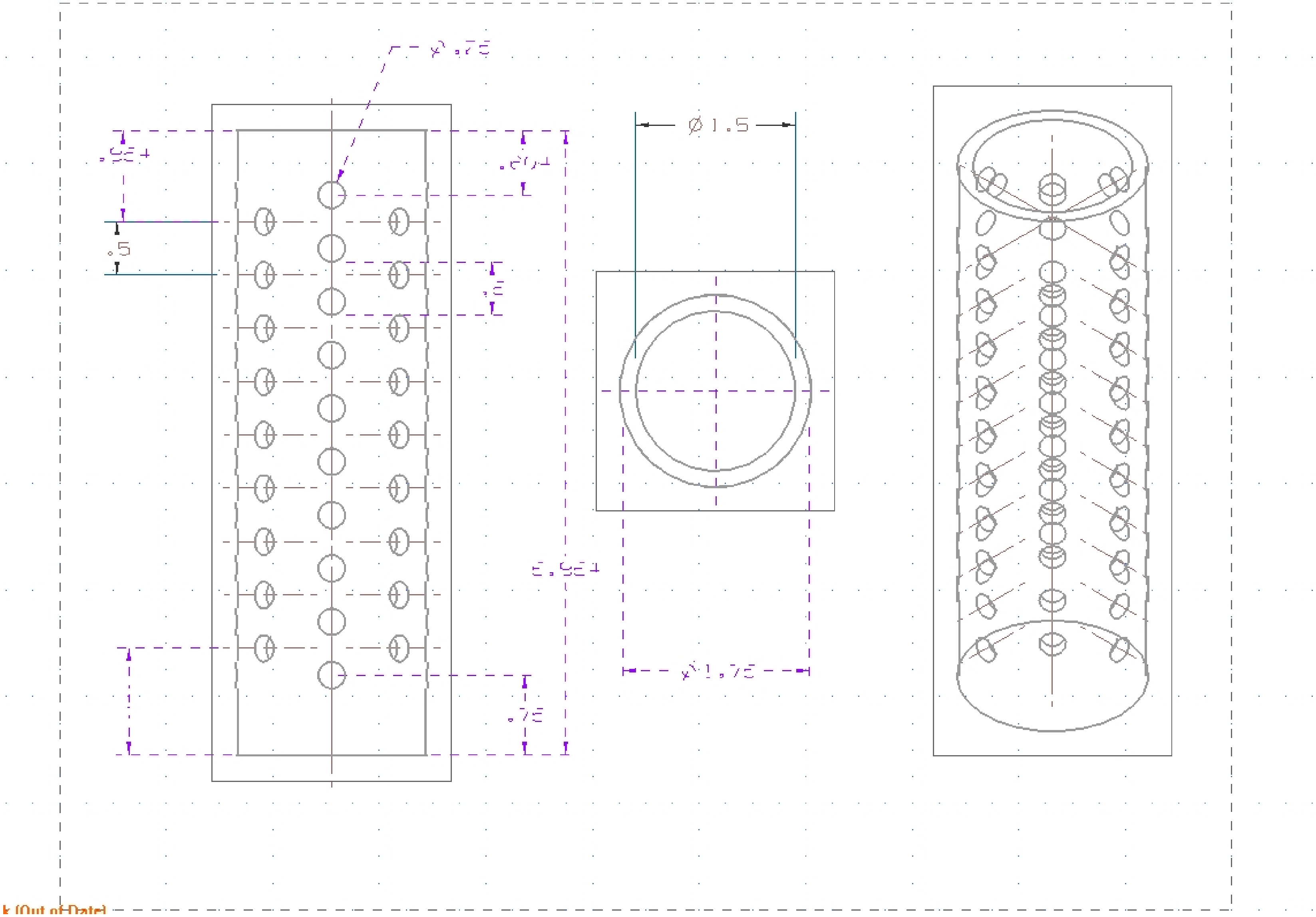
70,0
25,0
25,0
Ø4,0
Ø5,0
Ø4,0
Ø10,0
33,1
60,053,353,353,360,0
7,9

APPENDIX L: Dimensioned drawing for PVC machining process



k (Out of Date)

APPENDIX M: Material Selection for Internal System

- Supporting material

Functions:
To hold the membrane rigid vertically
To hold the collecting clean water

Objectives:
Maximized fracture toughness
Minimized cost
Minimized density

Constraints:
Non-corrosive and non-biodegradable
Strong against alkali and acid
Non-reactive against methane (flammable)

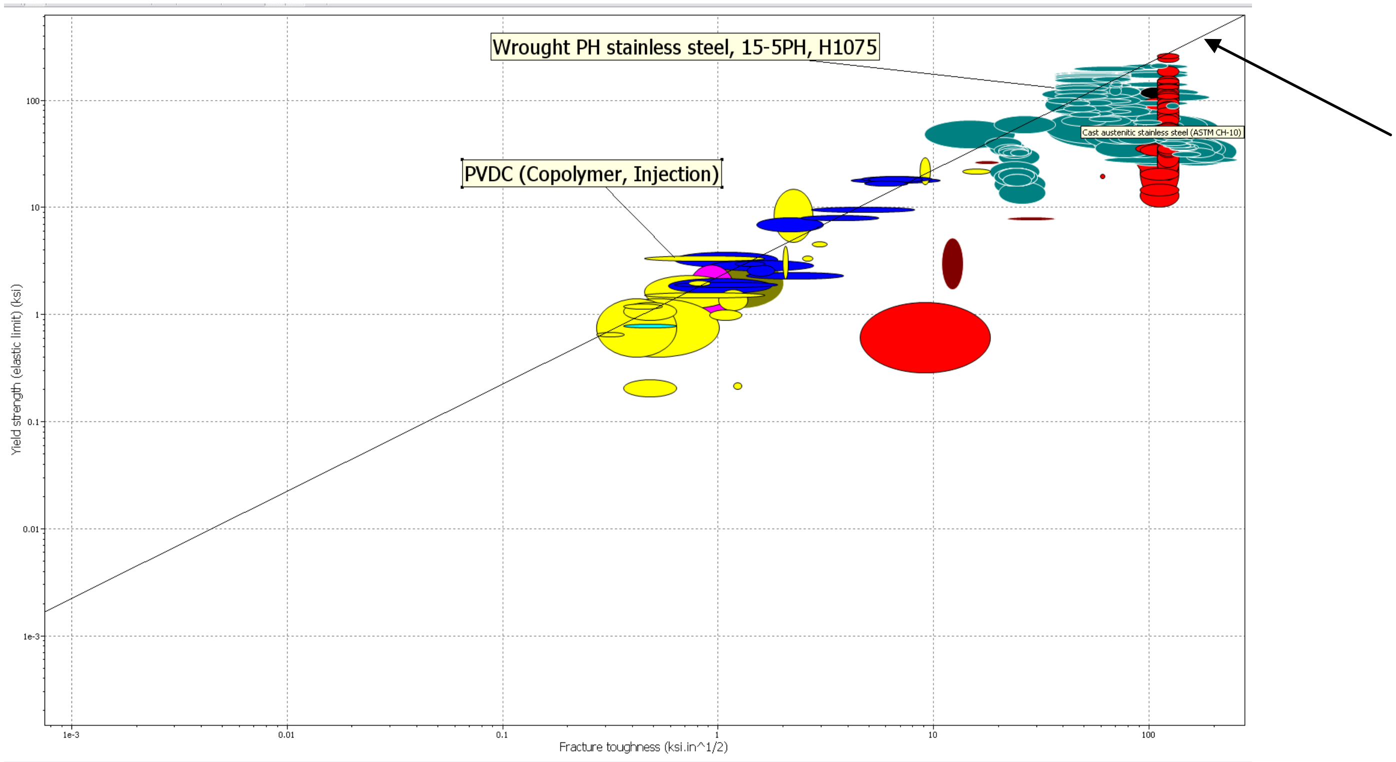
Appropriate material indices

$$M = \frac{K_{Ic}}{C_m \sigma_y \rho}$$

Using CES and its top 5 material choices
PVDC (Copolymer, Injection), Wrought PH stainless steel, Cast aluminum alloy, Polyphtalamide, Alumina

Final choice
PVDC

1) Apply the corrosion and flammability criteria under the Durability category.
2) Create a graph for maximized fracture toughness and minimized yield strength to isolate the materials that have passed the 1st stage. This is shown below with the slope line.



