APPLICATION OF SYSTEMS ENGINEERING AND PROJECT MANAGEMENT FOR ALGAE PHOTO BIOREACTORS

by

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PREFACE/ACKNOWLEDGEMENTS

Special thanks to Dr. Yarrow Nelson and Dr. Brian Hampson for providing this great opportunity and for all of your help. Also, thanks to Alex Burns for being such a great project partner. Go A-Team!

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EXECUTIVE SUMMARY

Today there is much talk about different sources for biofuel to replace the decreasing supply of fossil fuels. Algae seem very promising with its abundance across the globe and relatively simple growing conditions. Lipids can be extracted from this organism which is then converted to biofuel. Although biofuel production from algae is not economically viable at this stage, researchers are suggesting using the by-products of algae for supplemental and healthcare use. If true, this could justify the economics of obtaining fuel from algae by creating more markets from various algae products.

Cal Poly State University's Food Science and Nutrition Department has requested that a new and improved system used for producing algae called a Photo Bio Reactor (PBR) be built by the end of Spring 2013. A grant was offered to create a system that allows better monitoring capabilities, reduced safety hazards, increased volume throughput per square area, improved portability, and ultimately decreased operating costs.

Throughout the project, concepts and methodologies from Systems Engineering, Human Factors, Project management, and Process Improvement courses were utilized to design, build, and test the final product. Tools used throughout this 9-month-long project included creating an A3 Diagram and Ishikawa Diagrams for conducting root-cause analysis and incorporating Human Factors concepts throughout the design aspect of the PBR. Statistical Analysis was used to verify the effectiveness of different assembly methods of components. Time studies were utilized at the very end to verify setup costs were decreased yielding an overall savings in operation costs. Project Management was used throughout the way to schedule deadlines.

After much analysis of the system, The System decreased setup rimes from 12.0 hours per week to 2.0 hours per week. This yielded an overall labor cost reduction of $4800.00 per year assuming a labor cost of $10.00 per hour and 48 weeks in an academic year. A payback period of approximately 1.5 years for the new PBR was calculated. Volume throughout increased from 33.33 Liters per square meter to 184.0 Liters per square meter. Ergonomic traits such as safety risks, portability and measuring capabilities were also improved.

INTRODUCTION

This project, in partial completion degree requirements for a Bachelors of Science in Industrial Engineering, has been performed to produce an improved Photo Bio Reactor system (PBR) with involvement from faculty and students from both the Food and Nutrition Science department as well as the College of Engineering. Several Professors at Cal Poly San Luis Obispo have taken the initiative and are currently conducting research on various algae strands and their potentials. The University currently holds one algae PBR to grow and produce the microorganism. The PBR is currently a small-scale platform used to grow algae in a series of transparent plastic tubes with an artificial light source. As carbon dioxide is fed through the tubing, small amounts of algae are mixed with water inside the tubing which is then pumped with a small pond motor. An entire harvest cycle takes approximately 3 days to complete and can vary depending on the strand of the organism [10].

As more in-depth analysis takes place, larger quantities of algae will need to be produced for further experimentation and analysis. Consequently, there is a demand for a photo bioreactor design with greater volume throughput while decreasing production costs. The current system has multiple areas in need of improvement including, but not limited to, better maintenance safety, increased portability, increased volume capability, decreased labor costs, and greater measuring capabilities. It is hoped that adding these features will improve research capabilities in the long-run.

OBJECTIVES:

- Investigate current PBR designs and systems used in industry and identify the components necessary for a fully-functional system
- Critique and evaluate the current system while identifying the causes for any of the defects within the current system
- Design a "bread board" or prototype system that reduces if not eliminates most of the issues encountered with the current system used by the Food and Nutrition Department. The design should be within the Research Grant's budget and be completed by the end of the Spring 2013 quarter

- Build and test the system. Identify any issues that must be reworked or fixed.
- Document the final results

The project will consist of one undergraduate Industrial Engineering student, one graduate Bio Chemistry Engineering student, one Environmental Engineering Professor, and one retired Food and Nutrition Professor with an emphasis on algae growth. Knowledge regarding growing conditions and biological factors necessary for proper growth of the algae will be based primarily on the expertise of the professors along from previous knowledge from the Bio-Chemical Engineering student. The team will thoroughly research the topic to gain insight on current methods of algae cultivation as well as successful PBR designs.

Industrial Engineering skillsets should be used to help accomplish this project. Systems engineering tools such as A3 thinking and Ishikawa (Fishbone Diagrams) should be utilized to evaluate the current system and identify root causes of problems for the system. A cost analysis of the current expenses in terms of time and money required to maintain the system should be performed to justify any changes implemented in the new design. If applicable, time studies may be applied to measure the amount of time necessary to clean and setup the system. Concepts in Human Factors should also influence the new design proposed in terms of instrument usability and safety hazard reduction. Ultimately, project management tools will need to be used to ensure proper communication amongst the team and those tasks are completed in a timely manner. Design of Experiments methodology may also be incorporated if necessary to test certain parts of the system.

It should be noted that this project consists only of the re-design of an existing functioning PBR system. Industrial Engineering practices and theory will be used when applicable to design and build an improved prototype of the old system. With that being said, no post-analysis regarding optimal maintenance and/or harvesting methods after the system is built will be performed. In addition, the system was built following extremely basic physics principles. This was due to limitations on resources, time constraints, and the small number of students involved in this project. However, this allows opportunities for potential future Engineering Senior Projects in the case that the system was to be further improved.

DELIVERABLES:

- Plan, design, build, and analyze a functioning Photo Bio Reactor
- Documentation of areas in need of improvement
- A report describing all of the steps taken and methodologies used during the project

BACKGROUND

Algae growth and research may be the key to developing the next generation of crude oil and highly nutritious animal feed for livestock. The great health benefits associated with this unique microorganism make algae a potential cure for certain diseases and sicknesses. Talks about developing the next big bio-fuel have become very popular topics as fossil fuels start to become depleted. Farmers continue to look for natural and nutritious feed for livestock in order to produce quality products without the use of hormones. There have been a series of universities including University of California San Diego (UCSD), Texas A&M University, and Massachusetts Institute of Technology (MIT), conducting research on this abundant plant often found in ponds, swimming pools, and streams. Once dried and condensed, a meal full of nutrients can be used for various purposes. Crude oil can also be obtained as a by-product during this same process.

Algae as a Promising Resource in the Near Future:

Cultivation of algae for human use has been an ongoing process since the early 1950's. This photosynthetic microorganism has been deemed a very powerful resource due to its health benefits when consumed as well as its potential for crude oil production. Both the Chlorella and Spirulina strand of algae have become of interest to researchers due to their ability to thrive in bodies of water with a high saline content. This characteristic makes these two abundant forms of algae highly attractive with the ability to grow in ocean water in comparison to other algal types which require fresh bodies of water. Fortunately, Spirulina and Chlorella are the 2 most common forms in the world. [10]. The focus of this project will be directed at modifying a photo bioreactor in order to improve growth conditions for the Chlorella strand.

Health Benefits of Chlorella:

According to the online article "Secrets of Longevity" algae is considered the "world's number 1 source of chlorophyll" containing more of the "plant blood" than most other photosynthetic organisms [12]. This unique property of having a larger concentration of chlorophyll allows the plant to flourish and grow very rapidly under favorable conditions. A single cluster can

quadruple in volume within 24 hours making it the fastest growing crop on earth. Algae has often been labeled a "detoxifying super food" with known capabilities of "naturally detoxing people form radiation exposure, heavy metal poisoning, as well as chemical toxicity from various pesticides, herbicides, fungicides, etc" [12]. Scientific studies have also shown that consumption of Chlorella can produce regenerative and anti-aging effects within the human body.

A unique characteristic of chlorophyll is its biological structure being so similar to red blood cells found in other living creatures. This close resemblance in cell structure allows it to be easily transformed into red blood cells making algae consumption very attractive to people suffering blood issues.

Few small firms have started marketing concentrated chlorella as a daily supplement for human consumption. These are often sold as "cracked wall chlorella" in which the cellular walls have been broken in order to allow absorption of vitamins during digestion. A single tablespoon contains 100% of the daily value (DV) of Vitamin C, Vitamin E, all known B vitamins, magnesium, potassium, zinc, iodine, 120% DV of Iron, 320% DV of Calcium, trace minerals, Omega 3 Fatty Acids (ALA, DHA, EPA), nucleic acids (RNA/DNA), as well as enzymes [12]. Trace minerals and omega 3 Fatty Acids are often said to only be found in organisms found in the sea including fish and other aquatic life species [11].

Algae in Bio Fuels and in Sewage Treatment:

With rising gas prices and the depletion of fossil fuels, researchers have been seeking alternative ways for powering modern transportation. Bio fuels are broken into two main categories: bioethanol and biodiesel. Bioethanol is commonly produced from crops but requires a good amount of labor for cultivation of the plants. Biodiesel is derived from vegetable oil but requires less labor than the former. Biodiesel is considered more environmentally friendly since glycerin, the waste resulting from biodiesel production, can be utilized in soaps whereas the original meal from crops in bioethanol production must be dumped into a landfill. Algae, once utilized for fuel, would fall into the biodiesel category [3].

The quantity of oil that can be obtained from algae is determined by the lipid content of the collected biomass. Lipid content is affected by the growing environment of the crop and includes factors such as light penetration/distribution, temperature, carbon dioxide input, water velocity, and nitrogen content. The development of an improved photo bioreactor will allow the user to change and monitor these settings in order to determine the best growing conditions for algae on a large-scale basis [10].

Cultivation of algae for fuel production is very promising with benefits including renewability, sustainability, widespread availability, and the bio mass being biodegradable. Algae production is extremely efficient due to its low input and high yield characteristics. The organism “can produce 30 to 100 times more energy per hectare compared to terrestrial crops” according to an online article titled “Energy from Algae” [8]. Another recent article on algae states that “Some companies are reporting that they can produce up to 6000 gallons of fuel per acre per year (gal/ac/yr) from algae, even though they’re not yet operating on a large scale. In comparison, palm yields 650 gal/ac/yr; canola, 150 gal; and soy, 50 gal.” [13].

A huge benefit seen with large-scale production of algae would be the decrease in greenhouse gases in the atmosphere due to the carbon dioxide requirement in photosynthesis. Sewage water could also be utilized to a certain extent to assist in the growth of algae while reducing the amount of harmful waste dumped. A report found on the Oilgae webpage states that “Algae are an important bioremediation agent, *and are already being used by many wastewater facilities*” [2]. An article written back in 2007 titled “Oil from algae? Scientists seek green gold” claimed that “an algae farm could be located almost anywhere. It wouldn't require converting cropland from food production to energy production. It could use sea water. And algae can gobble up pollutants from sewage and power plants” [18]. Other articles have claimed similar prospects and say “because algae consume CO2, algae companies plan to link up with power plants, cement factories, and other industrial plants to capture heat-trapping CO2 that would otherwise waft into the atmosphere” [13].

Algae and the benefits of a growing demand for animal feed:

Although it is possible to produce biofuel from algae cultivation, the process is neither easy nor cheap. Failure to find an inexpensive extraction process without harming the environment is perhaps the biggest reason why we still have not seen algae fuel at our local gas station. Algae must be dried before collecting oil which requires a large amount of heat. Next, the cellular walls must be broken in order to collect the lipids which would then become the oil. Production of algae in a closed environment is preferred over an open system due to contamination issues but is much more costly due to the materials requirement [13]. In the article "Algae: Fuel of the Future", Doug Henston, CEO of the start-up company Solix Biofuels, says, "Closed systems have shown over time that they have significant yield benefits and merits over open ponds." But others maintain that enclosed growth systems, commonly called "photo bioreactors", are far too costly to make algae competitive with fossil fuels. In addition to production costs, Polle notes that it's equally important to consider the energy balance of building enclosed systems. "Even if a photo bioreactor is 100 times more productive than an open pond, does it then work out in the economics and the energy balance?" says Polle. "All of the materials that go into a photo bioreactor cost energy to make." [13]. With these aspects in mind, algae production purely for the collection of oil does not seem to make sense economically due to the high price of processing.

However, there have been ideas of utilizing the remaining biomass as a highly nutritious meal for livestock. Dr. Brian Hampson, a retired Food Nutrition and Science Professor from Cal Poly, thinks "algae meal may contain approximately 20 times as much protein and nutrients than most other animal feeds currently on the market" [10]. Recent rising prices for animal feed have led to a decrease in livestock sustainability; thus, driving up the price of red meats and other dairy products. Algal feed may offer a solution by providing a cheaper yet healthier alternative to farmers across the country. Algae cultivation for the production of animal feed while collecting green crude oil as a "co-product" may provide a justified reason for full-scale algae production [10].

Another article claims that "microalgae also play a key role in high grade animal nutrition food, from aquaculture to farm animals. Comprehensive nutritional and toxicological evaluations have

demonstrated suitability of algae biomass as a valuable feed supplement or substitute for conventional animal feed sources. In addition to its importance in aquaculture, algae were reported to contain up to 5–10% of proteins which can directly be used to replace conventional protein sources in poultry feed" [11].

LITERATURE REVIEW

Pond Production vs. Current Photo Bioreactor Design:

Although open pond systems were once believed to be the solution for large-scale algae production, the high risk of possible contamination from other organisms as well as uncontrollable weather environments becomes an issue. Maintaining a clean environment for the culture is paramount when extracting the nutrients for pharmaceutical and other consumer goods. Another problem associated with open systems is the high surface area requirement for a low volume of output. Since sunlight penetrates only the top of a body of water, algae will typically only grow 2-3cm below the water surface. This creates another downfall as a large amount of land would be required for such a small volume of algal mass. [16]. It has also been observed that maintenance for large open bodies of water is very costly.

With these problems associated with outdoor production, scientists and researchers have shifted the mode of algae production from open systems to closed environments. These closed systems have led to the development of a machine known as a “Photo Bioreactor” which holds a variety of benefits over the traditional “pond growing” methods mentioned earlier. These devices are believed to be the solution for a large-scale production of algae.

The creation of the “Photo Bioreactor” (often called PBRs) is a relatively new concept. The purpose of the machine is to grow and nourish algae in a closed and controlled environment. A PBR essentially mimics any other growing environment where algae can be found. A simple PBR typically consists of a series of connected transparent modules or tubes containing water and algae. Algae are grown in the lab in small quantities where it is then dispersed throughout the PBR system in order to continue growth. The use of transparent modules is required in order to allow sunlight or UV light to enter the system where photosynthesis can occur. These modules are then fed various gases often through some sort of gas apparatus or pump. The pumps usually expel a combination of Carbon Dioxide and air which contain all of the necessary gases for algae growth. Gases required include Oxygen, Carbon Dioxide, and Nitrogen [16].

