Hydrogen from Microalgae and the Collection and Sensing Systems

Final Report

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ABSTRACT

Although it may not be readily apparent, energy directly correlates with the quality of life and technological resources that are available to people. As societies grow and become more advanced, the consumption and need for more energy increases. The augmented demand can put a strain on available resources, which is why there has been a heightened interest in alternative energy. This project will focus on hydrogen as an alternative energy source. A photobioreactor has been developed to aid in the production of hydrogen gases by allowing for a controlled environment. This controlled environment creates conditions in which microalgae can steadily create hydrogen gases. With steady self-sustainable hydrogen production, the hydrogen gases can be used in applications to create energy, such as fuel cells. This project seeks to create a photobioreactor that will operate continuously and cultivate micro algae for semi-continuous production of hydrogen.

ACKNOWLEDGMENTS

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BIOGRAPHIES

Nicole Alvarez: (Brazil Team Leader)

Born and raised as a military child, Nicole has had the opportunity to grow up around the world, including many states in the USA, Italy, Argentina, and Bolivia. She is currently studying mechanical engineering at FSU and has held internship positions with Rolls-Royce and Pratt & Whitney. Her work within and outside of school has grown her interest to pursue a career in the aerospace industry.

Jonatan Elfi: (Lead ME and Webmaster)

Born In Patagonia, Argentina, Jon is currently a mechanical engineering student at Florida State University. During his studies at FSU, Jon has worked at FCAAP under the supervision of Dr. Farrukh Alvi in high velocity fluid mechanics. After graduating he plans on attending graduate school at UCF and later hopes to work in the film industry or in renewable energy applications.

Ariel Johnson: (Treasurer)

Born and raised in Jacksonville, Florida, Ariel Johnson is currently a student enrolled at the Florida State University majoring in Mechanical Engineering. She has participated in the Air Force ROTC program for 2 years since her collegiate experience started in the summer of 2010, and would like to serve her country as an Officer in the Air Force upon graduation.

Angeline Lenz: (Team Leader)

Angeline is a senior double majoring in Mechanical Engineering and Applied and Computational Mathematics. After graduation, she plans on attending graduate school to study either Petroleum or Ocean Engineering.

James Richardson:

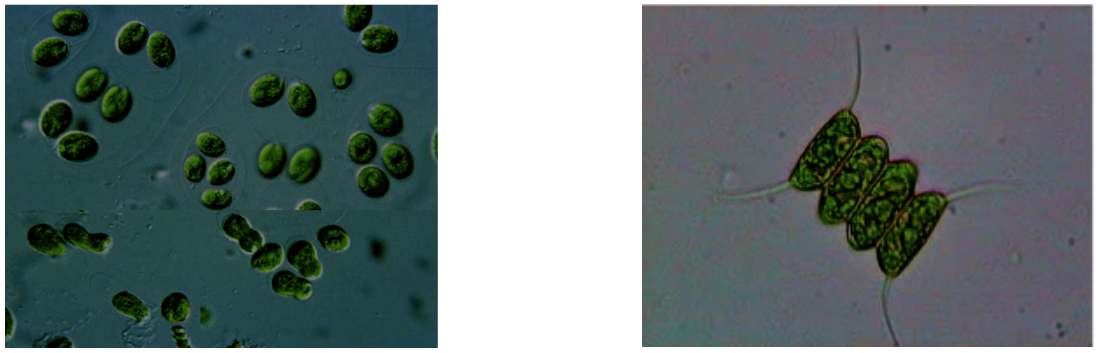
Ben is a senior graduating from Florida State University in May, 2015 with a Bachelor of Science in Mechanical Engineering. He is currently working in Curitiba, Brazil at Universidade Federal do Paraná studying microalgae growth and calibrating a hydrogen sensor with a team of American and Brazilian students.

Introduction and Background

Hydrogen gas has become an ideal fuel source for the future since it burns clean and generates a large amount of energy per unit mass allowing it to be more fuel-efficient than other resources [1]. Using hydrogen in renewable energy processes has become of greater interest due to the depletion of natural oil reserves. However, because of low concentrations at its pure form, hydrogen is not cost efficient for everyday use, making the study of biohydrogen one of great interest [2]. This calls for the exploration of hydrogen generation as a waste product of anaerobic respiration of green and blue algae from a photo bioreactor. When a controlled environment enables and regulates the proper anaerobic conditions necessary for the cultivation of algae, a photobioreactor is constructed to allow larger amounts of bio hydrogen to be produced and utilized as clean energy [3]. This occurs through biophytolysis of water by algae. The presence of light irradiation catalyzes the event and water is broken down into its hydrogen and oxygen components [4]. The phenomenon in which hydrogen is created as a waste product during the photosynthesis of algae must be promoted in a way that overcomes various issues [5]. These issues include creating a system that enables steady and continuous microalgae growth that is cost effective. The evolution of hydrogen results in an amount of fuel that is useable in commercial applications. The scope of this project will be directed toward the design and development of microalgae and measuring and collecting the hydrogen produced.