Anything below this slope is eliminated since we want maximized fracture toughness (x-axis) and minimized yield strength (y-axis)

Figure A. Material Types that passes the durability (corrosion and flammability) criteria

3) Do price comparison on the materials that pass the 2nd stage

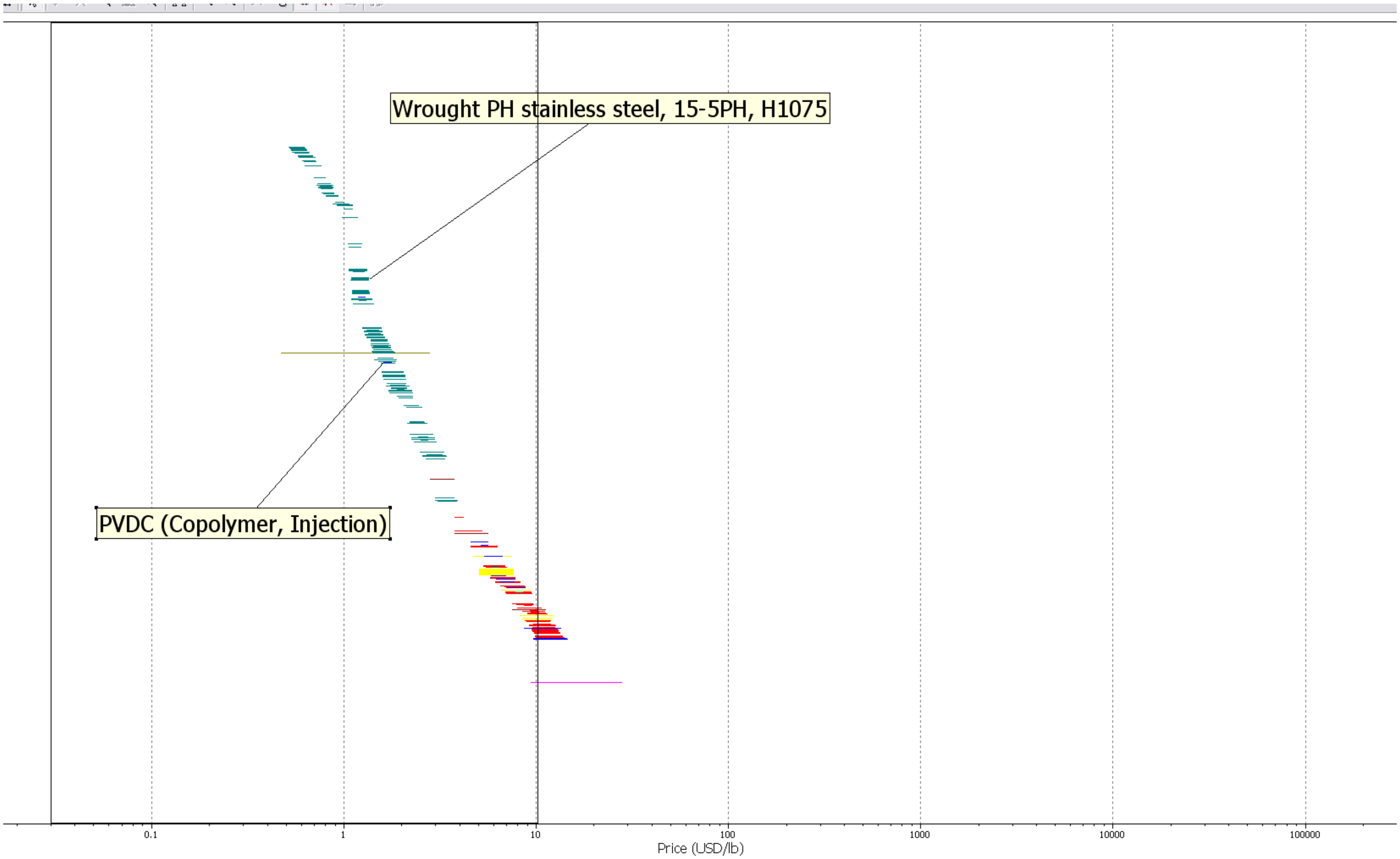


Figure B. PVDC and stainless steel are approximately similar in price.

4) Do density comparison on materials that pass the 2nd stage

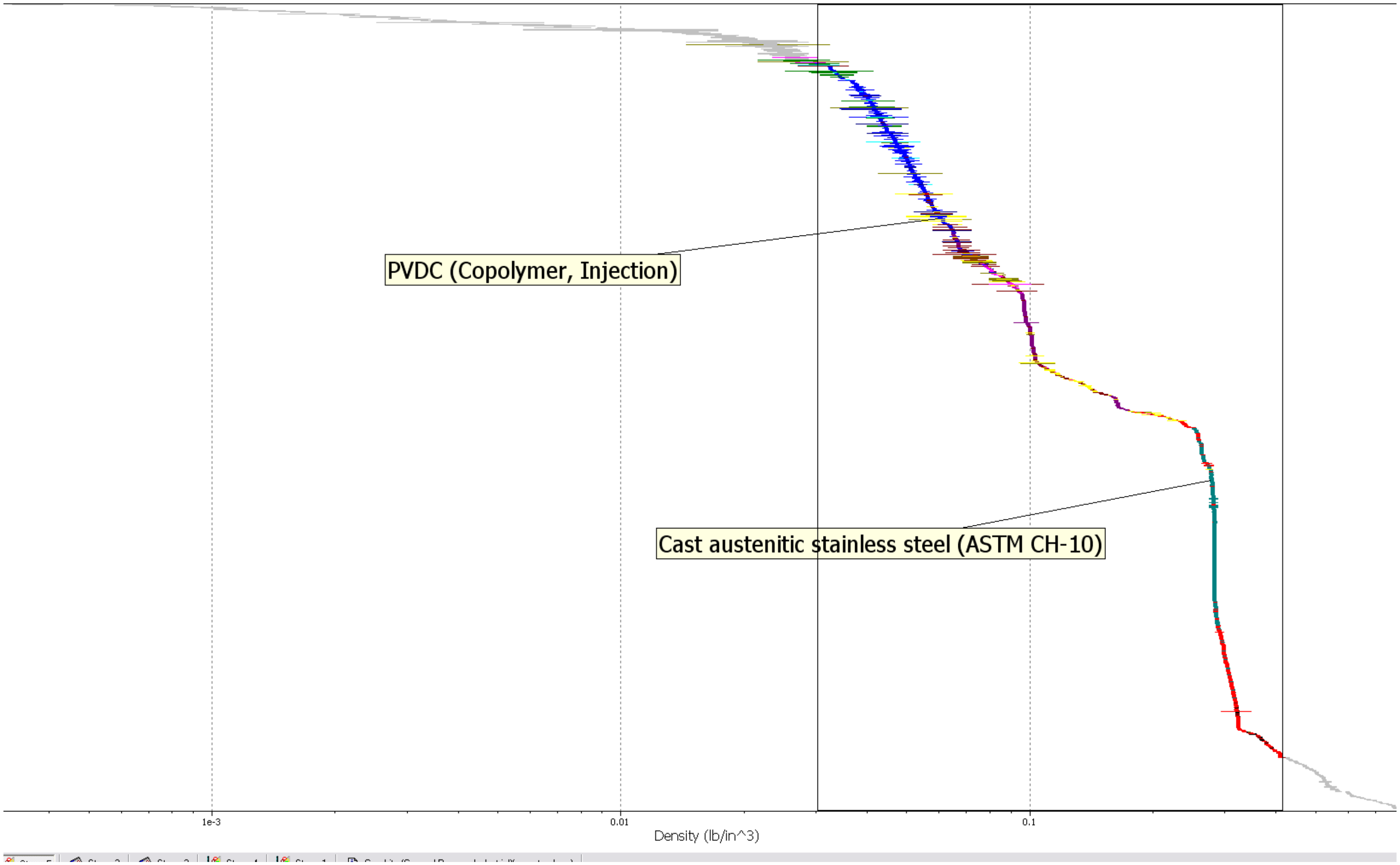


Figure C. PVDC is less dense than stainless steel

- Diffuser

Functions:
To act as sparging mechanism to alleviate fouling
To support mainframe of our system - membrane and supporting material

Objectives:
Maximized compressive strength
Minimized density
Minimized cost

Constraints:
Non-corrosive and non-biodegradable
Strong against weak acid and alkali
Either stainless steel or Celcon plastic

Appropriate material indices

$$M = \frac{E^{1/2}}{C_m \rho}$$

Final decision
POM (Celcon plastic)

1) Apply the corrosion and flammability criteria under the Durability category.
2) Create a graph for maximized compressive strength and minimized density to isolate the materials that have passed the 1st stage. Maximized performance based on material indices is determined by the slope line.