The pump also serves to transport the algae mix throughout the tubes in the system which then helps disperse gases and promotes algae growth. Two modes of transportation currently exist for

PBRs: horizontal and vertical flow. Horizontal flowing systems have tubes in a horizontal array and have a snake-like flow from side-to-side. These systems usually require a powerful pump to "push" the algae water throughout the system and are more expensive to operate than a vertical-flow system

A vertical-flow system consists of tubes standing in an upright fashion. A benefit to this style of setup is the "airlift" effect created when gas bubbles are pumped from the bottom. As gas enters through the bottom, small bubbles rapidly flow to the top carrying small amounts of mass to the top. A currently successful design is to have tubes paired off in sets of 2. One tube is fed gas from the bottom to create the elevator effect which carries algal mass to the top. At the top of the gas tube, a downward incline connecting the 2 pipes allows the mass to "spill down" into the next chamber. The mixture then falls to the bottom using gravity where it will then connect to another tube powered by a gas pump. The cycle then repeats itself in this fashion until a complete circuit is achieved. A summary of the conditions of the current system are listed as follows:

Liquid Volume Capacity and Ergonomics

Currently, the system uses long 2" diameter plastic sleeves as tubing. Pros of the current tubing material include being cheap, easy to replace, durable, and transparent enough to allow photosynthesis to occur. On the downside however, these tubes are relatively small in diameter limiting the growth potential of the algae and vastly decreasing the volume of biomass output compared to other current PBRs. The use of non-rigid plastic sleeves also prevents many measuring devices from being connected to the system.

The current system also has the issue of hovering approximately 10 feet above the ground. While increasing height does increase the volume capacity of water throughout the system, this results in a height often too tall for people when inserting algae culture into the system. Because the mixture is inserted through an opening at the top, this can be difficult, if not dangerous, when individuals climb a ladder to insert the large quantity of culture. To make the system safer, the new growth modules are not to exceed 6 feet in height. This is to make culture addition easier for people servicing the system.

System Frame Structure:

Another major area for improvement will be the design of the frame holding the entire system. The current PBR has a major flaw of being unbalanced and is supported by cables from the ceiling. This structure had toppled once in the past due to an unbalanced weight distribution and a poor frame design. Fortunately nobody was injured because the growth modules were made of soft plastic sleeves. Had these modules been made of glass or another solid material, the consequences could have been lethal [9]. Because the new system will have rigid plastic modules instead, it is important that the frame will be stable and capable of holding a heavy load.

Gas Diffusers:

By switching to a diffuser with smaller bubbles, the algae can be mixed more thoroughly providing a better dispersion of gases. This would result in improved growth since nutrients are scattered more appropriately. Smaller bubbles also travel upwards more slowly which would cause the biomass to flow but at a speed that is not destructive to the algae microorganisms [24].

DESIGN

The idea of doing a senior project on PBR design actually sprouted several years back after seeing several tubes full of green slime in the same facility during a Process Improvements Project with Cal Poly Chocolates. Years later, a little networking along with a simple email inquiring about the tubes led to contact with several professors at Cal Poly involved in algae growth and research. The issues they addressed with the PBR's functionality and capabilities at the time quickly evolved into an opportunity for a senior project.

Original PBR Characteristics and Issues

The PBR system towered approximately over 3 meters in height and lay about 3 meters across and 1 meter in depth. A large 12-inch wide gas manifold at the bottom would feed gas into long 9-feet x 2-inch wide plastic sacks. These sacks would then connect to another large manifold at the top which would hang from a series of cables attached to the ceiling. A close up of these algae containing sacks can be seen in **Figure 1**. Fluorescent lights backed by reflective foil would hang behind all the tubes stimulating algae growth. Inside the sacks were bright green mixtures containing water and algae. Although appealing to the eye, the large system poised a major safety hazard when students had to climb a ladder in order to drop in algae cultures from the top. Occasional leaks from the system usually meant wet and slippery floors around the area making utilization of ladders extremely risky. The size of the structure along with its very elongated shape made the system prone to toppling over during maintenance and harvesting. A photo of the original PBR is shown in **Figure 2**.

Figure 2. Close up of plastic sack used in former PBR

Figure 1. Photo of original PBR

The use of non-rigid plastic sacks holding the algae posed a major problem as it prevented certain instruments from being used in order to measure and monitor the growing environment. Use of instruments become critical when monitoring growing factors such as pH levels, temperature, light intake, turbulence, and pressure. The system's behemoth size also made it very difficult, if not impossible, to transport and relocate. This prevented testing and researching growing conditions in new environments such as outside near lakes and docks. The sizes of the components in the system also made it very difficult to take apart, clean, drain, and repair the system resulting in a very high labor cost. The idea was to design and build a modified prototype that would reduce if not eliminate these issues. The completion of the entire project from planning and design to purchasing and assembly would span across 3 quarters. Each action taken throughout the project will be summarized and separated by quarter throughout the rest of the Designs section. Details regarding the actual process, analysis, and methodology taken for each step will be highlighted in the Methods section.

Quarter I: Fall 2012

Building Versus Purchasing:

The concept became an actual Senior Project after meeting with Dr. Brian Hampson and Dr. Yarrow Nelson who then mentioned another Graduate student looking to finish his thesis on algae growth and testing. The project would provide an opportunity to use Industrial Engineering concepts to improve a system process while enabling cheaper and easier algae growth for future research. The project would also allow Professors involved to utilize an unclaimed science research grant at the University. Although it would have been possible to use the research grant to purchase a professionally constructed PBR from Industry, these systems are difficult to place a price tag on due to the complexity of each system. A quote for a pre-constructed 100-Litre system kit with the required characteristics, measuring devices, measuring software, and hardware would cost around $50,000 - $100,000 [18]. The exact dollar amount of the research grant will not be listed for privacy purposes but was significantly less than the required funding needed to purchase a fully-functional PBR. In general, the concept and development of PBRs is relatively new and the opportunity to build a basic fully-functioning PBR from scratch calculated to be more beneficial for several reasons:

- Building a PBR from scratch would be SIGNIFICANTLY cheaper than purchasing one
- The PBR could be custom-built whereas such features would have cost more when purchasing one through a manufacturer
- Defining specs and having an outside company design a system for the school becomes a copyright issue as the manufacturing company holds rights to the design. The users of the PBR system do not wish to pay for copyrights on a system in the case that more PBRs are built in the future.
- Building a PBR from scratch is parallel to Cal Poly's philosophy of "learn-by-doing". This generates several opportunities for senior projects, thesis topics, as well as other University research projects.

After deciding to build the PBR from scratch, the team decided to do research on current PBR designs and identify any major components necessary for a functioning PBR system. Most cultivated algae grown in PBRs are grown using either horizontal or vertical systems. Horizontal systems are much less energy efficient due to the larger amount of energy needed to "push" water across the pipes. A horizontal system is shown in **Figure 3**.

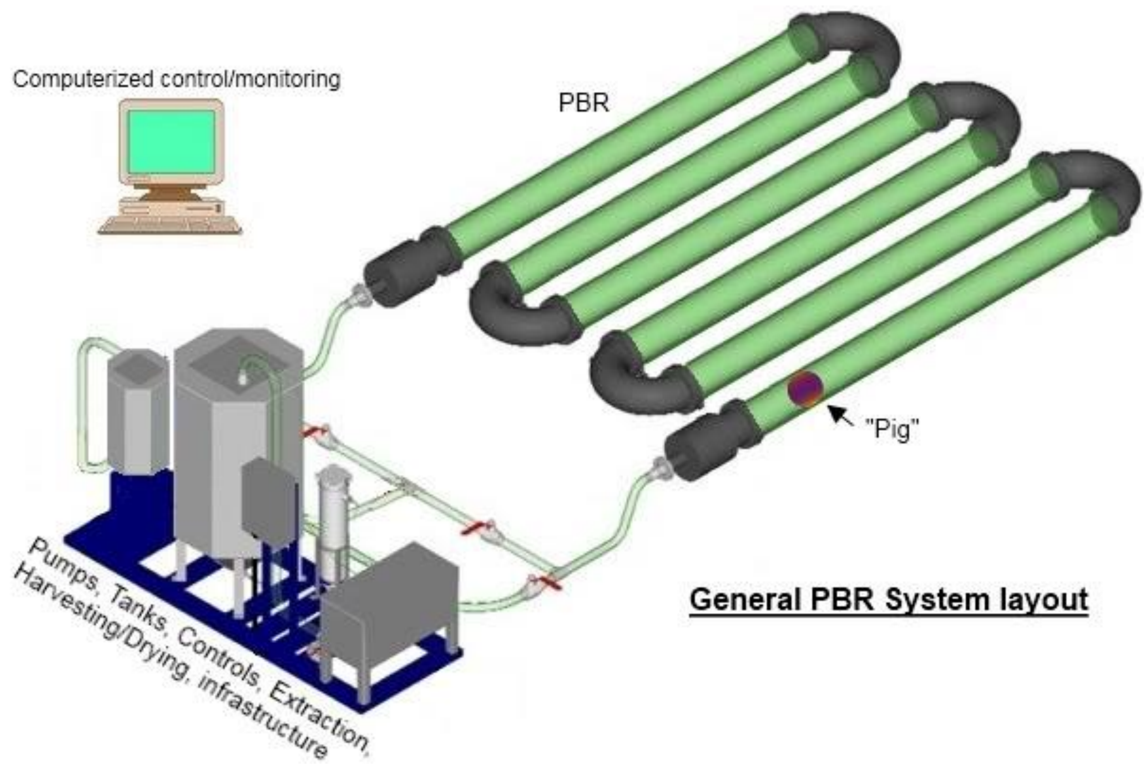

Figure 3. Horizontal Flow PBR. *Courtesy of MarketPlayground.com* [23]

A vertical system uses an “airlift” type of mechanism where bubbles are dispersed at the bottom of each tube and push biomass to the top. Once reaching the top, algal mass falls and spills down into another column of tubes and is cycled throughout the system in this fashion. An example of a vertical lift system is shown in **Figure 4**. The former PBR utilized a vertical lift system and the same was chosen for the new PBR over a horizontal system for cost reasons. After doing some research on other PBRs, it should be noted that vertical systems are much cheaper to operate as they utilize basic physics principles of buoyancy to have material float to the top rather than requiring energy and force to push water through the system. Because physics states that energy must be conserved, water in a series of columns or tubes will minimize potential energy by keeping a constant water height throughout the system. A simple sketch of this concept is shown in **Figure 5**.

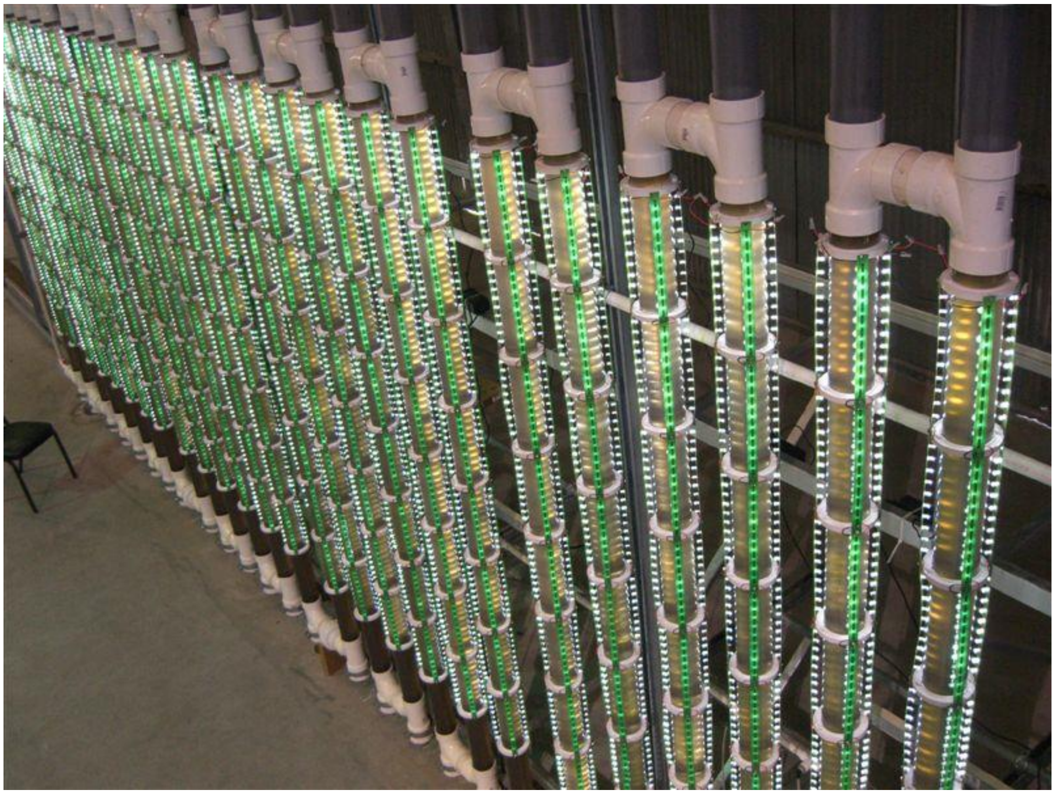

Figure 4. Vertical-Lift PBR System. *Courtesy of Oilgae.com*[1]

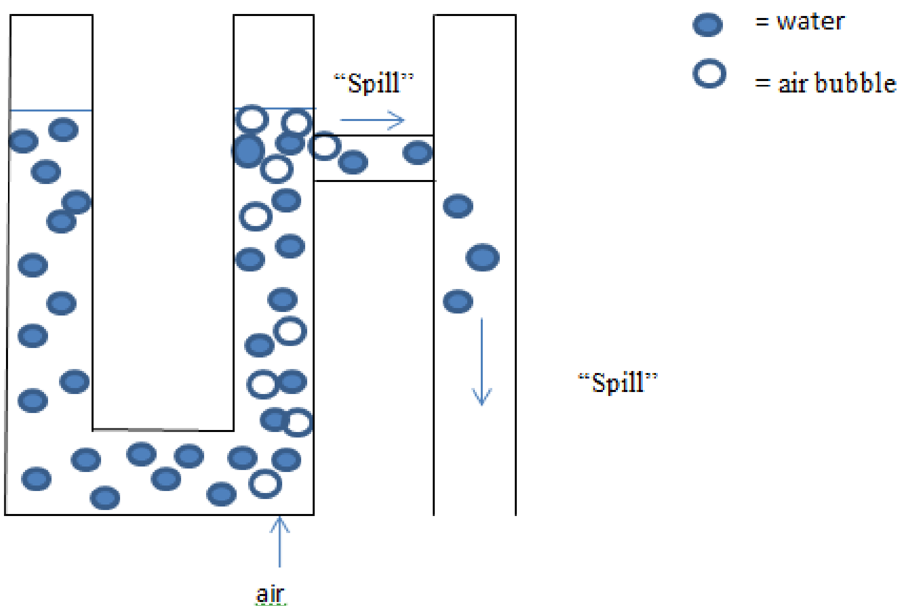

Figure 5. Basic fluid mechanics of a vertical PBR System

Necessary Parts List:

A fully-functional vertical-flow PBR requires the following basic parts to flow properly:

- Air pump(s)
- Gas diffusers
- Tubes or pipes for air/gas to flow to the diffuser
- Containers or vessels for holding water or algae culture
- PVC plastic elbows to connect tubes
- Rigid structure or frame for system stability

These are the basic necessary components for an operating PBR without any algae in the system. Lighting modules would also be needed for proper algae growth but were beyond the scope of building the main PBR system. Due to time constraints, these parts were regarded as non-essential and could easily be added later if necessary.