In today's world the need for renewable/sustainable energy has never been greater. Coal, petroleum, and other types of non-renewable sources provide much of the energy used today. Within the next century, these energy resources are projected to be fully depleted. Hydrogen is at the top of the list of biofuels that can solve the energy crisis that future generations face. Hydrogen in the simplest element known to man and it is usually combined with other elements. For example, hydrogen combines with oxygen to form H_2O, the most abundant resource on our planet [1]. However, it has proven difficult and expensive to split hydrogen from water to use as an energy source [2]. The most common form of this element is found as hydrocarbons, a product of organic compounds, which makes up gasoline, methanol, and propane. Hydrogen can be extracted from hydrocarbons through the application of heat, a process known as reforming [1]. The downside of reforming is the byproduct CO2, which contributes to the greenhouse effect.

One alternative for hydrogen production comes from algae. Using sunlight as their energy source, and under the right conditions, algae can give off hydrogen. The research that is currently being done is aimed at two types of algae: Scenedesmus sp. and Chlamydomonas reinhardti, figure 1a and 1b, respectively. These types of algae are favored due to their high degree of adaptability and fast reproductive cycle [3]. Our sponsor has given us the primary tasks of designing and developing an H_2 producing photobioreactor, and designing and developing an electronic H_2 mass measuring sensor to test such systems.



(a) **(b)**

Fig 1: (a) *Scenedesmus sp*. (b) *Chlamydomonas reinhardtii*

In order to produce H_2 from algae, the algae must be cultivated in a controlled manner. There are two ways to cultivate algae: open ponds and photobioreactors. Photobioreactors (PBRs) are closed systems that provide a controlled environment where algae productivity is high. PBRs are used to better control CO_2 supply, water supply, temperature, etc. [4]. Figure 2 shows a basic schematic of a PBR. The main components of such a system include a light source, hot plate, thermocouple, container, and a gas collection apparatus. Previous senior design teams at Florida State University have built working photobioreactors. One such team was team 7 from 2013 who was successful in designing and fabricating a bioreactor, which can be seen in figure 3. Their bioreactor has sensors that can monitor algae concentration, mass flow rate, and CO_2 concentrations. The bioreactor is installed in the AME building at the FAMU-FSU engineering school.

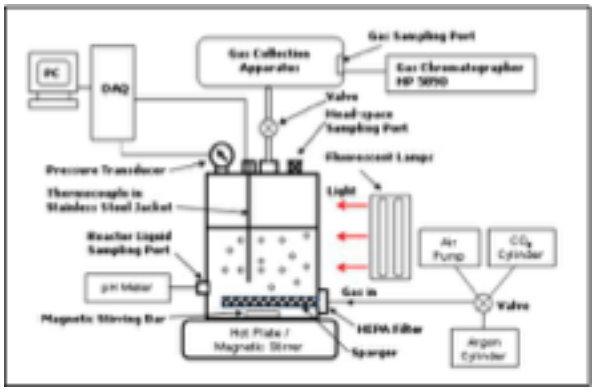


Fig 2: Schematic of a Photobioreactor.

A. Need Statement

Florida State University and the Federal University of Parana have joined together to sponsor this project. There is need for a scalable and sustainable process for producing hydrogen from microalgae cultures such as Scenedesmus sp. and *Chlamydomonas reinhardtii* to demonstrate the feasibility of photobioreactors in the field of alternative energy. Additionally, an automated sensing system will be needed to monitor the hydrogen content of the resulting PBR system.

B. Goal Statement

The goal of this project is to further the development of alternative energy with the use of a

sustainable process for producing hydrogen from microalgae. To consider this project as successfully completed, the project sponsor provided several objectives that need to be met.