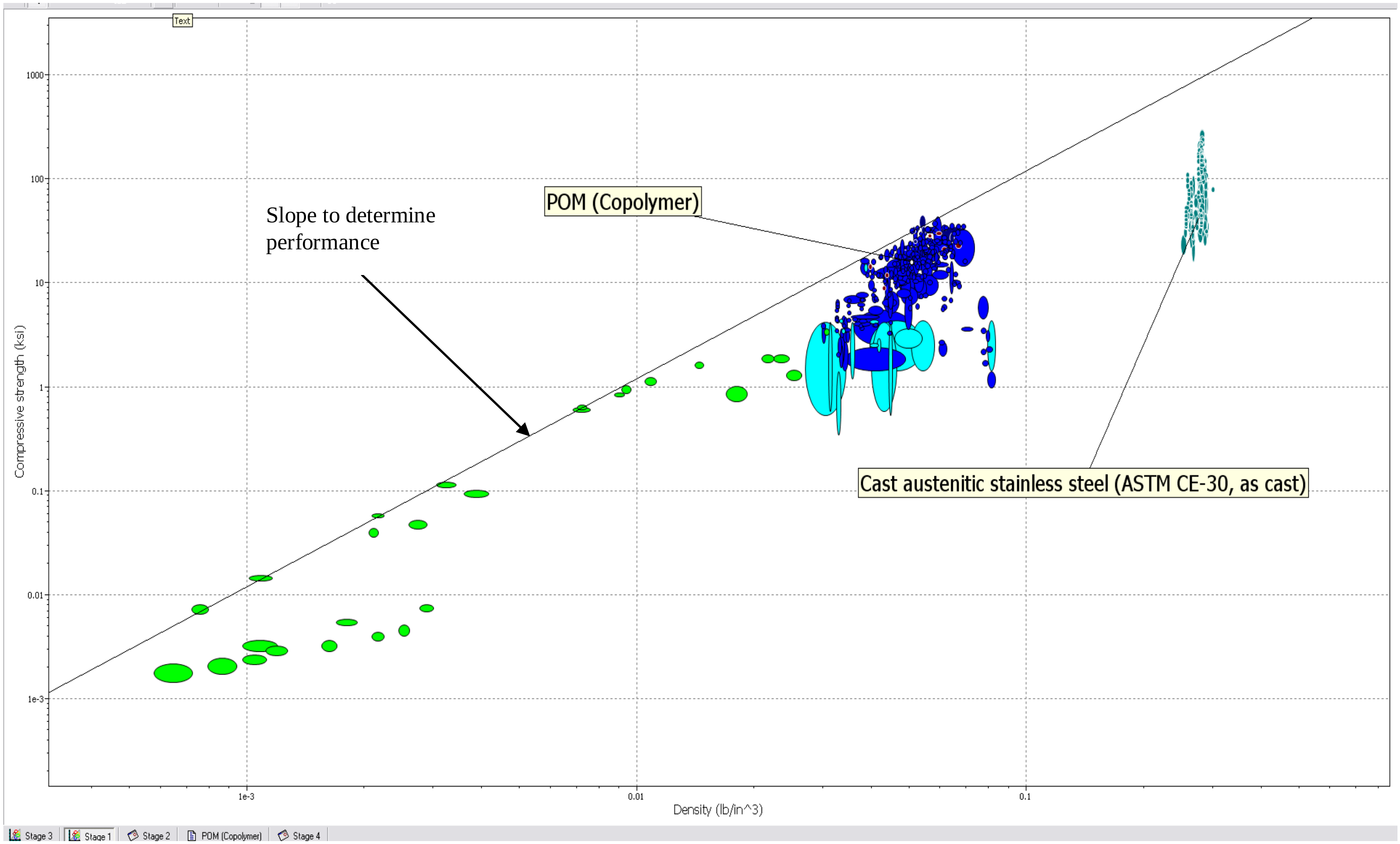


Figure D: POM exhibits better performance than stainless steel based on our material indices based on the slope of the line

3) Do price comparison on materials that have passed the 1st stage.

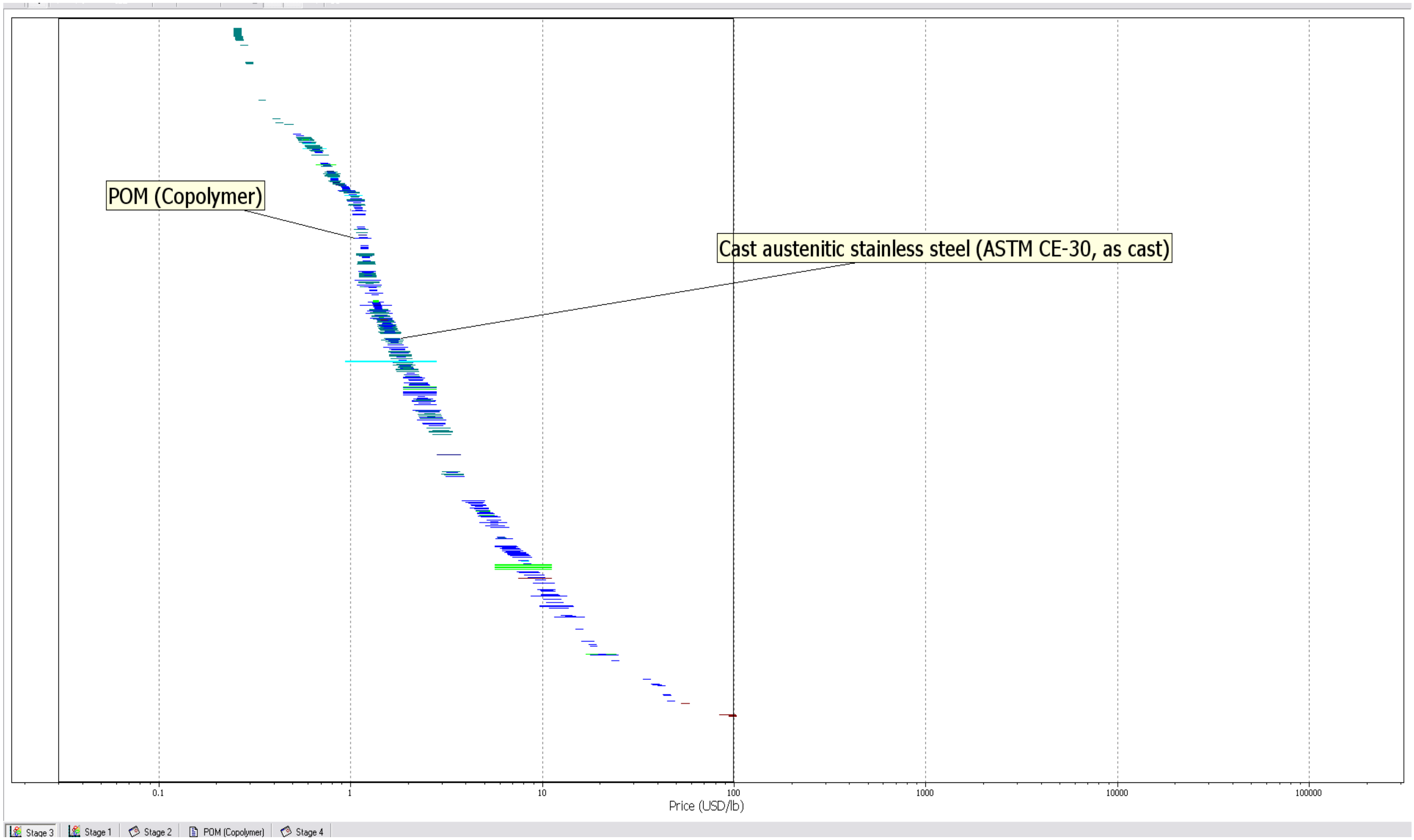
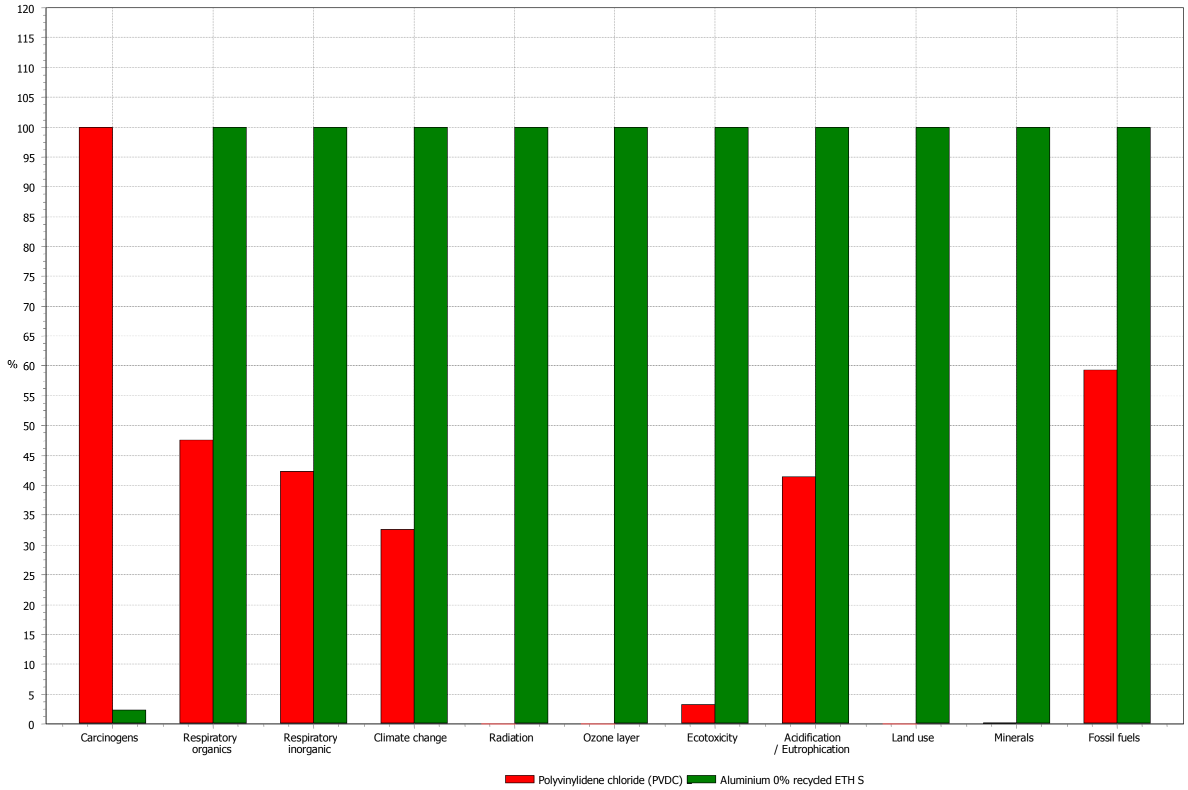


Figure E: POM is slightly cheaper than stainless steel, making POM an even better choice

APPENDIX N: Design for Environmental Sustainability

Component: Supporting material for internal membrane system



Comparing 0.2 kg 'Polyvinylidene chloride (PVDC) E' with 0.2 kg 'Aluminium 0% recycled ETH S'; Method: Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A / characterization

Figure F. Relative Impacts in Disaggregated Damage Categories for PVDC vs. Aluminum. Based on the above, in all categories except carcinogens, aluminum has a stronger effect on the environment.