Scheduling:

Meeting times were also established during the beginning of the in order for the team to meet and touch base regarding project progress. Throughout the project, the team would meet at a minimum of once a week to ensure that objectives were established and being met. A series of GANTT Charts would be used for the remainder of the project in order to ensure deadlines were met and objectives were achieved. However, during the project, there would be multiple times where plans had to change due to limited access to certain parts and resources. These GANTT Charts can be found in the **Appendix** section of the report

Analysis and Ergonomics of Original PBR:

A cost analysis was performed on the current system to identify activities that required the most resources. A basic Pareto Chart analyzing the current PBR operating times can be seen in **Figure 6**. After comparing overall costs for each type of activity, initial setup and harvesting ended up being the most difficult procedures and thus the most costly. Setup consisted of attaching algae vessels, tightening and securing components, filling the system with water, and inoculating the system with algae culture. This was the setup time for only one worker. With that being said, a

strong emphasis was placed on ease of use, portability and safety making these the key points of the project.

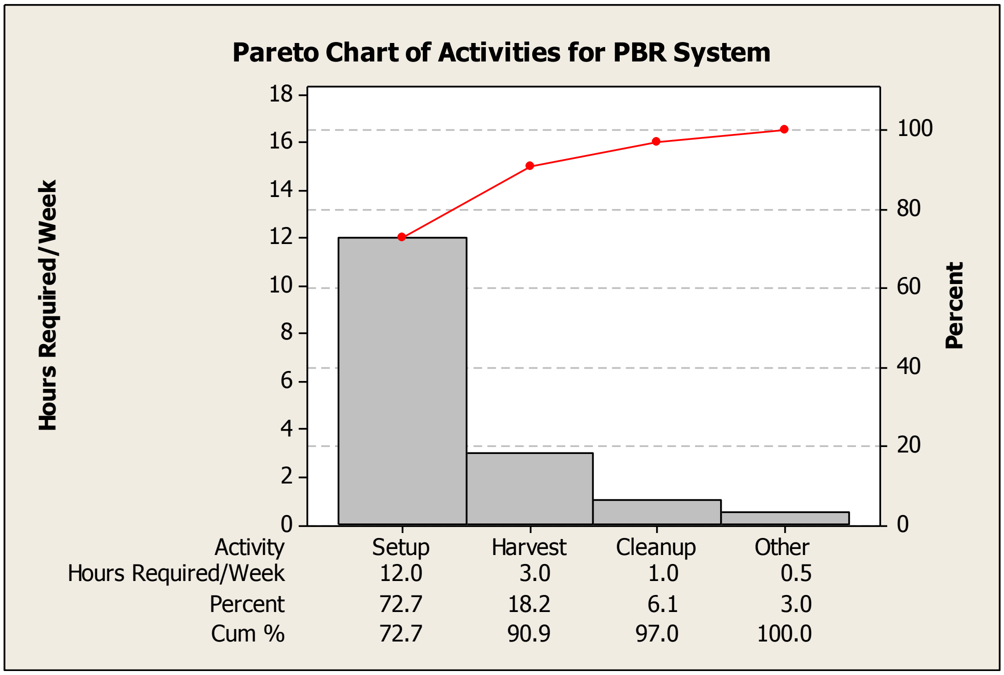

Figure 6. Pareto chart of Activities for PBR System

Shrinking the overall size of the system became an inevitable task in order to make servicing and maintenance much safer. The new system would have to be more stable and become less prone to falling. That is, the center of gravity would have to be lowered by reducing the height of the system and creating a more stable base. By decreasing the height to that of an average human being, an appropriate height not to exceed 6 feet was established. This would hopefully get rid of the need for ladders during servicing and harvesting and reduce any hazards associated with falling or toppling.

Portability was another major concern for the new system. The ability to load the system into the back of a pickup truck or two and drive to its new destination for outdoor testing was paramount. The dimensions of the bed of a standard pickup truck were measured and came out to exactly 8 Feet x 4 feet or 32 square-feet. With that being said, an initial size parameter was to not exceed 8 feet x 8 feet. The idea was that the system could be dismantled into two 4 feet x 8 feet halves and each be placed into one truck each if necessary.

The ability to properly load the system without any need of special equipment became another important factor. The PBR should be able to be moved without any cranes and would be able to fit into a standard elevator if needed. Building 13 on the Cal Poly campus used to be the home of an older PBR until a storm knocked it over and destroyed the system. By utilizing an elevator within the building, it was hoped that moving the system up several floors could be done with ease. The elevator dimensions were also measured and came out to be 8 feet long, 6 feet wide, and 7 feet tall. The width of the doors measured to be 4 feet wide with a height of 6 feet. A diagram of the elevator in Engineering 13 is shown in **Figure 7**. This still enabled the initial plan of building an 8 feet x 8 feet system with each half of the system being loaded onto the elevator separately.

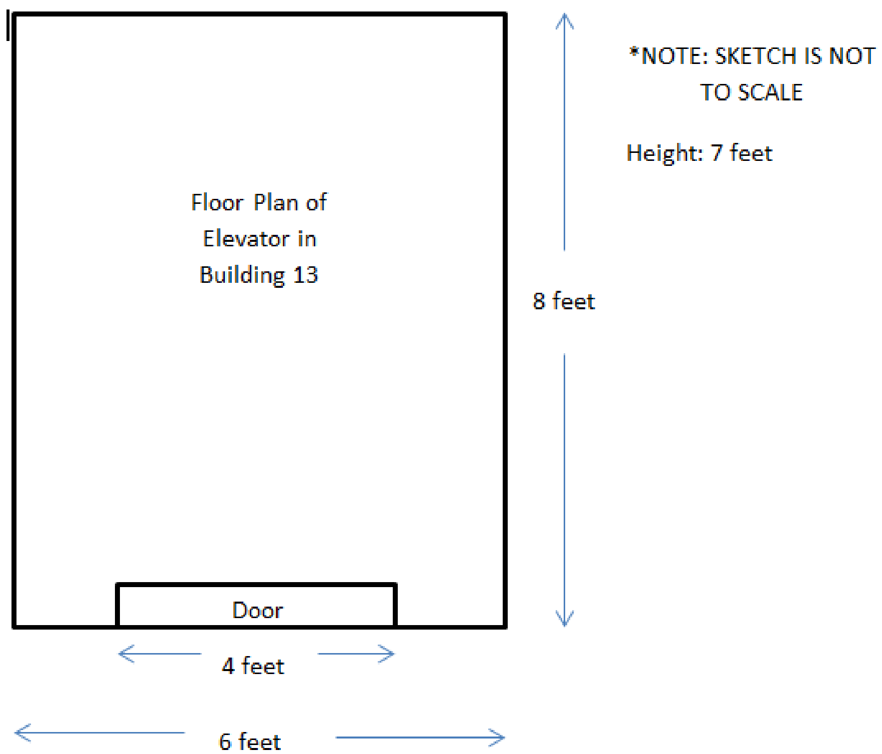

Figure 7. Floor plan of Bldg. 13 elevator

As far as loading onto trucks, the system could be loaded via 2 ways as shown in **Table 1**.

Table 1. Forklift Capability Analysis

Method	Pros	Cons
Load with a pallet jack or fork lift while assembled	Easiest and quickest mode of transportation	Places a size constraint on the overall PBR dimensions. System frame design has to be “forklift” friendly.
Dismantle before loading. Load by hand.	Allows more flexibility with PBR size	Not as convenient as the first option. Requires more time for assembly and disassembly.

The team has already performed measurements in order to calculate dimensions needed to fit into the back of a pickup truck bed as well as into a standard elevator car. A large basis of this project revolved around portability. To follow the second option would defeat the whole purpose of being portable and result in more headaches than necessary. It would ultimately increase labor hours and costs needed to assemble and disassemble to system. The decision was to make transportation and loading convenient and make the prototype moveable by utilizing standard pallets at the bottom.

Water and Algae Volume Capacity:

As mentioned before, the tubing diameter would be expanded from 2” to something larger in order to boost the volume throughput of algae. Five inches would have yielded the most volume throughput without sacrificing photosynthesis from lack of light penetration. However, research showed that a larger diameter requires more plastic and drastically increases overall cost for parts. In addition, research on different items revealed that 3” is the standard size for plastic PVC elbows. Elbows larger than 3” would have to be custom-ordered and would end up costing significantly more than its 3” counterpart. Additionally, the custom-order would have taken longer to get delivered placing a longer lead time before the project could be assembled. A complete set for 3” tubes and PVC elbows also proved to be within the budget of the Research Grant. A cost analysis for the various sized plastics researched is shown in **Table 2** below. Although 5” yielded the optimal cost per liter of fluid, the total cost was beyond the budget of this project. Larger size tubing also meant heavier materials which would have made the project less ergonomic during maintenance. As a result, 3” tubes were chosen.

Table 2. Optimal Plastic Tube Sizing Analysis

Item	Quantity Needed	Fluid Volume (L)	Unit Cost ($)	Total Cost ($)	Cost per Liter
3” Diameter Plastic Tube	20	5.56 (per 4’ Column)	12.37/ft	247.40 (per 80 feet)	*
Corresponding Size PVC Elbow	20	*	24.35	487.00	*
Total for 3” Tube “Set”	*	*	*	**734.4**	**6.61**
4” Diameter Plastic Tube	20	9.88 (per 4’ Column)	Approx. 22.00/ft	440.00 (per 80 feet)	*
Corresponding Size PVC Elbow	20	*	Approx. 37.00	740.00	*
Total for 4” Tube “Set”	*	*	*	**1180**	**5.97**
5” Diameter Plastic Tube	20	15.44 (per 4’ Column)	Approx. 29.00	580.00 (per 80 feet)	*
Corresponding Size PVC Elbow	20	*	Approx. 55.00	1100.00	*
Total for 5” Tube “Set”	*	*	*	**1680.00**	**5.44**

At this point in the project, the number of tubes to be used in the system was not yet established. Testing and advances in the overall design would have to be made in order to identify the ideal number of tubes placed in the PBR.

Research Grant Deadline Creates Complications:

Unfortunately, the Research Grant which had been awarded to this project in late-October had an expiration date before January 1st of 2013. As a consequence, funding had to be spent before the end of the 2012 academic year resulting in a very rushed order of parts. As a consequence a general Process Flow Diagram of the Assembly Procedure was created. This Process Flow Diagram is shown in **Figure 8**.

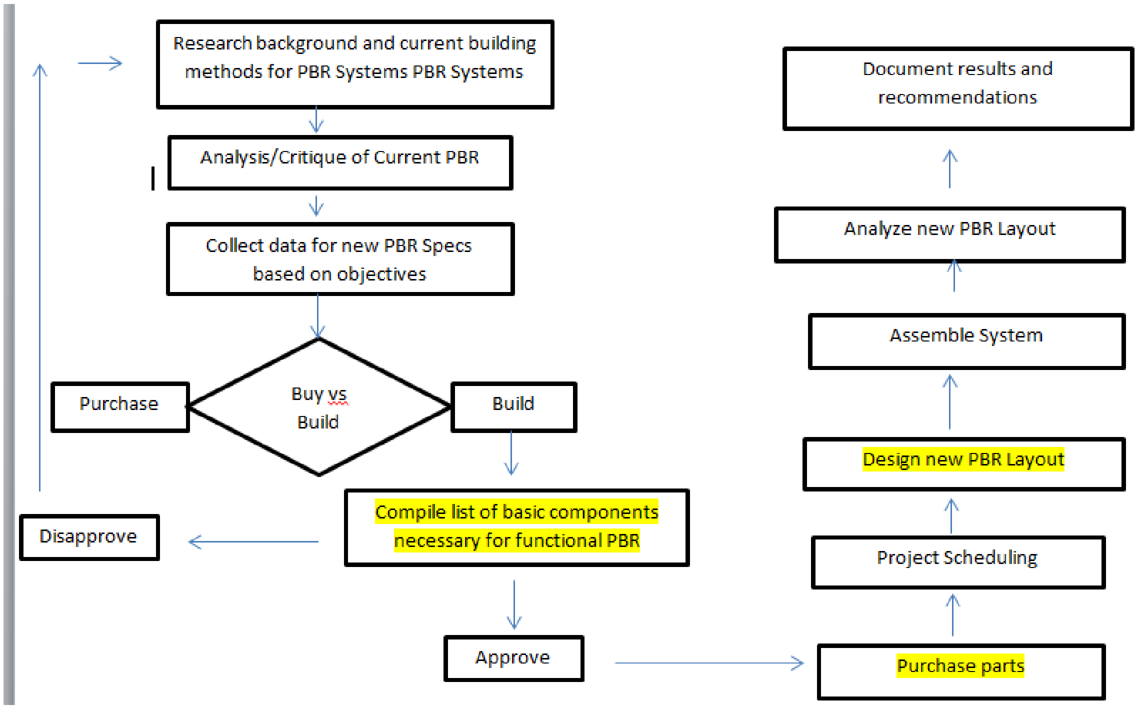

Figure 8. Process Flowchart of PBR Project

Parts were researched as much as possible until several vendors were picked. A list of the different vendors and their characteristics is shown in **Table 3**. After much calling and receiving several quotes, the team decided to purchase the cheapest parts which provided the most basic functionality. As a result, parts were purchased from different companies. The parts were then ordered by the professors in late November and were chosen based on a combination of the major parts list compiled earlier and previous knowledge obtained through PBR showcases where they learned about assembly techniques for the PBRs. More time for proper research would have been beneficial but the short window frame to determine parts and vendors forced the team to a purchase rather quickly. This was the only way to guarantee any hardware for the project before the funding disappeared.

Table 3. Supplier Analysis

Supplier/Company Name	Characteristics	Cost Rating
Grainger	Specialty Products regarding plumbing and water parts.	$$$$
Solar Components Corporation	Specializes in PBR Components. Parts can be made to order. online only	$$$
U.S. Plastics.Com	Sells basic PVC and PET Plastic parts. Online Only	$
GrayLineInc.Com	Large variety of Plumbing and water project parts. From different country and involves long lead times	$$

After doing as much research on pricing and quantities, the team initially decided to order the following items listed in **Table 4**.