C. Objectives and Sponsor Requirement

The sponsors of this project include Florida State University and the Federal University of Parana. They have asked that we pursue and complete the following general project and prototype objectives:

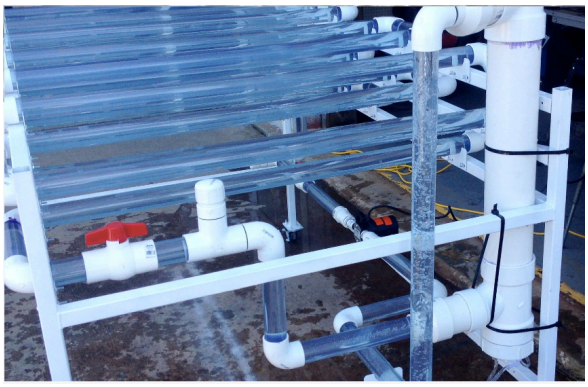


Fig 3: Team 7's 2013 photobioreactor

General Project Objectives

- Design and construct operational H_2 producing units
- Design and construct an electronic H_2 mass measuring sensor
- Provide enough experimental data to test the operation of the H_2 producing designed units
- Provide mechanical drawings of the entire system and sensor for future product scale up
- Write an invention disclosure (FSU team) to be submitted to the USPTO by the OTT/FSU, and a patent request (Brazilian team) to be submitted to the Brazilian INPI, for the H_2 producing photo bioreactor system developed Prototype Objectives
- It should be fully automated
- It should be low-cost
- It should be readily scalable

D. Constraints

There are many engineering issues such as appropriate bioreactor designs and scaling-up the system, preventing interspecies hydrogen transfer to non-sterile conditions, and the purification and separation of hydrogen. The photobioreactor should be designed in such a way that it is easily scalable. The workspace in the lab is small which means the size of our bioreactor will be smaller. Because of space restrictions, the size of the bioreactor was changed from 8' x 3' to 4' by 3'. However, if this type of system is to potentially be used as a major source of energy in the future, a much larger bioreactor is needed. The bioreactor also cannot be used until a gallon of algae is grown. Until then, the algae will initially be grown in small glass bottles or beakers.

Our team is working with a budget of roughly $1000. This creates issues when it comes to growing and maintaining healthy algae. The food for the algae is very expensive to buy premade so it is important for the team to learn how to make the food. The biggest constraint for this project deals with maintaining a large amount of healthy algae and the time is takes to produce that amount. It can take weeks to grow an adequate amount of algae and without a large amount, hydrogen production won't be maximized. Many of the students working on this project have

little background in the growth processes of microalgae and microorganisms in general. This insufficient knowledge could lead to a lack of understanding on how to integrate hydrogen production with other processes. The processing of biomass feed stock is also very expensive. If this it to become a widespread energy source in the future, the cost of production must be reduced.

1. Concept Generation

There are four main components that are essential to successful production and storage of hydrogen: hydrogen generator, hydrogen refiner, hydrogen compressor, and a pressure vessel[10]. In this project, an airlift bioreactor was designed to cultivate algae, which would generate hydrogen. The hydrogen gas sensor will be attached to the gas outlet to measure the concentration of hydrogen. Once the hydrogen has reached the desired concentration level, gases will enter the hydrogen refiner. Along with hydrogen, there will be many other gases present in the bioreactor. The gas purifier is used to refine the hydrogen and separate it from unwanted gases and contaminants resulting in a pure form of hydrogen. After refining, the purified hydrogen will flow through a mechanical compressor so that it may be safely stored in a compressed tank.

A. Design

Due to time and budget constraints, it was necessary to use a previously constructed photobioreactor. The decision was made to use the prototype built by the 2014 senior design team. This design was chosen because of its simplicity and the fact that it is an airlift bioreactor, which has the advantages of good mixing, effective mass transfer of CO_2, high S/V ratio, and good removal of O_2. The final 2014 design can be seen in figure 4(a). After analyzing the 2014 senior design team's prototype, several modifications would have to be made to optimize the system for hydrogen production. The current proposed final design can be seen in figure 4(b). The first change made to the design was the increase in size, and the change in the horizontal angle of the upper horizontal tube, known as the gas separator. This component is critical for gas exchange i.e. where hydrogen bubbles separating from the liquid to air. Gas exchange can only occur if there is headspace in the gas separator. This design criteria was omitted from the previous year's prototype because their purpose was to extract biomass not hydrogen. The horizontal angle of the gas separator will also be modified. An angle of three degrees will be implemented to prevent gas buildup and allow the hydrogen to move towards the exhaust port. This angle can be altered if complications arise.