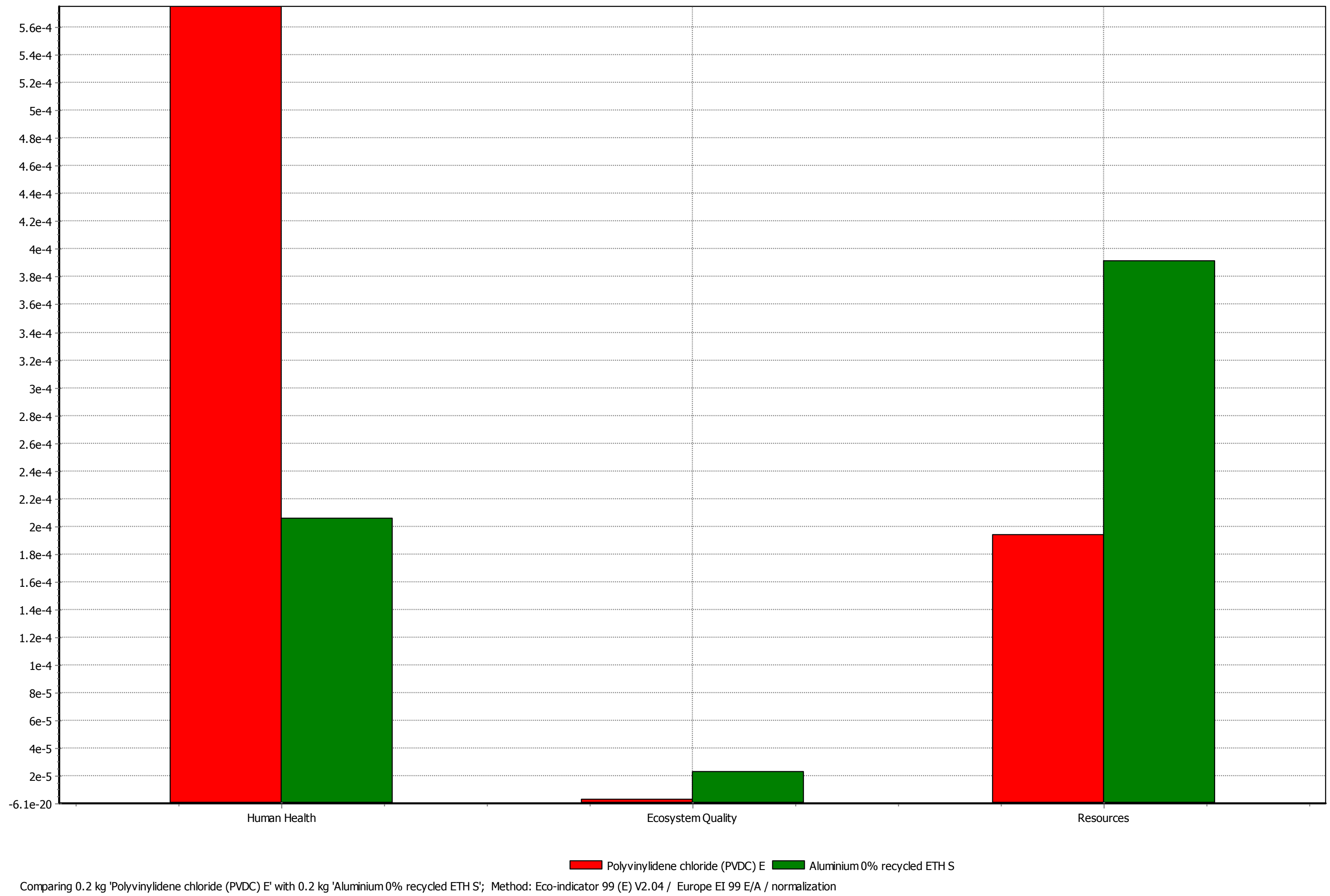


Figure G. Normalized Scores in Human Health, Eco-toxicity and Resource Categories for PVDC vs. Al. Tradeoff between using the PVDC which affects human health negatively versus the use of resources which is more damaging with aluminum.

Comparing 0.2 kg 'Polyvinylidene chloride (PVDC) E' with 0.2 kg 'Aluminium 0% recycled ETH S'; Method: Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A / single score

Figure H. EcoIndicator Point Value for PVDC vs. Aluminum. PVDC affects the environment more than aluminum due to higher point value.

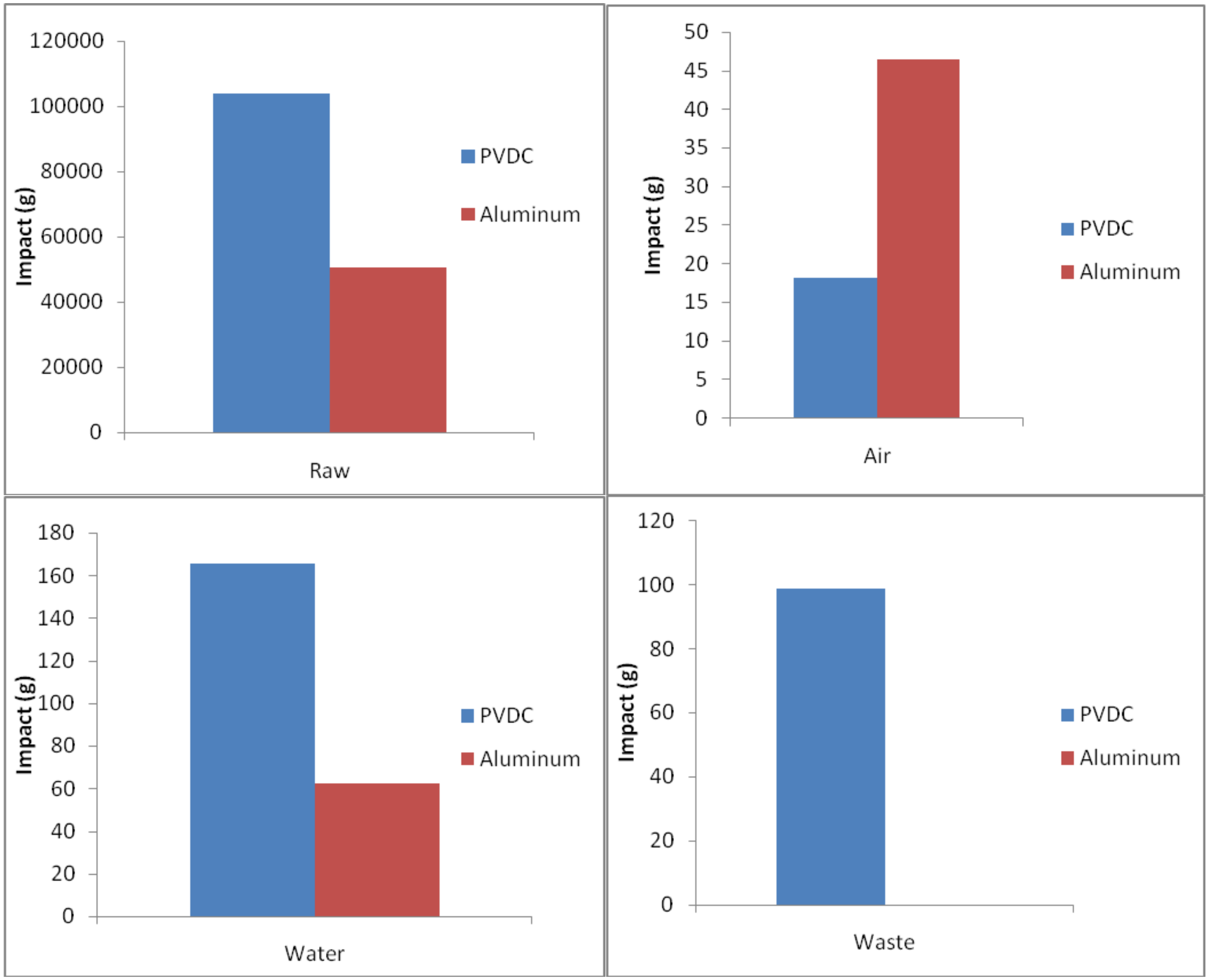


Figure I. Total Emissions of for PVDC vs. Al.