Table 4. Initial Parts List

Part	Quantity	Unit Price ($)	Total Cost
Silicone Paste Tubes	20	5.00	100.00
12” Diameter Conical Tanks (4’ Height)	8	375.00	3000
12” Conical Tank Friction Fit Caps	8	22.00	176
9” Gas Diffuser Pads	8	21.14	169.12
3” PVC Elbow	20	9.28	185.6
3” PVC Elbow with 2” hole	20	15.07	301.4
Parker O-Rings (Pack of 20)	3	20.00	60.00
3” Diameter Harvel Plastic Tubes	80 feet	12.37/foot	989.6
3” Diameter Mailing Tubes	80 feet	2.66/foot	212.8

Certain parts were taken off of the old PBR and recycled. These parts included an air pump and any fluorescent lighting modules. A large quantity of silicone was ordered in hopes of being able to attach the plastic tubes to their associated PVC elbows. The idea behind buying large amounts of silicone occurred after Dr. Hampson spoke to other people at a PBR showcase event and was told that silicone was an excellent adhesive used for attaching parts together. Tubes were sold in batches of 20. Because the team had very little knowledge about calculating the ideal number of tubes to be used within the system, the team decided to buy the minimum amount in a batch in hopes for later testing. A total of 20 Treated plastic Harvel tubes were ordered along with 20 vacuum-formed plastic "Mailing tubes". The idea behind ordering the significantly cheaper mailing tubes was to use them as a practice run before using the much pricier Harvel tubes.

At this point in time, the idea was to build 2 Photo bioreactors: one "test-run PBR" using the mailing tubes and a second with the Harvel pipes. Improvements and any corrections could be applied to the 2nd System after the first model was built and tested. To accommodate for all the initial 20 pipes, 40 elbows were purchased as well since an elbow would be required for each end. A total of 8 conical tanks were purchased: 4 for the PBR with the cheap plastic and another 4 for the ones utilizing the Harvel tubes. Once again the number of conical tanks per PBR had yet to be defined. These steps conclude the design work that took place during the Fall 2012 quarter.

Quarter II: Winter 2013

At the start of the winter quarter, the team had just received all of the parts ordered due to the Research Grant spending deadline. The team begins to discuss how the parts will become attached to each other and how the system should be assembled.

Initial PBR Layout Design:

After deciding a few basic dimension parameters during the previous quarter, the team had some ideas to play with. An initial plan consisted of using all 4 Conical Tanks with 5 smaller tubes accompanying each large Conical Tank. The idea here was to maximize the volume of water and algae. In other words, "More was better" was the concept of this design. The design consists of 1 Conical Tank connected to 5 smaller tubes in a snaking fashion. The tubes are all connected via series of elbows in which the water flows up and down through each smaller pipe until cycling

through the next conical tank. Each Conical tank is custom-built and contains approximately 112 liters or 29.5 gallons of water. Each small tube measures 4 feet long and holds 5.6 liters of water.

Two different arrangements were drawn out to accommodate for the sizing parameters established after measuring the truck bed and elevators The First Option featured a straight line formation of tubes in order to make tube and light placement easier and hopefully increase light exposure. The drawbacks of this design included requiring more space for the entire system. The second Option featured a “zigzagging” pattern between conical tanks to conserve space. The issue here would be proper placement of tubes during assembly to ensure proper alignment due to such an elaborate design. Another potential issue was despite saving space between conical tanks, light distribution to the outside vessels would be an issue since tubes on the insides would block light from the tubes on the outside. These initial drawings can be seen in **Figure 9** below.

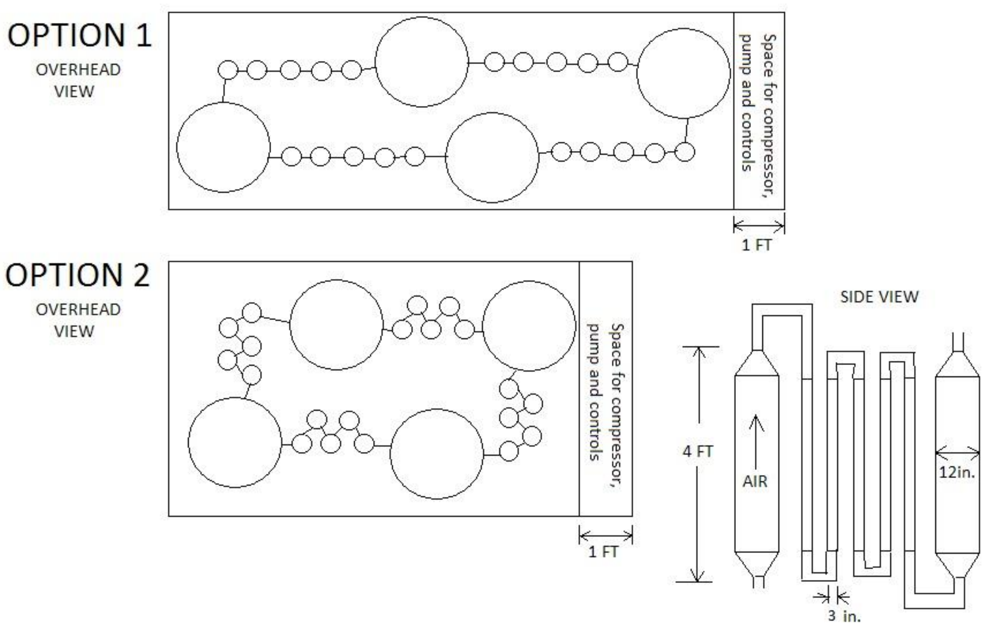

Figure 9. Initial Layout of New PBR System

Method1: Mailing Tubes and Silicone:

The team had ordered a large quantity of silicone after doing research and after one of the Professors had heard from word-of-mouth that silicone could be applied to attach plastic fixtures together. Silicone has many benefits including being cheap and resilient to water while providing flexible yet superior strength. Although the Harvel tubes and the Mailing tubes both spanned 3” in inner diameter, thickness had varied significantly. The Harvel tubes held a standard .25” thickness while the cheaper counterparts measured barely an eighth of an inch. This difference in

sizing created a major issue when attaching the “test-run” mailing tubes to the Plastic PVC elbows. The difference in diameter sizes resulted in a large misfit between plastic elbows and the tubes. As a consequence, some sort of filler needed to be applied inside of the gaps between the diameters. Keep in mind that buying better fitting tubes at this point was not an option since majority of the grant had been spent before the 2013 Academic Year. The game at this point was to build a system with the available tools and materials making the project a bit more challenging. After talking with the involved Professors about techniques on how to go about fixing this diameter difference, silicone seemed very promising.

The team decided to apply a thick layer of silicone using a calk-gun around one edge of each of the mailing tubes. After some experimenting, a special method was formulated in applying the silicone. This method involved applying copious amounts of silicone on the inside of the plastic elbow, then adding more silicone on the exterior wall about 2” up from one of the edges of the tubes. The mailing tube would then be inserted and twisted into the silicone-filled elbow until snug. Then, a final layer of silicone would be applied to the top edge of the elbow to “seal” any leaks that may become present later. An image showing this gluing process can be seen in **Figure 10** below.

Figure 10. Vessel Assemblies drying after silicone glue was applied

Because of the long curing time of the silicone, the elbows would simply fall off the tube unless they were positioned to dry properly. After a series of trial-and-error, utilizing metal stands, and trying to get the tubes to stand up straight the team decided to lay the tubes side-ways on a table with make-shift cardboard riser to keep the tubes straight. Duct tape is used to keep the tubes from moving on the table in order to conform to the desired shape before setting.

Testing and the Issues of Using Silicone Alone:

Once the tubes were dry, the team decided to test the tubes for any possible leaks. A single drying period for complete setting of silicone takes approximately 24 hours. A leak test was performed by plugging the opening at the bottom of the elbow with a rubber stopper purchased at a Hardware store. One person would hold the tube erect while the other would fill up the tube to the brim with a water hose. The goal was to fill each tube completely without spotting any visible leaks. This was often done either in a sink or near a drain. After several leak tests, the team was able to conclude that silicone alone was a poor method for attaching the tubes to the elbows. The silicone would simply give in to the water pressure at the joint of the tube and create small cracks where water would spew out. Applying Silicone to majority of the mailing tubes in the project was an extremely costly mistake and should have been performed on a single tube before applying to all of the tubes. Testing should have taken place on a smaller scale before applying the method to all of the assemblies. This was a harsh mistake to be learned from.

Method 2: Attempts At Sealing Cracks with Water Sealant:

After witnessing too many leaks with silicone alone, the team decided to attempt blocking the leaks with household supplies such as water-resistant sealant. The sealant was applied onto the outer edge joints of several tubes where the elbow connects to the mailing tube. After covering all of the silicone in sealant, the tubes were tested once more in the same fashion. **Figure 11** and **Figure12** show the tubes after sealant was applied. Unfortunately, leaks still persisted after this method. The leaks were so obvious that the technique alone was scrapped. The team continued attempting new methods until a solution that “worked” was achieved

Figure 12. Water Sealant applied to vessel

Figure 11. Water sealant applied to PVC Elbow Joint

Method 3: Using Duct Tape for Tube Rigidity:

After attempting to plug the holes with water sealant and failing, the team thought that a lack of structure and too much flexibility between the tubes and the silicone may have caused the leaks. Essentially, there was only a thick glob of silicone connecting the tubes to the plastic PVC elbows at this point. One of the members pulled on the tube only to realize that it could easily be slipped out of the elbow with little if any silicone residue stuck on the elbow. This showed that there was very little if any adhesion between the silicone and the elbows. **Figure 13** shows just how little adhesion there was between the elbow and the tube. The elbow practically created a silicone mold!

Figure 13. Photo of Silicone failure

After talking to the professors about the issue, the team was advised to research possible ways to get the 2 parts connected. One suggested talking to the owner of a local Fish Store called Tropix for any ideas on constructing water-tight assemblies. The owner was known for assembling his own aquariums using silicone and glass alone. After talking to the store owner, the team learned that silicone does in fact adhere poorly to PCV surfaces unless the plastic is sanded down beforehand. It was also mentioned to use O-rings in order to make the tubes water-tight and offer some sort of rigidity to prevent the tubes from flexing. Although great at preventing leaks, O-rings alone did not seem sturdy enough to support an entire column of water containing 5.6 liters of water from breaking off of the elbow. The bottom elbows had to be glued or secured onto the tubes. This news, combined with witnessing the lack of adhesion between the silicone and the PVC tubing, verified that the surface of the elbows should be sanded down before any gluing was performed.

A new technique consisted of applying water-proof tape on to the plastic tubes until a desired width was achieved. The team attempted removing the excess silicone on the tube but struggled miserably. In order to save time and maintain productivity, the tubes were flipped and tape was applied to the opposite end of the tube. An adhesive called “Frog-Tape” was used to wrap the tubes to achieve the required thickness. The tape served as an adaptor to help fit the tubes into the elbows while offering rigidity and snugness between the 2 parts. It is possible that the team could have ordered specially modified adaptors to serve this purpose but the dimensions were not standard and would have cost more money to have shipped. Time was another issue as ordering parts results in an increase in lead time for the finished product. **Figure 14** shows a tube with Frog Tape wrapped around the base.

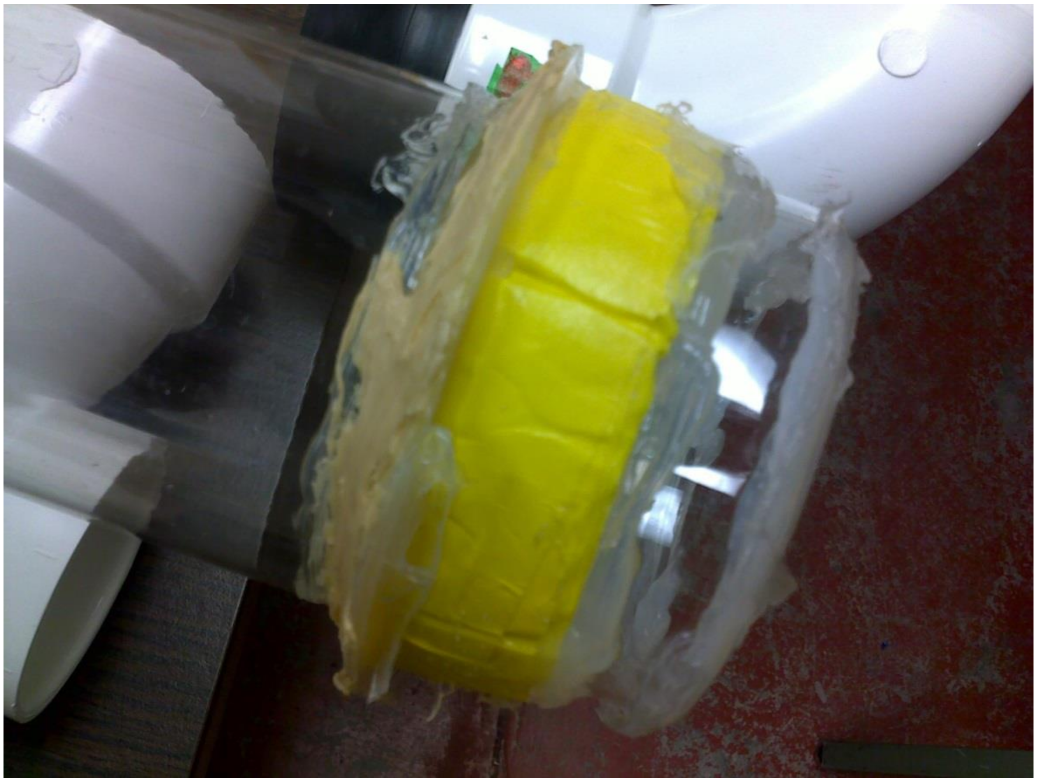

Figure 14. Photo of Frog applied to plastic tubing

A measurement regarding the exact length of tape applied to the tube was not taken. Rather, the total width of the tape between the outer diameter of the mailing tube and the inside wall of the elbow was measured. This width came out to be .25” per wall or .5” in terms of diameter. A sketch in **Figure 15** below helps explain this concept.

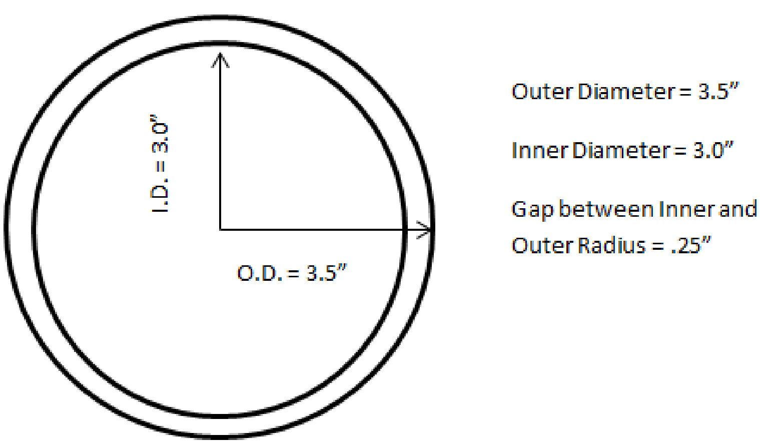

Figure 15. Diagram of PVC elbow gap

Once the tape thickness was measured, the tube would be test fitted into the PVC elbow for a snug fit. Tape would then be added or removed accordingly to achieve a nice fit. Once a tight fit was achieved, the interior of the elbow was sanded down with sand paper until a rough surface was achieved. Next, a thick bead of silicone was applied to the root edge of the tube just beneath the tape. The tube was then inserted into the elbow and set aside to dry. Once dry, more leak tests were performed. Once again the test yielded faulty results. Another method had to be performed.