Another significant change to the previous design is a reduction in the diameter of the down-comer tube, which is the vertical tube on the left side. The reduction in diameter improves gas holdup, which is the volume ratio of gas to liquid within the reactor. In addition, gas holdup has a heavy influence on CO_2 mass transfer, gas bubble velocity, and H_2 production. Pressure differences occur between the down-comer and riser if the diameters of each are the same. By reducing the diameter of the down-comer the pressure difference will decrease, gas holdup and superficial gas velocity will increase, which are important properties that impact hydrogen output. It can also be seen in figure 4 that the height of the bioreactor was modified. The previous team's design was 8 feet tall while the current proposed design will be roughly 4 feet tall. The reduction in height was necessary to artificially light the reactor and to reduce the pressure supplied for the air pump. As the reactor height increases so does the fluid pressure at the diffuser. The pumping pressure necessary to overcome the pressure induced by the column height will also increase and produce a greater shear stress on the algae, which can exceed the max shear stress of the algae strain.

As photosynthesis occurs, hydrogen and small amounts of oxygen will be produced. It is therefore necessary to purify the hydrogen by removing the unwanted O_2. The purification will be done with an H_2 purifier, which can reduce oxygen, trace amounts of water, and organic compounds. At the outlet of the purifier the oxygen content will be 5ppm. Hydrogen purity less

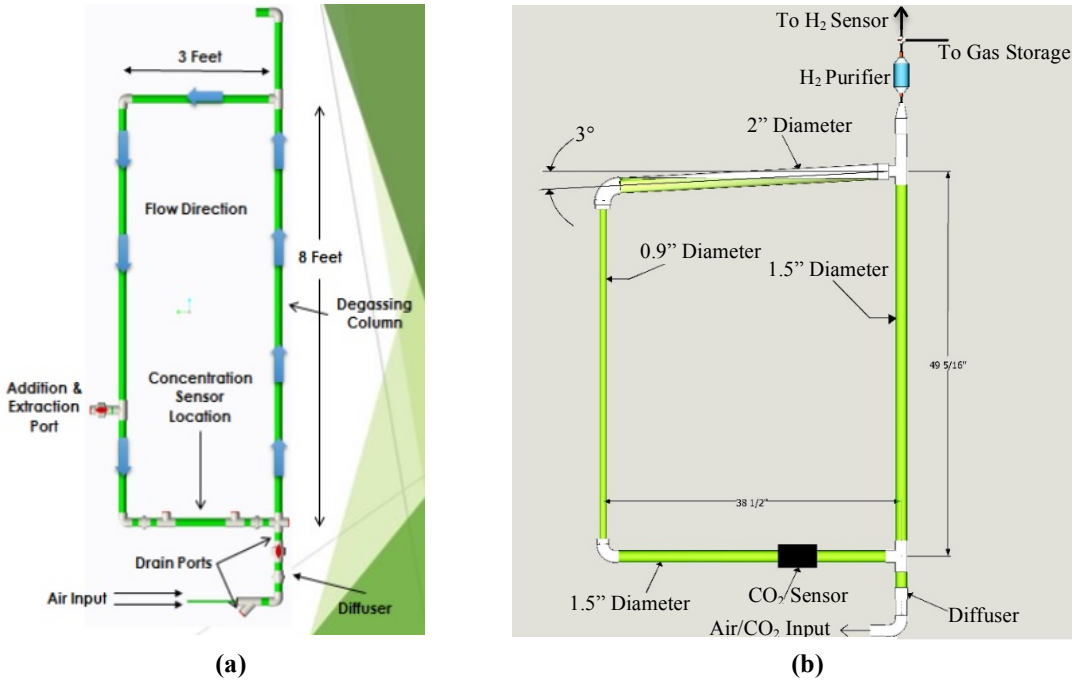


Fig 4: (a) Final design from 2014's Senior Team. (b) Current proposed design.

than 5ppm is beyond the scope of this project and should be done by an appropriate facility. The purifier has a ¼" fitting size and will be connected to the reactor via a 1.5" to 0.25" reducing PVC coupler. An airtight tee will be attached to the outlet of the purifier, which will divert the gas to the hydrogen sensor or the storage tanks. Some components of the proposed design will remain constant from the previous one. The CO_2 sensor will be used to make sure that the concentration does not exceed the amount required by the algae. The diffuser, air input, and drain ports will also be utilized in the proposed design as they are necessary. Detailed drawings of the current design can be seen in appendix A.