Component: Supporting Material for External Tubular System

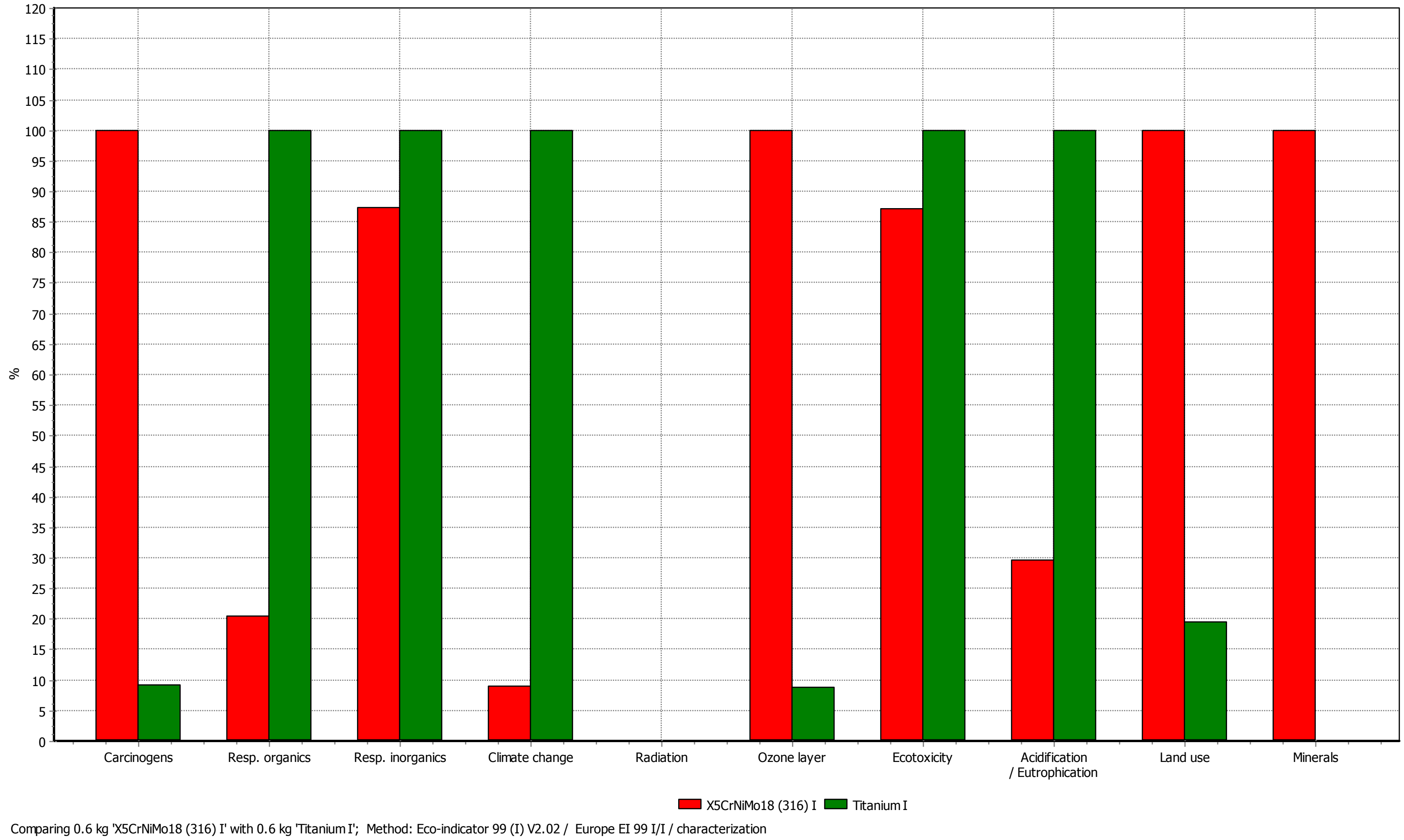
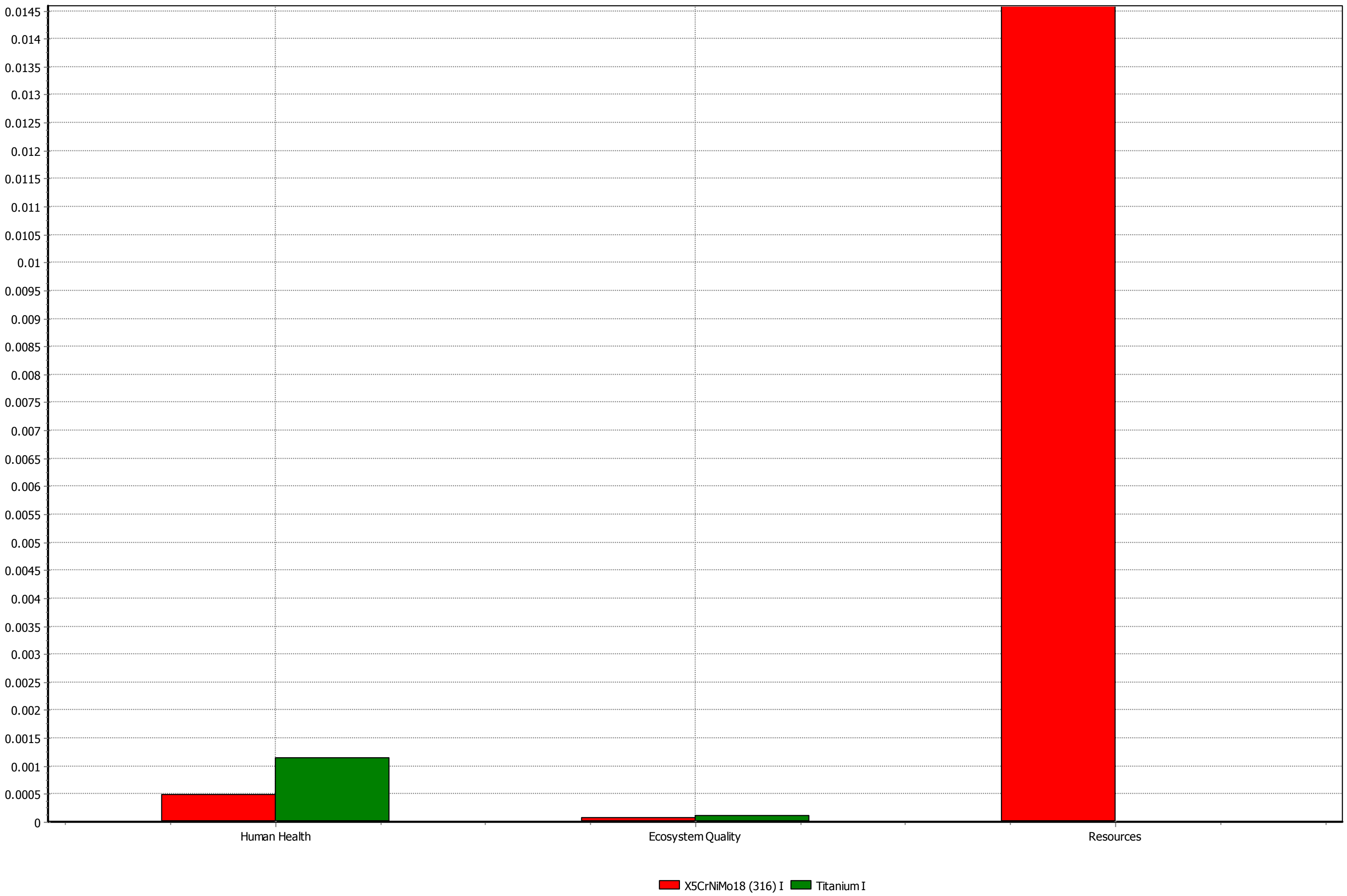
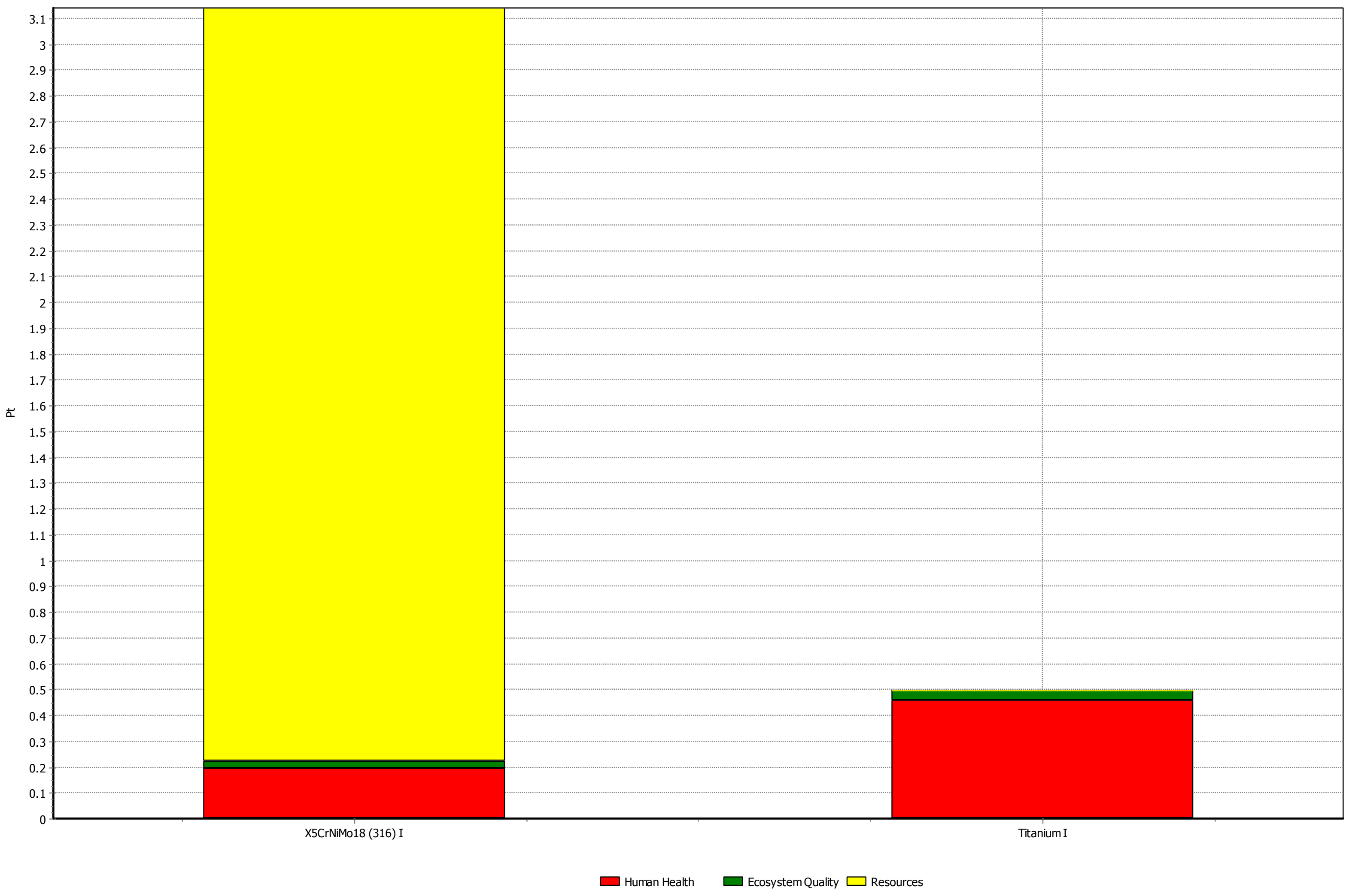


Figure J. Relative Impacts in Disaggregated Damage Categories for X5CrNiMo18 vs. Titanium.