Method 4: Tape and Epoxy Putty:

Because the tape method had failed, the team decided to try a stronger adhesive than silicone: Epoxy putty. Epoxy has many applications and is known for its incredibly strong bonding properties. After purchasing some Epoxy putty at Home Depot, Frog Tape was applied to the tubing in the same fashion as the earlier trial. This time however, epoxy clay was added to the edge instead of silicone. Because epoxy forms a strong chemical bind after mixing 2 separate ingredients, the clay had to be melded together before applying. This was a very-time consuming task as the clay was stiff and had to be thoroughly mixed. The tube assemblies were set to dry overnight and then leak-tested the following day. After several trials, the epoxy seemed promising but eventually failed as well. After comparing results, Method 3 seemed to be more effective in stopping leaks than this Method. An in-depth analysis regarding the effects of silicone is discussed in the Methods section of the report.

Using Ishikawa Diagrams to Identify Root Causes for Leaks

Several other tricks were attempted including using a rubber gasket instead of the clay but yielded the same poor results. In order to identify the reason for the leaks, an Ishikawa Diagram was utilized to identify any root causes for the leaks. The Diagram helped point out that leaks were due to several reasons. The biggest reason was use of a poor adhesive. Neither the silicone, the sanded PCV elbows, nor the clay allowed strong enough bonding. An adhesive which would permanently bond vacuum-formed plastic to PVC was needed to form a water tight connection. Another issue was the tape. Although Water Proof, tiny creases formed while applying the Frog Tape around the tube which would often allow small veins of water to creep through the structure. These cracks would expand as water pressure increased ultimately resulting on leaks. Another issue was the location of silicone. Silicone alone yielded very poor adhesion results and structural support to the PVC. The corresponding Ishikawa Diagram can be seen in **Figure 16**.

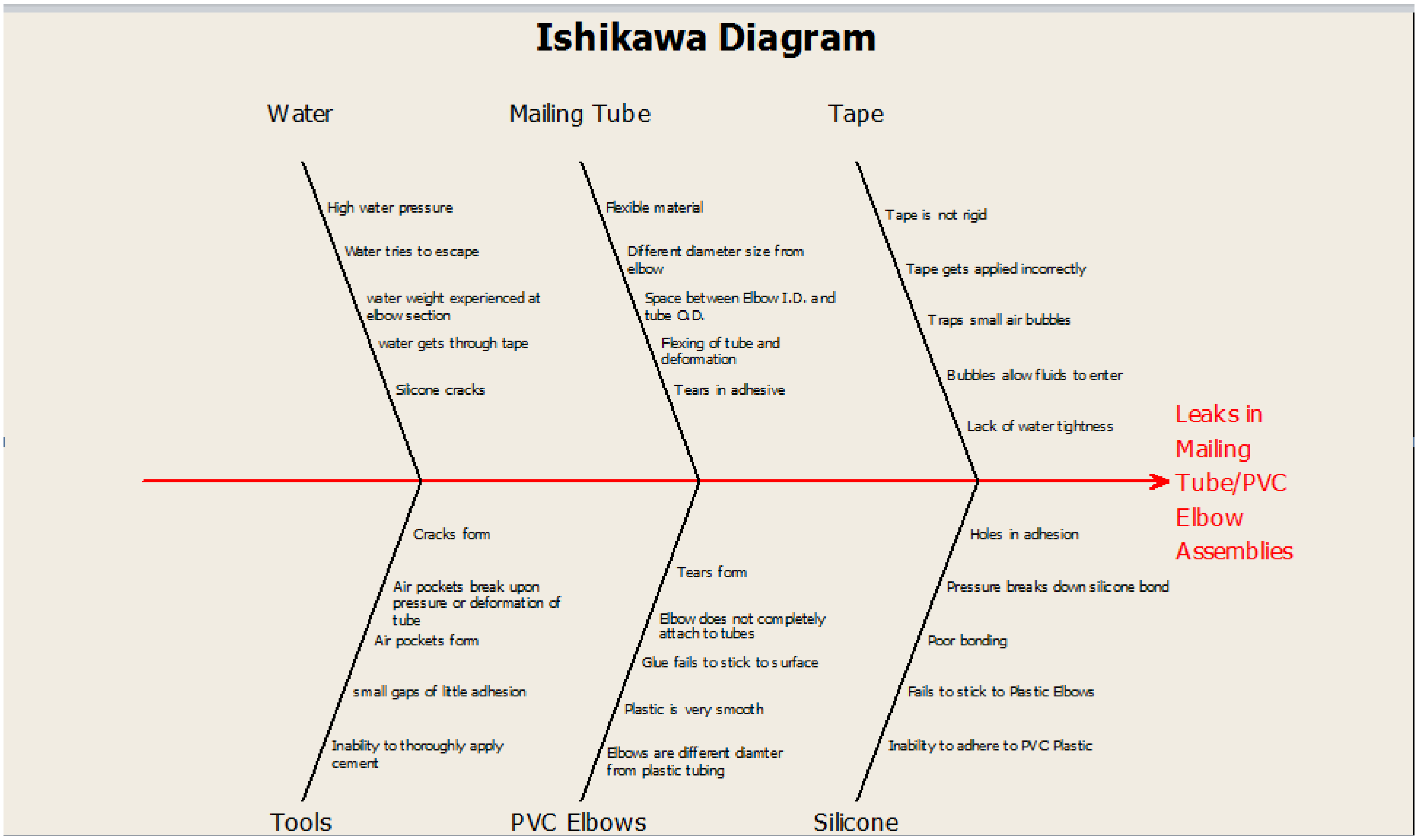

Figure 16. Ishikawa Diagram used to Analyze Leaks

Method 5: PVC Pipe, PVC Cement and Silicone

The Ishikawa Diagram ultimately highlighted some of the important reasons why the tubes would continue to leak. With the analysis performed, the team decided to try PVC cement and PVC tape. The cement would melt some of the PVC plastic material onto the mailing tube creating a permanent seal. PVC cement comes in various viscosities but can be very harmful if breathed in. As a result, the procedure had to be conducted in a very well-ventilated room if not outside. The PVC tape like the Frog Tape was Water Proof but less prone to forming creases during application. The tape was stumbled upon by luck but after testing several times on some scrap tubing, the material yielded a much more snug fit. The tape was originally purchased for its cheaper price tag than the Frog Tape but ended up becoming a much more suitable substitute.

First, the PVC tape was applied to a clean surface of the tube. At this point in the project, the team would use the side of tubes where silicone had not been applied since silicone removal was nearly impossible. The tape would be rolled repeatedly over the tube until a desired thickness was placed around the tube. Once measured, the tube would be test-fitted into the elbow for a snug fit. Next, high viscosity PVC cement was applied to both the inside of the

sanded PVC elbow and the root-edge of the tube just below the tape. **Figure 17** and **Figure 18** further illustrates this procedure.

Figure 18. Blue PVC Cement applied to a PVC Elbow

Figure 17. Blue PVC Cement applied to a Vessel Assembly

After both surfaces were cemented, the tube was pushed into the elbow until a snug fit was achieved. Next, a thick layer of silicone was applied above the tape as a last barrier of defense against any leaks that may emerge from any small cracks in the PCV cement. The justification for this addition of silicone was that although a poor adhesive when used alone, it did offer some support in blocking leaks as long as the PVC elbows were properly sanded. This is shown in **Figure 19**.

Figure 19. Silicone applied to a vessel assembly

The assemblies are then placed aside to cure overnight. Once again a leak test is performed and the tubes are plugged and filled with water. The results were positive with no leaks at all! Several more were then tubes constructed in a similar fashion and not a single leak occurred making this unique process a success at the time being.

Method 6: Using Injection Methods over Swabbing PVC Cement:

A single can of PVC Cement is enough to build about 4 Pipe/Elbow Assemblies. When a refill was needed, the Hardware store happened to be out of stock of the High-Viscosity PVC Cement. Instead, Low-viscosity cement was purchased and tested on several tubes as a substitute. Because the cement was less viscous, a syringe had to be used to apply the chemical in order to prevent excess dripping. Tape was applied in the same way it was applied in the previous method. Instead, the cement was injected onto the root-edge of the tube giving a "fuller" dose of cement. The low viscosity of the new cement seemed to fill in gaps more smoothly than its higher viscous counterpart. Leak tests yielded zero leaks again making the new cement a suitable alternative to the previous type. However, during another round of leak testing with tubes that were constructed with the High-Viscosity Cement, a sudden leak occurred.

After some more root-cause analysis, it seemed probable that by being more viscous, the cement was more prone to curing with air bubbles within the bond. Once filled with water, these air bubbles were prone to breaking allowing water to creep through the entire elbow assembly. By using the thinner cement, there was a less chance of this situation from occurring as the cement would automatically fill up any gaps present eliminating any chance of air bubbles. Further testing with the less viscous cement resulted in zero leaks and will be analyzed in the Methods section. Thus, Method 6 became the preferred method for building the Pipe and Elbow Assemblies.

Statistical Analysis was performed to evaluate the performance of both the High and Low Viscosity Cements. Each type of cement was tested using 10 samples. Each tube was tested twice for leaks and received one of 3 possible scores. These scores are summarized in **Table 5.**

Table 5 . Rating system used for statistical analysis of 2 types of PVC Cement

Score	Description
0	Vessel experienced leaks after 1st test. Tube set aside and not tested a 2nd time.
1	Vessel experienced leaks after 2nd test.
2	Tubes did not experience any leaks after both tests

A list of the results is shown in **Table 6**. The data was then analyzed using a Box-an- Whisker Plot and is shown in **Figure 20**. Samples which utilized the Low-Viscosity Cement yielded an average score of "2" while High-Viscosity Cement Samples averaged a score of "1.5".

Table 6. A list of scores associated for each sample during PVC Cement Test

PVC Cement Type	Leak Test Rating
High-Viscosity	0
High-Viscosity	1
High-Viscosity	2
High-Viscosity	2
High-Viscosity	1
High-Viscosity	1
High-Viscosity	2
High-Viscosity	2
High-Viscosity	2
High-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2
Low-Viscosity	2

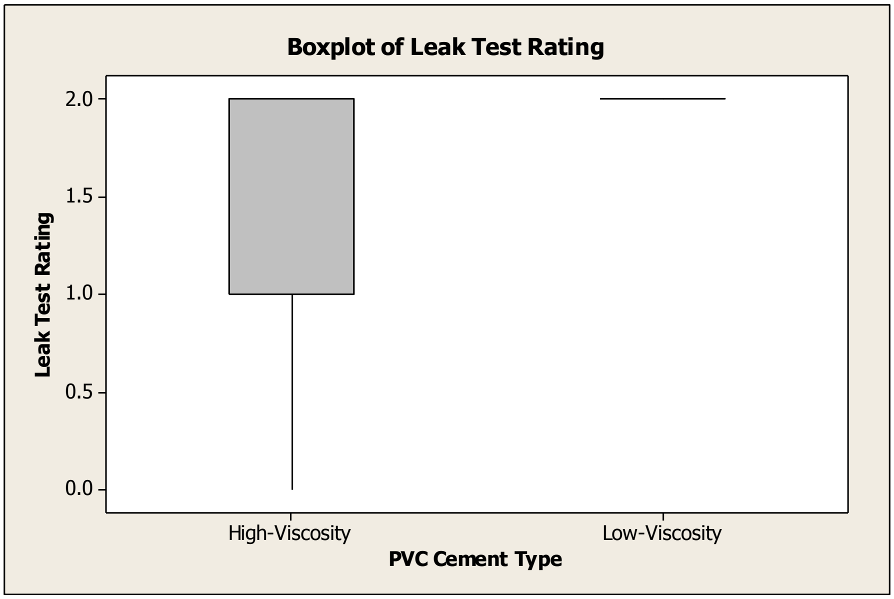

Figure 20. Box plots used to analyze traits of each PVC Cement type

Attaching Pipes at the Top Using O-Rings:

Once the rest of the tubes were built using Method 6, a method for attaching the tube from the top elbows had to be analyzed. O-rings seemed very promising due to their nature of forming water-tight seals. The goal was to make one end of the tube assembly removable for easy cleaning and maintenance and utilizing O-Rings would meet this objective. Pressure at the top would also be significantly lower than that experienced at the bottom joints. After determining the correct diameter to fit around the tubes, a set of O-Rings were ordered from Parker to test on the top portion elbows. At first a single O-Rings was placed between the elbow and the tube. With the bottom elbow plugged and the top elbow held with a single O-Ring, the tube was filled with water until the water would spill out of the above elbow. **Figure 21** shows this methodology. Leaks were witnessed to slowly emerge between the elbow and the pipe.

Figure 21. Photo of vessels undergoing leak tests

The same test was repeated but with 2 O-Rings this time. No water leaked between the elbow and the tube causing further testing with other tubes. None of the tubes produced any leaks with this method. A benefit to having top elbows which can easily be removed is the ability to adjust as necessary unlike the bottom elbows which are permanently attached. This becomes a valuable characteristic during cleaning, maintenance, and adjustments. This concludes the work performed during the winter 2013 Quarter.

Quarter III: Spring 2013:

Leaky tubes result in Change of Project Goals:

The initial goal of the project was to build 2 PBRs with all of the supplies purchased at the end of the Fall Quarter. The first system would be an experimental and less costly system while the second would be an improved and more durable model. Unfortunately, the construction of the Mailing tube vessels and the time required to resolve the leaking issues required significantly more time than expected. The consequence was a change in plans regarding the expected deliverables. As a result, the team switched its focus from assembling 2 PBRs to building just one basic functioning prototype. Hence, construction of the second PBR would have to be completed at some later time.

PBR Design Changes to better meet Ergonomic Needs and Time Limitations:

Back in the fall quarter, the team had designed a layout consisting of 4 conical tanks and 20 vessels. After some critical thinking, an idea was proposed to cut the system in half and create a smaller and much more simplistic layout utilizing only 2 Conical Tanks and 10 vessels. Due to the conflicts encountered from all of the leaks during the Winter Quarter, it was believed to be beneficial to build a functional system as quickly as possible in order to allow proper time for testing. A basic Systems Engineering Principle states that failure rates increase as systems become more complex. Decreasing the number of vessels in series was a plan to reduce the likelihood of failure while operating. As a result a new layout was designed changing the dimensions from 8 feet x 4 feet to 4 feet x 4 feet. This new layout incorporates 2 conical tanks instead of 4 and 10 vessels instead of 20. The design is shown in a sketch in **Figure 22**.