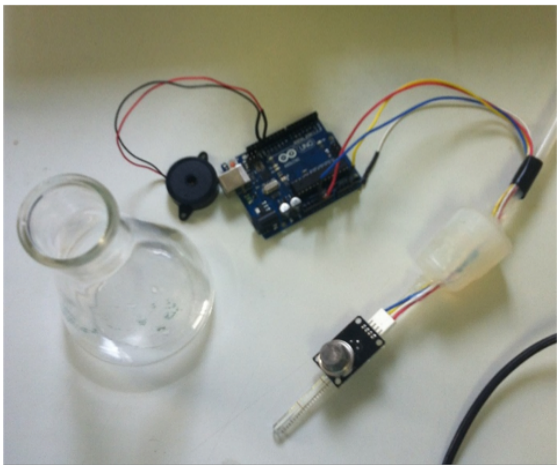


Fig 5: Prototype of H2 sensor system.

The sensor is a MQ-8 hydrogen gas sensor with a sensitivity of 100 – 10,000 ppm and is controlled through an Arduino Uno microcontroller board. The board has 14 digital input/output pins, 6 analog inputs, and a 16 MHz clock. The H_2 sensor and board requires programming and calibration for a correct readout. Figure 5 shows the prototype that has been assembled by the team in Brazil at UFPR. The system will operate on

5V with an input voltage of 7 – 12V, which will be supplied by an appropriate power adapter. When hydrogen is present, the system will alert the user through a chain of LEDs that light depending on the percent concentration, e.g. one LED for 5% concentration, two LEDs for 10% etc.

The hydrogen sensor will be placed within an airtight beaker with a sample of the algae being cultivated. As seen from the tests run at UFPR, if hydrogen is present, it will only take a few seconds for the alert programmed for the sensor to go off. The setup of the sensor within the beaker can be seen in figure 6. The sensor is programmed to continuously sense a concentration of H_2, but a constant reading will be unnecessary. If regular checks show hydrogen present, we are able to assume a constant hydrogen production. The full hydrogen sensor program code and dimension drawings can be seen in Appendix B.

Hydrogen can be stored as a gas, a liquid, or a solid using a metal hydride. Gaseous hydrogen storage is the most common form and perhaps the simplest storage method. Hydrogen gas is usually stored in a cylinder tank around 150-200 bars and at a temperature of 298 K. Adversely, gaseous storage is limited by volume considerations as a result of hydrogen's low density. Storage at high pressures can increase the energy density of gaseous hydrogen. Even at high pressures, large volumes of storage space are required which lead to high material cost.

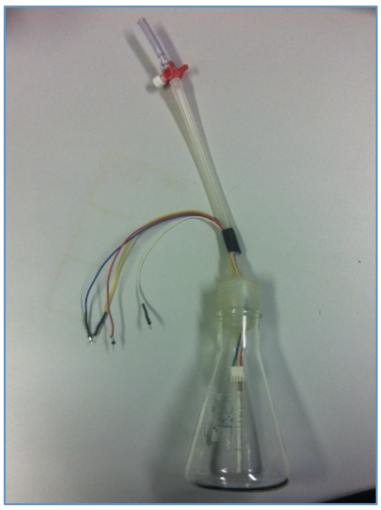


Fig 6: *Airtight beaker with sensor.*

Liquid hydrogen must be compressed more than gaseous hydrogen. The liquidification of hydrogen requires a large expenditure of energy, which may not be cost efficient. Liquid hydrogen is stored in cryogenic tanks. These tanks are usually spherical or cylindrical in shape in order to minimize surface area, which will also reduce heat transfer. In order to maintain its liquid form, it must be continually kept at a low temperature (i.e. less than 20 K). Cryogenic tanks are double walled with an evacuated layer of Perlite insulation to help sustain constant low temperatures. If the temperature of the liquid hydrogen rises too much, a high pressure could accumulate and result in damage or explosion. This is reflected by the high expansion ratio of liquid hydrogen to gaseous hydrogen.

Metal hydrides store hydrogen as a solid using some type of metal alloy. Hydrogen molecules are adsorbed into a metal matrix, which create a gas storage density that is higher than liquid hydrogen. Metal hydrides adsorb hydrogen at low temperatures and release the hydrogen when it is heated up. The need for heating and cooling requires that metal hydrides have additional control systems, which could be very expensive. Metal hydrides have the highest volumetric density and work well for restricted spaces. Although they store more hydrogen in a smaller space, they may not work well in systems that have weight restrictions.