Comparing 0.6 kg 'X5CrNiMo18 (316) I' with 0.6 kg 'Titanium I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/A / normalization

Figure K. Normalized Scores in Human Health, Eco-toxicity and Resource Categories for X5CrNiMo18 vs. Titanium.



Comparing 0.6 kg 'X5CrNiMo18 (316) I' with 0.6 kg 'Titanium I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/A / single score

Figure L. EcoIndicator Point Value for X5CrNiMo18 vs. Titanium. The X5CrNiMo18 has a much higher point value according to the ecoindicator which means it will have a bigger impact when the life cycle as a whole is considered.

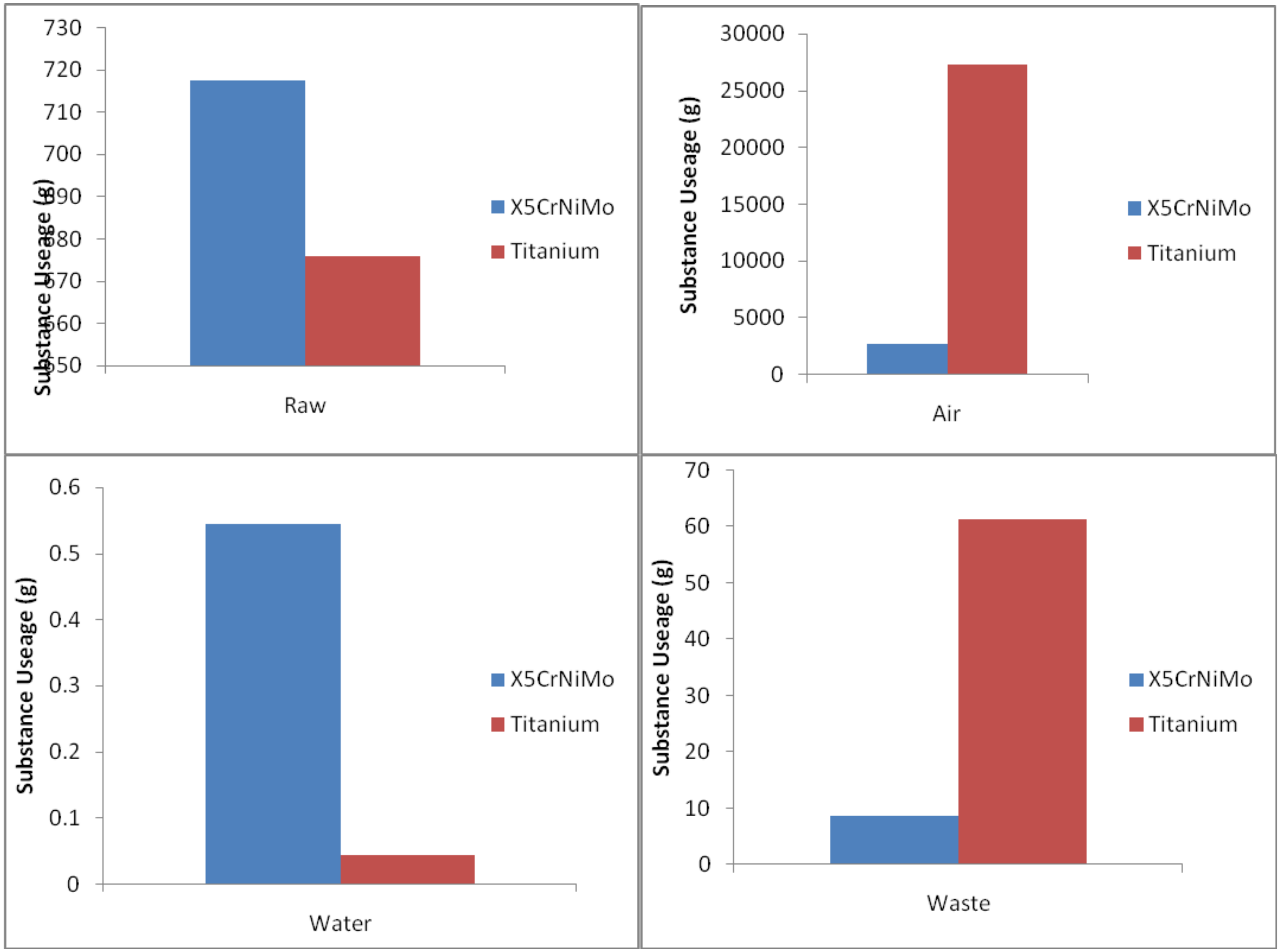


Figure M. Total Emissions of for X5CrNiMo18 vs. Titanium.

APPENDIX O: Design for Safety

Application:	External tubular system	Analyst Name(s):	Team 27
Description:		Company:	
Product Identifier:	External tubular membrane system	Facility Location:	EWRE room 40
Assessment Type:	Detailed		
Limits:			
Sources:			

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

User / Task	**Hazard / Failure Mode**	**Initial Assessment Severity Exposure Probability**	**Risk Level**	**Risk Reduction Methods /Comments**	**Final Assessment Severity Exposure Probability**	**Risk Level**	**Status / Responsible /Reference**
engineer All Tasks	Mechanical: fatigue Constant pressure gradient	Minimal None Negligible	Low	Periodic inspection	Minimal Occasional Possible	Moderate	In-process ALL
engineer All Tasks	mechanical : break up during operation loose fittings	Serious Remote Possible	Moderate	periodic inspection and tighten fittings	Minimal None Possible	Low	In-process ALL
engineer All Tasks	mechanical : machine instability vibration from motor and	Slight None Possible	Low	replace with another motor with lesser vibration	Minimal Remote Possible	Low	TBD ALL
engineer All Tasks	ergonomics / human factors : duration long test duration leads to insufficient monitoring	Minimal Occasional Probable	Moderate	employ more manpower or use an automated alarm system	Minimal None Unlikely	Low	TBD ALL
engineer All Tasks	noise / vibration : fatigue / material strength motor vibration and sparging	Minimal Remote Negligible	Low	periodic inspection	Minimal None Possible	Low	In-process ALL
engineer All Tasks	environmental / industrial hygiene : effluent / effluent handling methane and nitrogen	Slight Remote Probable	Moderate	proper ventilation	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	ventilation : concentration high nitrogen gas concentration	Minimal Occasional Unlikely	Low	proper ventilation	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	chemical : reaction to / with chemicals biomass spill	Minimal Remote Unlikely	Low	wear goggle and gloves	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	chemical : failure at key points and trouble spots loose fittings and pressure buildup	Serious Remote Possible	Moderate	install regulators and pressure transducers for detection	Minimal None Possible	Low	On-going [Daily] ALL

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
engineer All Tasks	chemicals and gases : nitrogen high nitrogen gas concentration	Minimal Occasional Unlikely	Low	proper ventilation	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	biological / health : bacterial biomass	Minimal Occasional Negligible	Low	wear gloves and goggle	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	fluid / pressure : high pressure air sparging gas	Slight Remote Possible	Moderate	tighten fittings	Minimal None Probable	Low	In-process ALL
engineer All Tasks	fluid / pressure : fluid leakage / ejection loose fittings due to high pressure flow	Serious Remote Unlikely	Moderate	tighten fittings and periodic inspection	Minimal None Possible	Low	In-process ALL

Major risks

- Long duration of the experiment may limit inspection or monitoring, and thus may be deemed as potential danger when something goes wrong without being noticed
- Proper ventilation of the methane and nitrogen gas
- Loose fittings causing leaks
- Pressure buildup
- High pressure sparging gas may cause rupture in certain components
- High pressure cross flow system may cause fatigue and rupture

Unexpected risks

- Long duration of the experiment may limit inspection or monitoring, and thus may be deemed as potential danger when something goes wrong without being noticed.
- High nitrogen and methane gas concentrations in the room unless there is proper ventilation in the room
- Fatigue in our components due to constant high pressure flow

Application:	External flat	Analyst Name(s):	Team 27
Description:		Company:	
Product Identifier:	External flat membrane system	Facility Location:	EWRE room 40
Assessment Type:	Detailed		
Limits:			
Sources:			

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

User / Task	**Hazard / Failure Mode**	**Initial Assessment Severity Exposure Probability**	**Risk Level**	**Risk Reduction Methods /Comments**	**Final Assessment Severity Exposure Probability**	**Risk Level**	**Status / Responsible /Reference**
engineer All Tasks	mechanical : break up during operation rupture due to pressure	Catastrophic Remote Unlikely	Moderate	effective gas removal system	Minimal Remote Probable	Moderate	On-going [Daily] ALL
engineer All Tasks	ergonomics / human factors : duration long test duration	Minimal None Probable	Low	employ more man power	Slight None Negligible	Low	TBD ALL
engineer All Tasks	environmental / industrial hygiene : effluent / effluent handling methane and nitrogen gas	Minimal Occasional Probable	Moderate	proper ventilation system/storage system	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	ventilation : concentration high nitrogen concentration in the room	Minimal Remote Possible	Low	proper ventilation system	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	chemical : failure at key points and trouble spots mixture of fluids at T-connectors and nozzles causing	Serious Remote Possible	Moderate	periodic inspection and maintenance	Slight Remote Unlikely	Low	Complete [4/5/2008] ALL
engineer All Tasks	chemicals and gases : nitrogen nitrogen concentration in room	Minimal Occasional Unlikely	Low	proper ventilation	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	biological / health : bacterial biomass	Minimal Remote Negligible	Low	wear gloves and goggle	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	fluid / pressure : high pressure air sparging	Slight Occasional Possible	Moderate	Install regulator/prevent pressure buildup	Minimal Occasional Possible	Moderate	In-process ALL
engineer All Tasks	fluid / pressure : pneumatics rupture pressure buildup	Catastrophic Remote Possible	High	effective gas removal in the system	Slight Remote Probable	Moderate	On-going [Daily] ALL