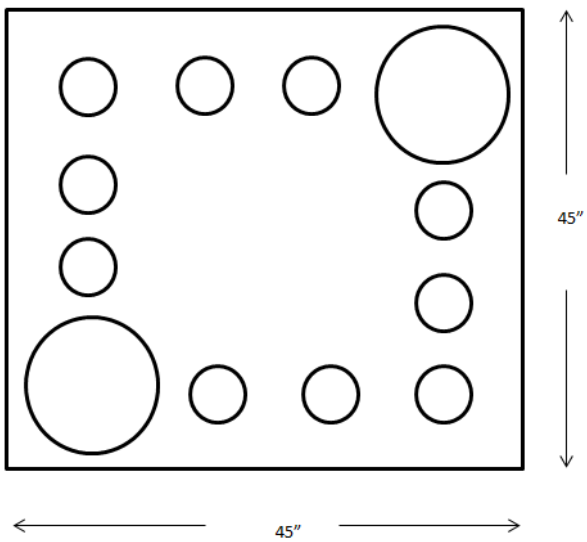

Figure 22. Layout for the revised PBR layout

This reduction in size yielded many benefits as well including the following:

- Smaller dimensions mean easier transportation and mobility.
- The new design would only require 1 truck to move
- Having multiple individual units was easier to setup than having the additional steps of having to connect 2 halves together
- A smaller system could make setup and maintenance significantly easier and cheaper

Characteristics regarding the structural frame design changed as well. During the Winter Quarter, there had been talks about machining and welding together a frame made of stainless steel. Unfortunately, building a stainless steel frame would require some skill in metal work and welding which the team lacked. Instead, an alternative plan of action had to be established. The new plan would be to build a frame out of wood considering wood is much easier to work with than metals. The frame would still have to offer structural support to the vessels as well as to the Conical Tanks while completely filled with water. A suggested solution would be to use a standard 45" x 45" wooden pallet for the base. Wooden pallets can support a large amount of weight and would allow easy transportation via forklifts and pallet jacks. After doing research, a standard wooden pallet was said to be capable of supporting a load over 1,500lbs. This was calculated to exceed the requirement of supporting approximately 600lbs for the new PBR System while filled with water.

With a new dimension limit of 45" x 45", the team began to try new layout designs for the PBR configuration. Eventually, a final layout was designed. This final layout design is shown in **Figure 23**.

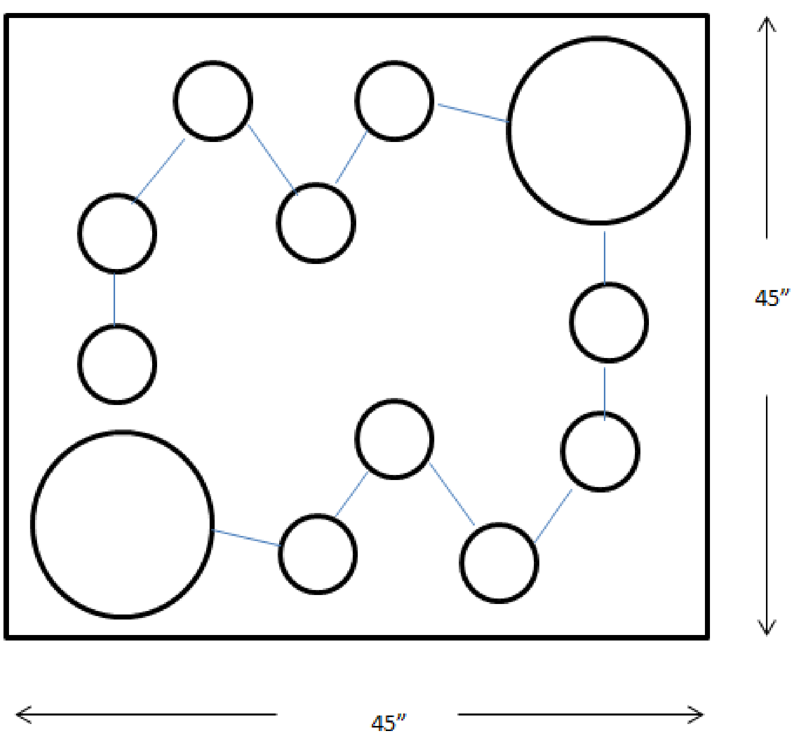

Figure 23. Finalized layout for "Pallet PBR System"

Once a layout was established, the conical tanks were machined in order to allow proper attachment between the tanks and the vessels. A 3” hole was drilled into each conical tank in order to install a bulk head fitting. Once again, leak tests were performed to ensure no water loss occurred between the vessels and the conical tanks. The hole is shown in **Figure 24**.

Figure 24. Bulk head fitting installation

Next, pipe unions were installed at the base of each conical tank. This would allow easy removal of the first vessel from the conical tank during maintenance and setup. Leak tests pursued installation. Leaks were fixed by applying grease lubricant between the threads of the unions which ultimately stopped leakage.

The frame was built from wooden components and installed onto the pallet. Although not as sturdy as a steel frame, the pallet method would provide a temporary solution for students and faculty looking to grow algae in the short-term. A series of 2” x 4” wooden pieces were used to construct the frame. The wood was cheap and known for having durable strength in other woodworking applications. It was also suggested to incorporate a removable gate to allow easy maintenance and access to the different components in the system. The frame was assembled using a standard drill, wood screws, wood glue, and machinery in Cal Poly’s Machine Shop. The completed wooden frame is shown in **Figure 25**.

Figure 25. Completed Wooden Frame

Wooden "shoes" were also constructed to support the vertical vessels at the base of each elbow. A simple half-pipe design was chosen to fit around the circular elbows and offer structural support. These shoes are shown in **Figure 26**. Once a frame was built, plastic zip ties would be used to secure the tanks and vessels to the frame itself. Upon completion of the frame, leaks were tested and fixed using grease, or a foaming sealant called "Great Stuff". The Sealant was tested and quickly removed any leaks that were apparent in the system.

Figure 26. Wooden Vessel Supports or "shoes"

Diffusers were not installed due to missing components and the long lead times in obtaining the necessary parts. The diffusers are expected to be installed at a later time once proper parts are researched and ordered. In short, completion of the project was defined as having a system loaded onto the pallet filled with water without experiencing any leaks. This concludes the final assembly of the PBR System.

METHODOLOGY

The first task was to perform a cost-analysis on the amount of resources spent on servicing the original PBR. The number of hours spent per maintenance service on the original PBR is listed in **Table 7**.

Labor cost: $10/hour

Table 7. Weekly Labor Analysis

Activity	Number of Hours	Cost ($10.00/hour)
Setup/ Addition of culture	12	120.00
Cleaning/Maintenance	.5	$5.00
Harvesting	3	$30.00
Cleanup	1	$10.00
Total Cost	16.5	$165.00
Total Annual Cost (Assuming 4 weeks x 12 months)	792	$7980
Total Annual Cost for **Setup** (Assuming 4 weeks x 12 months)	576	**$5760**

As mentioned earlier, the most time consuming part of the Process was the setup time taking nearly 75% of the time and labor resources. The Pareto chart used to display this is shown again in **Figure 6**. An estimated $8000 was spent per year on total operating costs. Yet nearly $5800.00 was spent on setup costs alone! One of the goals was to incorporate characteristics that would decrease this setup time by 50% or more.

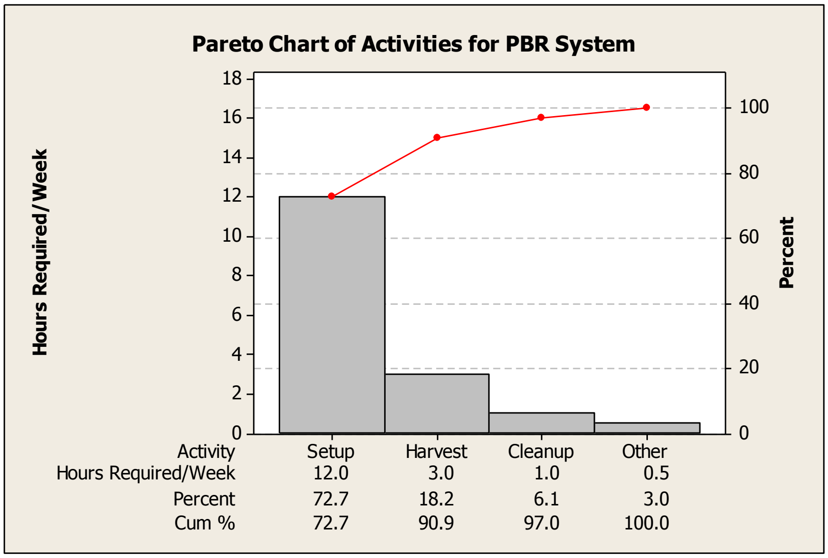

Figure 6. Pareto Chart of Activities for PBR System

Features that were improved in the new PBR system are listed below in **Table 8** displaying what actions were taken along with the result of each action:

Table 8. Ergonomic Features Table

Suspected Cause	***Action Item***	***Responsible***	***Finding***
System is too tall and requires ladder	Shorten Height	Andrew, Alex	System is less prone to falling and hurting people
System requires too much space	Decrease area of system and build vertically	Andrew, Alex	System capacity increased from 33.33L/Sq-M to 184.43 L/Sq-M
Non-rigid sacks prevents use of measuring devices	Make growing vessels rigid	Andrew, Alex	Rigid vessels allows easy use of monitoring devices
System cannot be transported via trucks, elevators, nor forklifts	Limit dimensions to allow various modes of transportation	Andrew, Alex	System dimensions allow easy transportation via trucks, elevators, and forklifts
Parts not easy to access during service or setup	Make components easy to access and correct. Shrink size of components	Andrew, Alex	Major components are now lighter and smaller

The volume output of the new PBR was also analyzed in terms of volume per square area. A comparison between the former and new PBR is shown in **Table 9** below. This data is also illustrated in **Figure 27**.

Table 9. Data Comparison between New and Old PBR

	Old PBR	**New PBR**
Length	3 Meters	1.143 Meters or 45”
Width	2 Meters	1.143 Meters or 45”
Height	2 Meters	2 Meters
Total Floor Area Required	6 $Meters^2$	1.31 $Meters^2$
Volume capacity	200 Liters	241.6
Volume per Square Meter	**33.33 L/M^2**	**184.43 L/M^2**

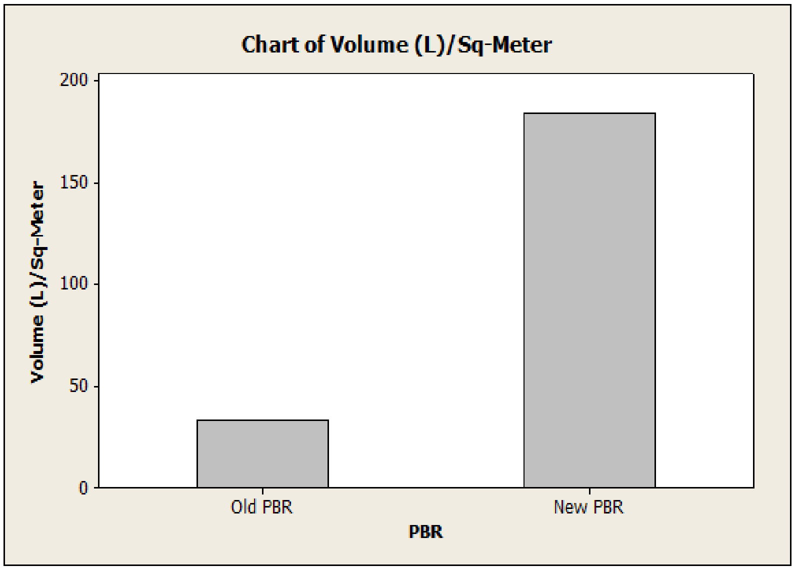

Figure 27. Bar Chart of Volume Throughput/Area

The finalized layout for the new PBR is shown below in **Figure 23**. The arrangement of the vessels had to be switched in order to allow the entire system to fit on a pallet.

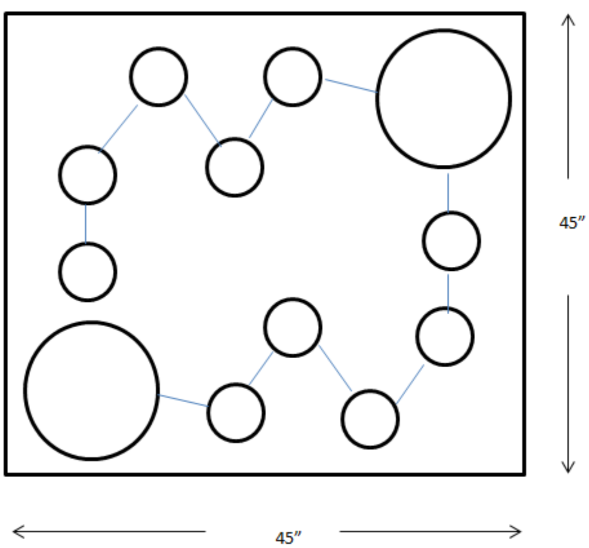

Figure 23. Finalized layout for "Pallet PBR System"

In order to test setup times for the new PBR, very basic time studies were conducted. The methodology for set-up was standardized by placing separate parts in a designated area. Next several trials were conducted where a single member of the team was chosen and timed with a standard stop watch while assembling the PBR. Members switched off roles performing this task

and corresponding times for each complete setup were recorded. The parts were arranged in such a way to replicate a scenario as though the major components had just been dropped off of a truck. The placement of each major component is shown in a layout in **Figure 28**. Parts were laid approximately 2 feet from each other.

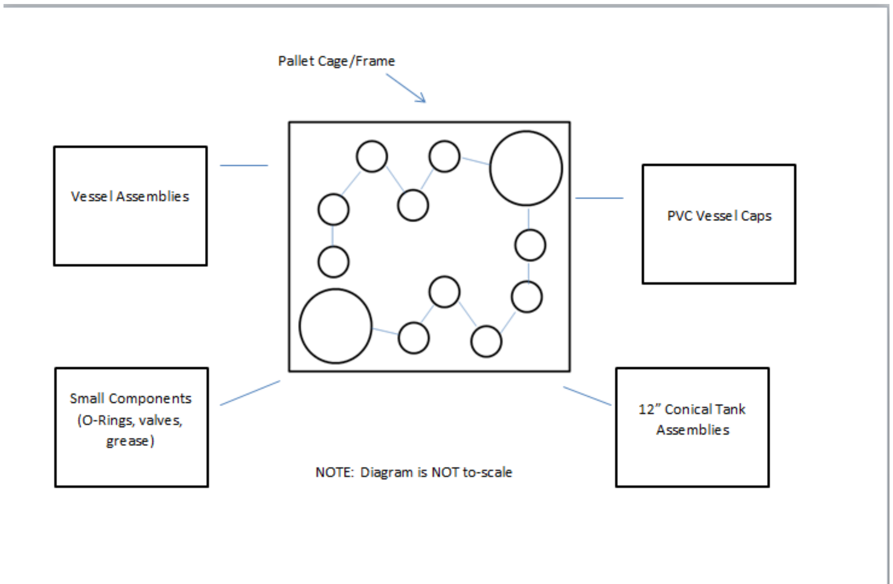

Figure 28. Time Studies Parts Placement Layout

The participating member was then asked to follow a simple list of instructions to put the PBR together. Average Times were rounded to the nearest 10 minutes. Although the diffusers have not yet been assembled, these parts would be built as a major component like the vessel and tank assemblies. These parts, once built, would simply be dropped into each conical tank with very little adjustment necessary. A worst-case scenario of requiring 10 minutes for installation was assigned for the gas diffuser step. The light fixture had not yet been assembled as well as it was not part of the scope of this project. In order to incorporate the time required for a complete setup, the installation time required in the original PBR was used instead. The time requirement for the lighting fixture was approximately 1 hour.

Next, the water fill up time was measured by timing the time required to fill up the entire system. While using a standard hose with a speed of .25Liter per second, the total required time for fill-

up was approximately 20 minutes. **Table 10** summarizes the time required for the entire setup below. All raw sample data can be found in the appendix of this report.

Table 10. New PBR Setup Time Analysis

Activity	**Required Time (Minutes)**
Assembly of components to pallet cage	30
Installation of Gas Diffusers (theoretical worst-case scenario)	10
Filling up of entire system with water	30
Installation of light fixtures	60
Total	120

Once establishing the required setup times for the new PBR, the data was then translated to a dollar amount or labor cost. Note that Cal Poly lab assistants are typically paid at least $10.00 per hour. Keeping this in mind, a table comparing the total Labor Costs of Setup between the Old PBR and the New PBR was created and is shown in **Table 11**. Annual labor costs were calculated by assuming 4 weeks per month and 12 months per year.

Table 11. New vs. Old PBR Labor Costs

	Old PBR	New PBR
Time Required for Setup [Hrs]	12.0	2.0
Labor Cost of Setup per Week [$]	120.00	20.00
Total Annual Labor Cost for Setup (Assume 48 weeks/year) [$]	5760.00	960.00

Next a Table displaying all of the Material Costs associated with the construction of the New PBR was created. Note that along the way, there were many additional components which had to be purchased on top of the original parts bought at the end of 2012. This list of parts along with their associated costs is shown in **Table 12** in the Appendix. The total material cost required for the construction of the New PBR came to approximately $5840.00.

Finally, the Payback Period was calculated and analyzed to determine the overall savings achieved by utilizing the new PBR. An initial cost of $5840 for the materials was required to

build the new system. A Setup Cost of $5760.00 was required to operate the former PBR each year whereas the New PBR only requires $960.00 per year. A chart is shown in **Figure 29** to see the potential savings which can be experienced by utilizing the new system. A payback period of about 1.5 years was calculated.

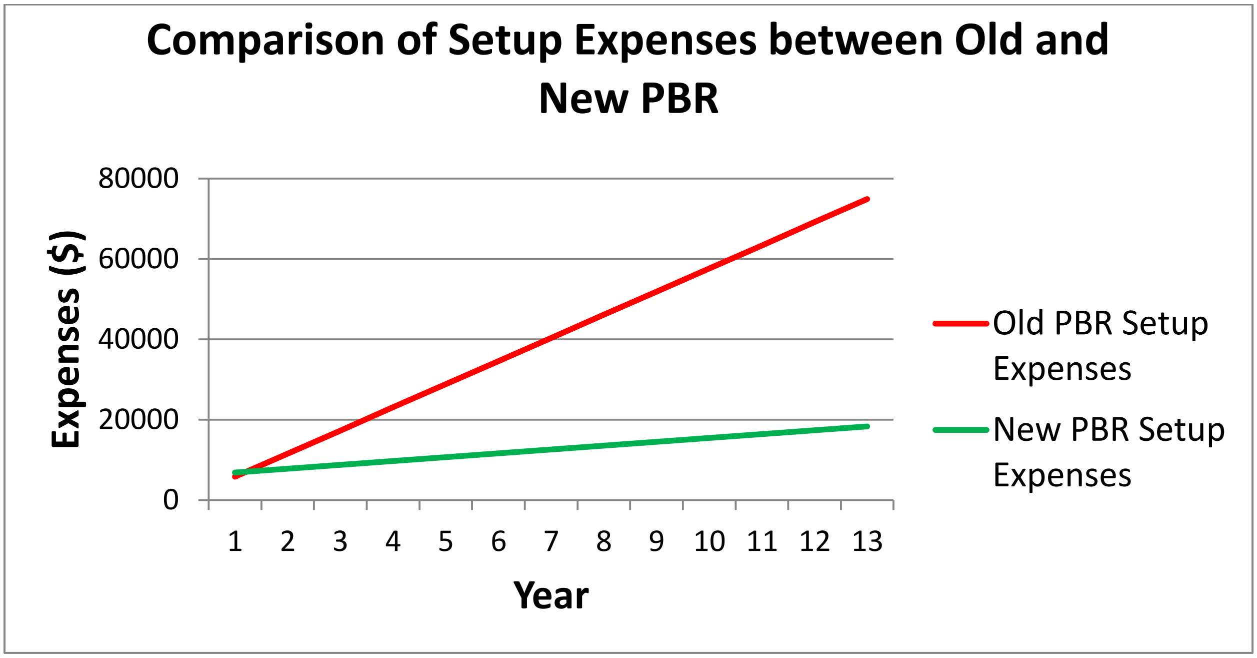

Figure 29. New PBR Payback & Savings Graph

RESULTS

Ergonomics

An upgrade in ergonomics and testing capabilities was one of the prime concerns of this project. In general, the size was vastly decreased in terms of height and length. The new system fits in a standard elevator and can be loaded onto the back of a single pickup truck. The unique "pallet" design also allows easy transportation via pallet jack and or forklift. Components are now smaller and lighter making installation easier and quicker. The system has been tested for leaks and repairs were made when necessary. The height has been decreased to prevent the need for a latter and to reduce slipping and falling hazards. Although a cost of injury was not calculated for this project, it is probable that cost of injuries will be greatly decreased with the new design. The use of rigid vessels allows monitoring of growing conditions via special measuring devices.

The new small design allows easier and faster maintenance capabilities. The overall smaller design, thanks to the new pallet parameters, allows the system to be stowed and used in smaller areas as well.

Liquid Volume Throughout per Square Meter

The new system also produces significantly more liquid/biomass per square area. While the former PBR produced an average of 33.33 Liters per square meter, the new system will produce roughly 184.0 Liters per square meter. This is over a 450% increase in volume throughput per square meter.

Reduction in Setup Times and Overall Labor Costs

Perhaps one of the better features of the new PBR is the simple design that allows easy setup and maintenance of the system. While the initial PBR required on average 12.0 hours per week to setup the system, the new system requires no more than 2.0 hours to get ready. This reduction in setup times reduces the setup Labor Cost from $120.00 per week to $20.00 per week. This translates to a reduction from $5760.00 per year to $960.00 per year or a 500% decrease in setup expenses. After a payback period of about 1.5 years, the new system is expected to yield savings at about $4800.00 per year!

CONCLUSION

Aside from building the gas diffusers, the new PBR successfully met all of the project objectives. By completing all of the required tasks, the new PBR System will likely save thousands of dollars in the long run while conducting research. The new system offers new capabilities such as utilization of monitoring devices and portability. Ultimately, safety hazards will be vastly decreased reducing the risk of injury and associated costs.

A major bottleneck to the completion of the entire project was due to not having a designated workspace. Although the team met routinely in the Food Facilities building, there were many issues with building the project in the same facility that produced food. There were times where the team had to stop building the PBR because certain parts were not permitted inside of the facility due to risk of food contamination. Cal Poly Chocolates were also produced in the same building limiting access to certain rooms during various times of the day. The team also routinely lost designated workspaces outside of the building due to reserved spots for other school projects. Due to the complexity of the PBR System itself, it was difficult to find a place to build while allowing proper testing of various components. The consequence was a huge increase in non-value added activities such as unnecessary transit time while assembling and testing the system.

The close deadline of the Research Grant also caused a rushed selection of parts. This ultimately led to encountering issues during the assembly process from lack of research on proper components and attachment methods. It is possible that having more time to do research would have allowed a better parts selection and a system with fewer leaks. Better fitting tubes could have been purchased preventing all of the time spent for attaching the mailing tubes to the PVC elbows.

The Project would have ultimately benefitted by having more members on the team from different Engineering Disciplines. Although 2 people were barely sufficient, having a Materials Engineering Student would have helped when it came to deciding the best method of attachment between various plastics. A Mechanical Engineer could have performed a thorough analysis on

the frame and weight distribution which would have led to a better design than the basic pallet-method.

If mailing tubes are to continue being used for the PBR in the future, one may wish to perform more statistical analysis to determine which assembly method is best and what other factors constitutes to leaks.

The gas diffusers are expected to be built during the summer 2013 Quarter at Cal Poly. Once completed, the PBR is expected to be used for research projects regarding biofuel production and health supplement use after this quarter.

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APPENDIX

Table 12. Parts and Price List

Item	Quantity	Price ($)	Total Price
Silicone Paste Tubes	20	5	100
12" Dia. Conical Tanks	8	375	3000
Conical Tanks Friction Fit Caps	8	22	176
9" Gas Diffuser Pads	8	21.14	169.12
3" PVC Elbows	20	9.28	185.6
3" PVC Elbow with 2" Hole	20	15.07	301.4
Parker O-rings (Bag of 20)	3	20	60
3" Diameter Plastic UV-Resistant Tubes (per foot)	80	12.37	989.6
3" Diameter Plastic Mailing Tubes (per foot)	80	2.66	212.8
PVC Cement	4	5.5	22
PVC Tape Rolls	5	5	25
"Frog" Water-Resistant Tape	1	10	10
Epoxy Clay	1	6	6
Epoxy Glue	2	5	10
Water Sealant Adhesive	1	7	7
Plastic Tubes for Diffusers (per foot)	15	2	30
Vessel Valves	6	4.5	27
1" Plastic Nipples	6	0.8	4.8
2" Plastic Nippes	4	1.25	5
90 Deg Bend Plastic 1" Joints	6	1.5	9
Great Stuff Foam Sealant	1	8	8
Bulk Head Fittings	2	15	30
3" Plastic PVC Unions	2	8	16
3" PVC Plastic Bushings	10	3.5	35
Wood Glue	2	5	10
Set of 100 Wood Screws	2	10	20
Metal Wood L-Brackets	30	0.85	25.5
Large Metal Brackets	4	1.8	7.2
8' Wooden "2x4" Planks	3	4	12
6' Wooden "2x5" Planks	1	8	8
45" x 45" Wooden Pallets (donated for free)	2	0	0
2" x 2" Metal latch set	2	5	10
8' x 2" x 2" Wooden Planks	2	3	6
Zipties (obtained for free)	0	0	0
Air Pump	1	300	300
Grease lubricant (obtained for free)	3	0	0
Total			**5838.02**

	Task Name	Duration	Start	Finish	Predecessors
1	Discuss Scope of Project	1 day	Thu 10/11/12	Thu 10/11/12	
2	Research Background on PBRs	15 days	Fri 10/12/12	Thu 11/1/12	1
3	Analyze current condition of PBR	14 days	Fri 10/12/12	Wed 10/31/12	1
4	Create alterntive designs for new PBR	7 days	Fri 11/9/12	Mon 11/19/12	2,3
5	Decide whether to purchase or buy PBR System	5 days	Tue 11/20/12	Mon 11/26/12	4
6	Compile list of essential components for PBR System	5 days	Tue 11/27/12	Mon 12/3/12	5
7	Do research on possible parts and vendors. Pricing analysis	7 days	Tue 12/4/12	Wed 12/12/12	6
8	Purchase required components for new PBR	2 days	Thu 12/13/12	Fri 12/14/12	7

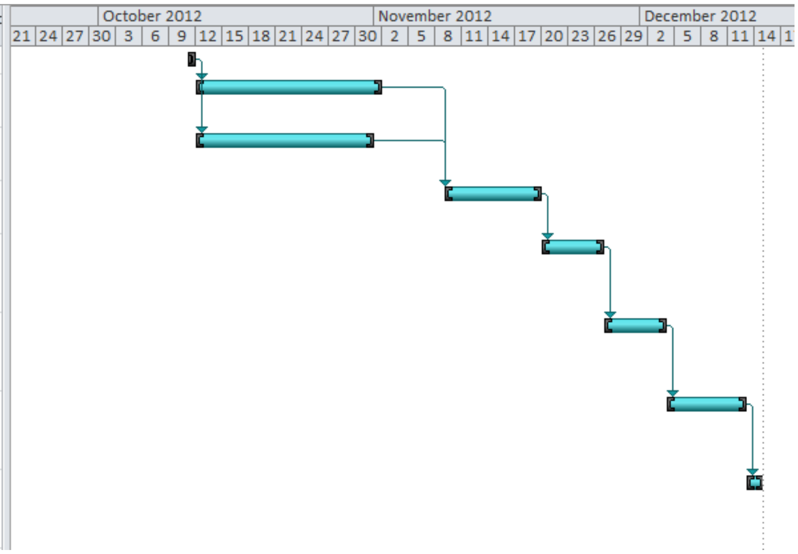


Figure 30. Fall 2012 GANTT Chart

	Task Name	Duration	Start	Finish	Predecessors
1	Inspect shipped parts	1 day	Mon 1/7/13	Mon 1/7/13	
2	Continue creating designs and evaluating designs	21 days	Tue 1/8/13	Tue 2/5/13	1
3	Create way to attach PVC elbows to vessel tubes	28 days	Wed 2/6/13	Fri 3/15/13	2
4	Test vessel assembly for water leaks	7 days	Mon 3/18/13	Tue 3/26/13	3
5	Evaluate vessel assembly for structural rigidity and functionality	35 days	Wed 2/6/13	Tue 3/26/13	2
6	Construct physical layout of vessels and conical tanks	35 days	Wed 2/6/13	Tue 3/26/13	2
7	Recognize and design methods for attaching components into a single system	5 days	Wed 3/27/13	Tue 4/2/13	5,3,6
8	Brainstorm issues that need improvement and fixing	7 days	Wed 4/3/13	Thu 4/11/13	7
9	Brainstorm & Design PBR System Frame	7 days	Wed 4/3/13	Thu 4/11/13	7