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
engineer All Tasks	fluid / pressure : fluid leakage / ejection loose fittings	Serious Remote Possible	Moderate	periodic inspection	Minimal Remote Unlikely	Low	TBD ALL

Major Risk

- Long duration of the experiment may limit inspection or monitoring, and thus may be deemed as potential danger when something goes wrong without being noticed.
- Loose fittings due to high pressure flow
- Pressure buildup causing rupture
- High nitrogen and methane gas concentrations in the room
- Mixing of fluids causing contamination due to backflow

Unexpected risk

- Methane gas poses another challenge in terms of storing it or venting it and it is flammable
- Nitrogen gas concentrations in the room may be high since it is continuously released by sparging, and this is not an ideal situation!
- Fatigue in our components as they are constantly being subjected to high cross-flow pressure
- Leaks in fittings due to fatigue

Application:	Internal system	Analyst Name(s):	Team 27
Description:		Company:	
Product Identifier:	Internal Membrane System	Facility Location:	EWRE Room 40
Assessment Type:	Detailed		
Limits:			
Sources:			

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

User / Task	**Hazard / Failure Mode**	**Initial Assessment Severity Exposure Probability**	**Risk Level**	**Risk Reduction Methods /Comments**	**Final Assessment Severity Exposure Probability**	**Risk Level**	**Status / Responsible /Reference**
engineer All Tasks	mechanical : fatigue support material may crack due to fatigue under constant	Minimal Remote Negligible	Low	Periodic inspection	Minimal Remote Possible	Low	On-going [Daily] ALL
engineer All Tasks	mechanical : break up during operation Corrosion and fatigue on the supporting material and diffuser	Minimal Remote Negligible	Low	Periodic inspection	Minimal Remote Possible	Low	On-going [Daily] ALL
engineer All Tasks	ergonomics / human factors : duration Duration of test will be long, and this may cause it to be not	Slight Occasional Possible	Moderate	More manpower for monitoring. Or control system can be implemented to signal for something wrong	Slight Remote Unlikely	Low	In-process ALL
engineer All Tasks	fire and explosions : flammable gas Methane will be flammable	Slight Occasional Unlikely	Moderate	Methane needs to be vented or collected in a vessel	Minimal None Probable	Low	Complete [4/5/2008] ALL
engineer All Tasks	noise / vibration : fatigue / material strength vibration from vacuum pump	Minimal None Negligible	Low	Use a motor with less vibration	Minimal Remote Possible	Low	TBD ALL
engineer All Tasks	environmental / industrial hygiene : effluent / effluent handling Methane is flammable and nitrogen gas can cause pressure build-up	Minimal Occasional Unlikely	Low	Proper ventilation system	Slight Remote Negligible	Low	Complete [4/5/2008] ALL
engineer All Tasks	ventilation : concentration High methane concentration is dangerous	Slight Remote Unlikely	Low	Proper ventilation system	Slight Remote Negligible	Low	Complete [4/5/2008] ALL

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
engineer All Tasks	chemical : irritant chemicals Biomass may be irritant to skin	Minimal Remote Unlikely	Low	Wear a glove and goggle when dealing with biomass	Minimal None Negligible	Low	Complete [4/5/2008] ALL
engineer All Tasks	chemical : failure at key points and trouble spots leaks in fittings	Slight Remote Possible	Moderate	Inspect for leaks by checking drop in pressure	Slight Remote Unlikely	Low	In-process ALL
engineer All Tasks	chemicals and gases : nitrogen Sparging gas needs to be vented	Minimal Frequent Unlikely	Moderate	Proper ventilation system	Slight Remote Negligible	Low	Complete [4/5/2008] ALL
engineer All Tasks	biological / health : bacterial Biomass may cause irritation	Minimal Frequent Unlikely	Moderate	Wear a glove and goggle	Minimal None Negligible	Low	Complete [4/5/2008] ALL
engineer All Tasks	fluid / pressure : high pressure air sparging gas	Minimal Frequent Possible	Moderate	Use a regulator to control pressure	Minimal Occasional Unlikely	Low	On-going [Daily] ALL
engineer All Tasks	fluid / pressure : vacuum vacuum pressure may cause rupture or leak	Slight Remote Unlikely	Low	Use a high strength material for vacuum tubing	Minimal None Negligible	Low	Complete [4/5/2008] ALL
engineer All Tasks	fluid / pressure : fluid leakage / ejection Gas pressure build-up may cause rupture	Slight Remote Possible	Moderate	Ensure efficient gas removal in system	Minimal Occasional Possible	Moderate	In-process ALL

Major risks

- Long duration of the experiment may limit inspection or monitoring, and thus may be deemed as potential danger when something goes wrong without being noticed.
- Methane gas is flammable
- Leaks in fittings
- Proper ventilation for nitrogen gas
- Biomass may cause skin irritation
- High pressure sparging gas
- Rupture due to high pressure gas

The risks involve the engineers who will be conducting experiments and inspections periodically.

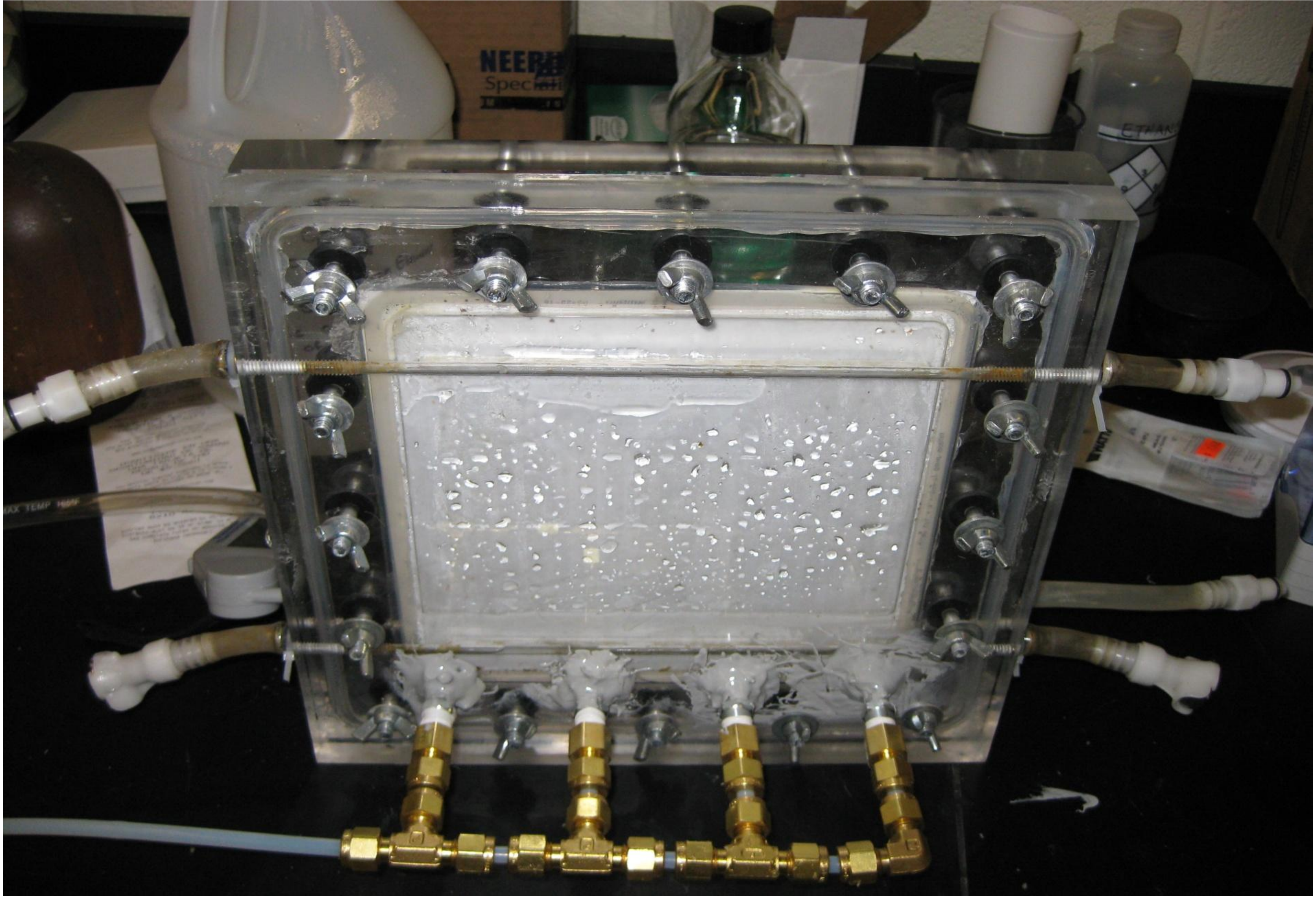
Unexpected risk

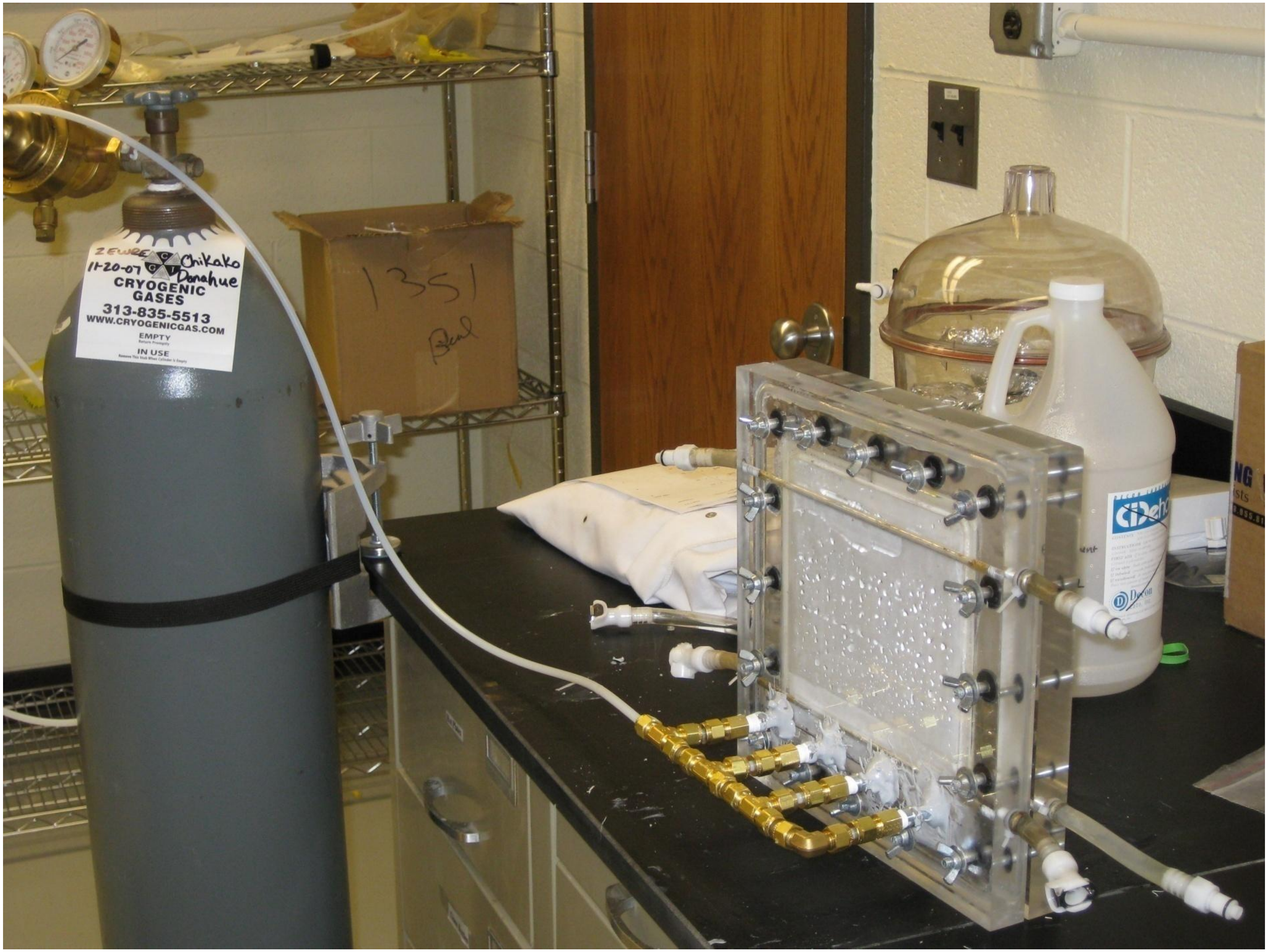
- Methane gas poses another challenge in terms of storing it or venting it and it is flammable
- Nitrogen gas concentrations in the room may be high since it is continuously released by sparging, and this is not an ideal situation!
- Fatigue in our components as they are constantly being subjected to vacuum pressure.
- Leaks in fittings due to continuous vacuum pressure

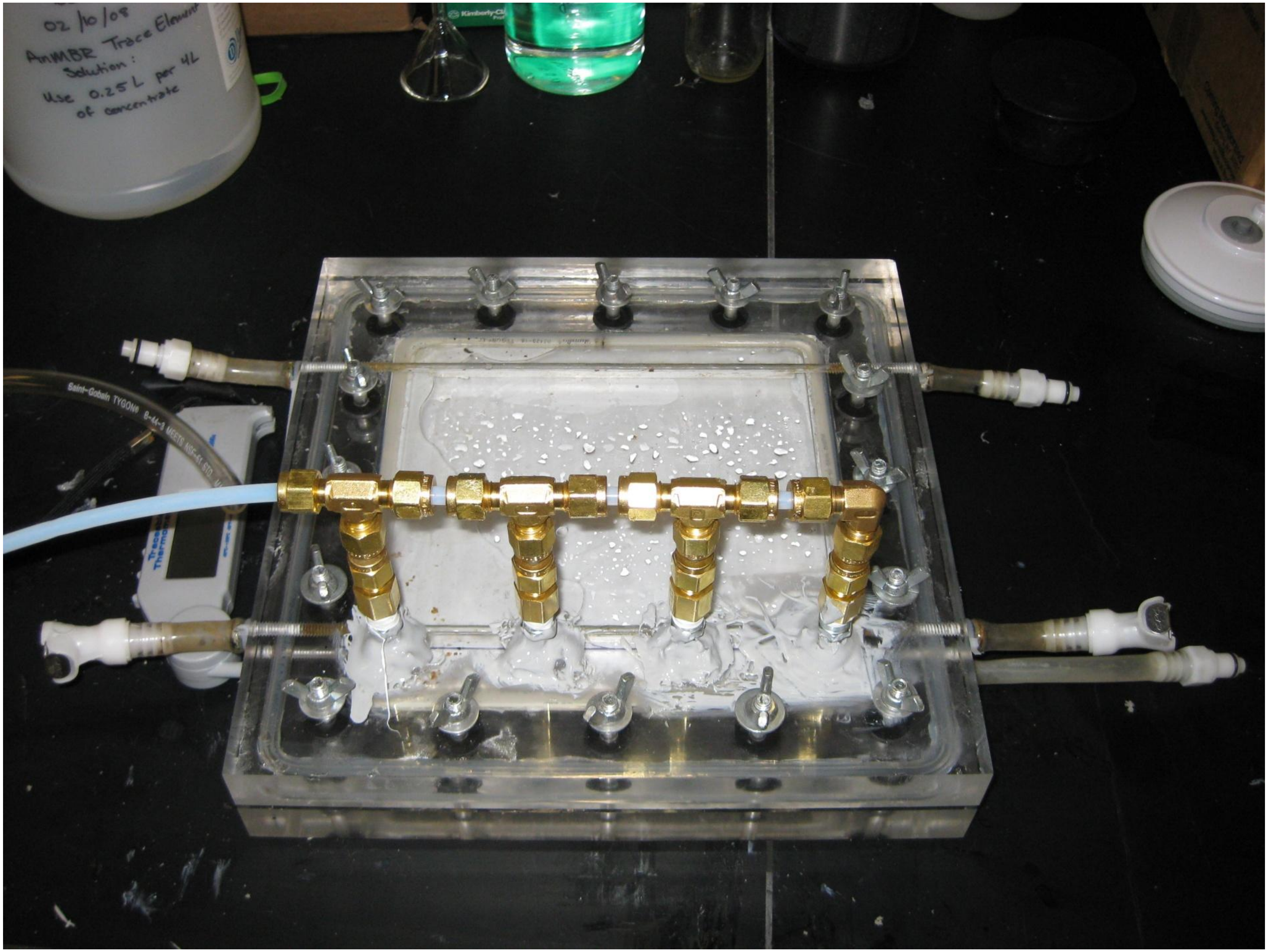
APPENDIX P: BUDGET

Part	Price	Quantity	Total
Vinyl Caps	14.25	1	14.25
10 mm Push to connect elbow	5.87	4	23.48
10 mm Push to connect tee	6.16	1	6.16
10 mm Nylon Tubing	0.8	10	8
316 SS 10mm to 1/4" coupling	21.93	1	21.93
10mm to 3/8" NPT elbow	7.04	2	14.08
304 SS 1/4" tubing 1 ft	11.79	2	23.58
316 SS 1/4" elbow	17.2	2	34.4
316 SS 1/4" tee	23.6	1	23.6
Brass 1/4" to 1/8" NPT Adt.	4.37	4	17.48
Brass 1/4" elbow	7.58	1	7.58
Brass 1/4" tee	11.63	3	34.89
Blowoff Nozzle 1/8" NPT	23.86	4	95.44
Check valve	19.37	2	38.74
1/8" NPT air release valve	24.93	2	49.86
Nylon 1/8" barb to 1/8" NPT	5.34	1	5.34
Polyethylene Wyes for 3/8"	8.55	1	8.55
Polyethylene 3/8" barb to 1/4" NPT	5.26	1	5.26
External Tubular membrane	435	1	435
Sparging Plates and caps	50	1	50
Aqua Epoxy	4.5	1	4.5
Sheet Metal	7.27	1	7.27
Aquarium Seal	3.81	1	3.81
PVC	1.57	1	1.57
		Total =$	**934.77**

APPENDIX Q. Real life pictures of our systems




ZEWRE
11-20-07
Chikako Donahue
CRYOGENIC GASES
313-835-5513
WWW.CRYOGENICGAS.COM
EMPTY
IN USE
1351


02/10/08
AnMBR Trace Element
Solution:
Use 0.25 L per 4L
of concentrate
Saint-Gobain TYGON®