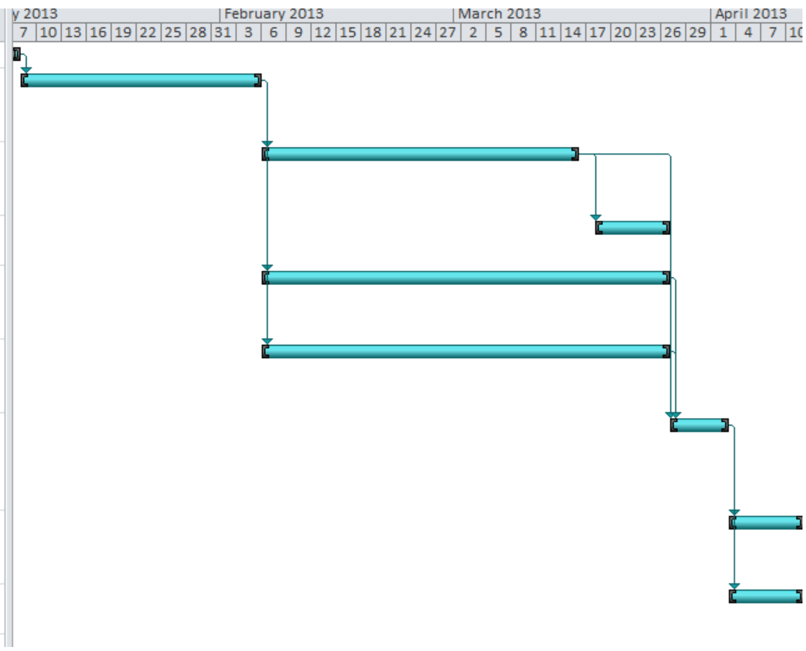
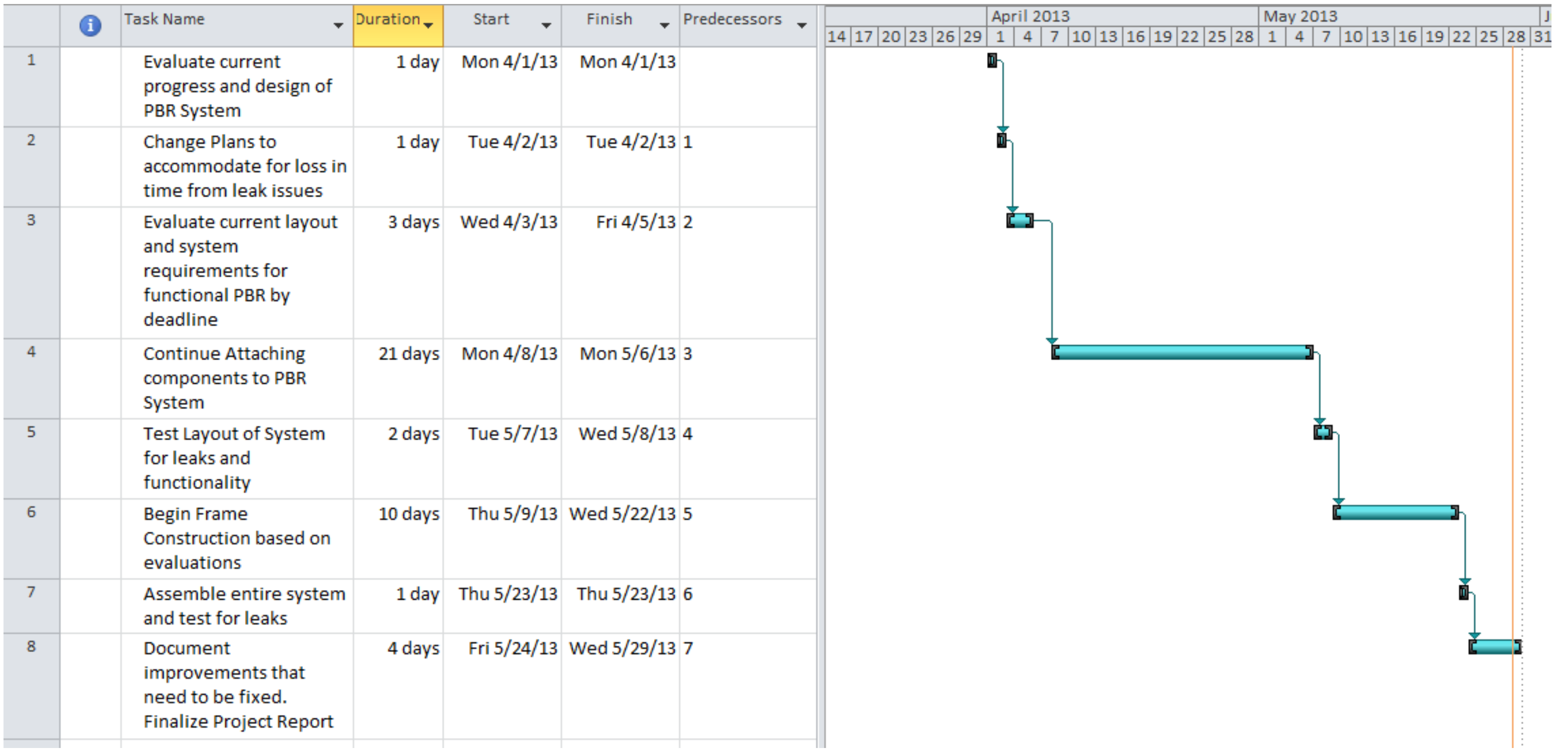


Figure 31. Winter 2013 GANTT Chart



	Task Name	Duration	Start	Finish	Predecessors
1	Evaluate current progress and design of PBR System	1 day	Mon 4/1/13	Mon 4/1/13	
2	Change Plans to accommodate for loss in time from leak issues	1 day	Tue 4/2/13	Tue 4/2/13	1
3	Evaluate current layout and system requirements for functional PBR by deadline	3 days	Wed 4/3/13	Fri 4/5/13	2
4	Continue Attaching components to PBR System	21 days	Mon 4/8/13	Mon 5/6/13	3
5	Test Layout of System for leaks and functionality	2 days	Tue 5/7/13	Wed 5/8/13	4
6	Begin Frame Construction based on evaluations	10 days	Thu 5/9/13	Wed 5/22/13	5
7	Assemble entire system and test for leaks	1 day	Thu 5/23/13	Thu 5/23/13	6
8	Document improvements that need to be fixed. Finalize Project Report	4 days	Fri 5/24/13	Wed 5/29/13	7

Figure 32. Spring 2013 GANTT Chart

Property	Unit	PETG	Rigid PVC
Optical			
Light Transmission	%	90	75
Refractive Index		1.576	1.5
Physical			
Melt Flow Rate (Melt Index)	g/10 min.	1.19	
Specific Gravity		1.27	1.32
Mechanical			
Tensile Strength at Yield	psi	7300	6500
	Mpa	50.3	62
Elongation at Break	%	110	150
Flexural Modulus of Elasticity	10^5psi	3	3.8
	Mpa	2067	2618
Izod Impact Strength	Ft. Lbs./in.	1.9	8 - 10
	J/m	101	267
Thermal			
Deflection Temperature (DTUL)	@264psi (Celsius)	147(64)	162(72)
Flammability Rating (UL94)	@0.125"	94V-2	V-0
	@0.625"	94HB	N/A
Use Temperature Range	Degrees F	0 - 148	Sub 0 -180
Barrier			
Gas Permeability			
CO2	cm^3*mil/100 in^2*24h	125	20 -50
O2	cm^3*mil/100 in^2*24h	25	5- 20

Figure 33. Plastic Types Comparison

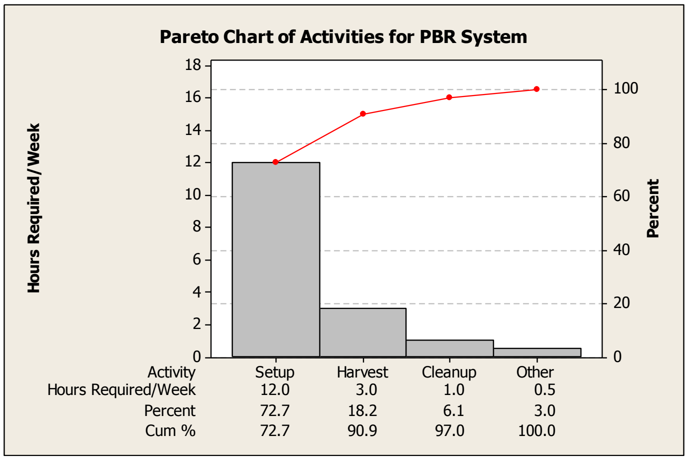
Figure 34. A3 Report for PBR Analysis

A3 Report: Analysis of Photo Bio Reactor Ergonomics

Background:

- Photo Bio Reactor (PBR) utilizes much space with limited throughput
- System cannot be transported easily
- Setup and servicing of system requires many hours to accomplish
- Height causes many safety hazards
- Limited ability to use measuring devices and hardware

Current Condition:

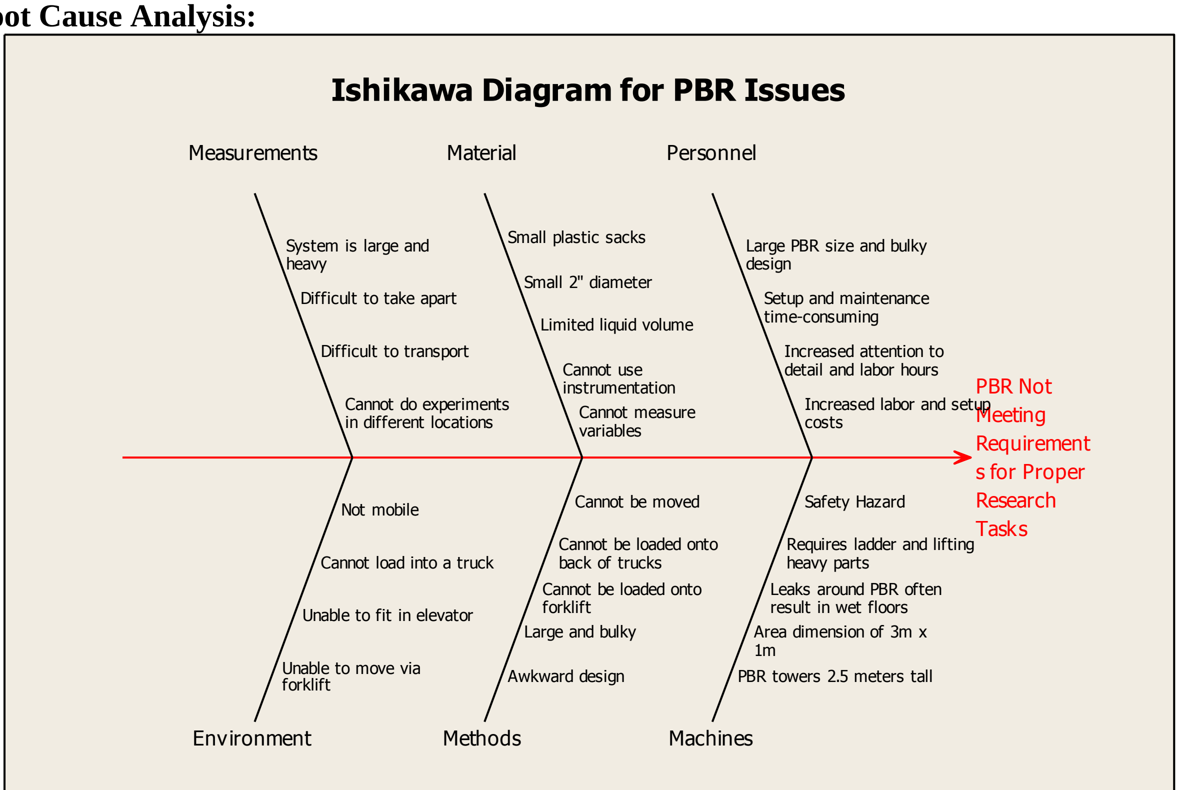


Features	Available	Not Available
Provides proper growing conditions for algae	X	
Mobile capabilities		X
Safe assembly and lightweight components		X
Capable of using measuring instruments		X
Carrying capacity of 100L per square meter		X
Requires less than 6 hours for setup		X

Goal:

- Increase fluid capacity to at least 100 Liters per square Meter
- Decrease overall Setup time required to at least 50% of current time
- Reduce if not eliminate all safety hazards associated with height and stability
- Design PBR that allows easy mobility
- Allow use of instruments in new design

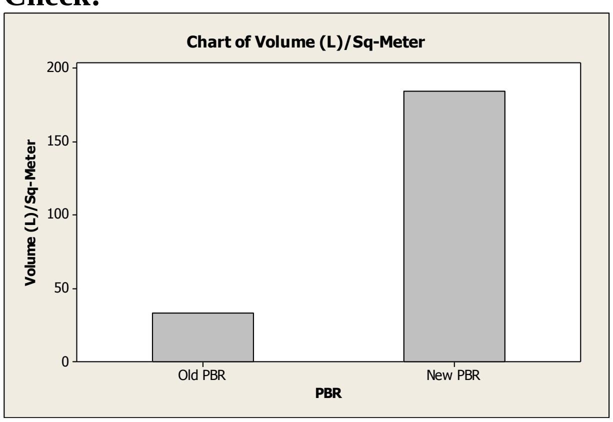
Root Cause Analysis:



Countermeasures:

Suspected Cause	***Action Item***	***Responsible***	***Finding***
System is too tall and requires ladder	Shorten Height	Andrew, Alex	System is less prone to falling and hurting people
System requires too much space	Decrease area of system and build vertically	Andrew, Alex	System capacity increased from 33.33L/Sq-M to 184.43L/Sq-M
Non-rigid sacks prevents use of measuring devices	Make growing vessels rigid	Andrew, Alex	Rigid vessels allows easy use of monitoring devices
System cannot be transported via trucks, elevators, nor forklifts	Limit dimensions to allow various modes of transportation	Andrew, Alex	System dimensions allow easy transportation via trucks, elevators, and forklifts
Parts not easy to access during service or setup	Make components easy to access and correct. Shrink size of components	Andrew, Alex	Major components are now lighter and smaller

Check:



- Rigid Vessels allow variable monitoring and better control of environment
- Smaller Size and "pallet-frame" makes system easier to move via truck, elevator, and or forklift
- Shortened height reduces likelihood of hazard risks associated with general maintenance
- Volume capacity increased from 33.33 L/M-Sq to 184.43 L/M-Sq or 453% increases from

Follow-up Actions:

- Ensure Mailing-tube vessels don't break. Switch to durable Harvel tubes eventually
- Build improved Stainless-steel frame to replace temporary wood frame
- Measure and record new setup times
- Check for defects when in outside environments
- Build "diffuser-rack" for easy removal of gas diffusers during maintenance

Table 13. PBR Setup Time Studies Data

Activity	**Test #**	**Duration (Minutes)**
System Setup	1	27.5
	2	26
	3	31
	4	30
	5	28
	Average	**28.5**
Water Fillup	1	19.4
	2	18
	3	21
	4	19
	5	18
	Average	**19.08**
Light Fixture Setup	Estimated	**60**
Installation of Gas Diffusers	Estimated	**10**
Total		**118**