B. Analysis

As mentioned above, physical properties of a reactor can influence light utilization of the algae and fluid properties such as gas holdup, superficial gas velocity, CO_2 mass transfer, and others. The surface area to volume ratio for tubular bioreactors is given as:

$$\frac{A}{V} = \frac{2\pi rl}{\pi r^2 l} = \frac{2}{r} = \frac{4}{d} \quad (1)$$

For the proposed design, the value of *d* used was the average diameter of 1.5 inches. Using equation (1) the area to volume ratio for the current proposed design is 2.67 in^{-1}. The higher the value for A/V the higher light utilization is. It should be noted that the value of A/V for this year's design is the same as 2014's design since it only depends on the diameter of pipe. Another important geometric property for bioreactors is the cross-sectional area ratio of the down-comer to riser. The area ratio is important for large-scale implementation as it shows a unit-less property of the reactor. The area ratio is calculated as:

$$\frac{Ad}{Ar} = \frac{\pi r_d^2}{\pi r_r^2} = \frac{r_d^2}{r_r^2} \tag{2}$$

The value of Ad/Ar for the proposed design was calculated as 0.36.

Along with light utilization, fluid properties can also influence the hydrogen output from the algae. Gas holdup is the volumetric gas fraction in a multiphase dispersion. It is calculated as:

$$\varepsilon = \frac{V_G}{V_G + V_L} \tag{3}$$

where V_G is the volume gas and V_L is the volume of liquid within the reactor. Gas holdup influences superficial gas velocity and the gas to liquid mass transfer [5]. Superficial gas velocity is the velocity of the gas bubbles that are produced by the air pump and diffuser. Superficial gas velocity is crucial in the cultivation of algae within the bioreactor. If the gas bubble velocity is too high, the shear stress produced by the bubble can exceed the max shear stress of the algae strain and break it apart. Gas bubble velocity was calculated for *Chlamydomonas reinhardtii strain using its max shear stress of 0.1 dyne/cm^2 or 0.01 Pa, which was determined from previous research [6]. No shear stress values were found for scenedesmus sp* so the same gas bubble velocity determined from *Chlamydomonas reinhardtii* will be used. Using the shear stress value of 0.01 Pa and the equation for shear velocity:

$$v_{(shear)} = \sqrt{\frac{\tau}{\rho}} \tag{4}$$

where τ is the shear stress and ρ is the density of water or solution. From equation (4) the value of the shear velocity is 3.16 x 10^{-3} m/s. To determine the gas bubble velocity it was assumed that the shear velocity is 1/10th the mean flow velocity, and the velocity of the gas bubble was determined as 0.0316 m/s [7]. Next, the required gas volumetric flow rate of the pump was calculated using:

$$v_{gas} = \dot{V}_g / A_r \tag{5}$$

where A_r is the cross sectional area of the riser. The calculated volumetric air-flow rate of the pump is $3.61\text{x}10^{-5}\,\frac{\text{m}^3}{\text{s}}$.

Algae specimens require inorganic carbon in order to produce biomass. Inorganic carbon exists in various forms in liquid environments when the temperature and pH levels are right. Resistance to CO_2 diffusion can be a limiting factor during mass transfer [13]. The rate of mass transfer can be calculated from:

$$N_{CO2} = k_L a(C_{CO2}^{*} - C_{CO2}) \quad (6)$$

Where k_L is the liquid-phase mass transfer coefficient and a is the area available for mass transfer.

The net energy ratio (NER) is defined as the ratio of total energy produced in terms of biomass and hydrogen divided by the operation energy:

$$\text{NER} = \frac{\Sigma \text{ Energy Produced}}{\Sigma \, Energy \; Input} \quad (7)$$

In order to make use of the hydrogen obtained from the microalgae, it must be purified, compressed, and stored. When hydrogen is initially collected from the bioreactor, there will be many other gases present such as oxygen, nitrogen, and carbon dioxide. A gas purifier is needed to obtain a more pure and usable form of hydrogen. For this project, an OxiClear inline gas purifier will be used. It has a maximum flow rate of 5 mL/min, an operating pressure of 5 psi to 125 psi and a fitting size of .25 in. This is smaller than the tube outlet of the bioreactor so a coupling must be installed. The purifier will be installed vertically to ensure satisfactory removal of contaminants. This specific purifier was chosen because of its high efficiency and low resistance to gas flow. Once the hydrogen gas has been purified it will then be compressed to an appropriate pressure based on the compressed tank used.

When hydrogen is stored, it does mechanical work and stores energy [13]. If hydrogen is treated like an ideal gas, the work needed for adiabatic compression of one mole of hydrogen can be found through the following equation:

$$W_{ad} = \int_{p_2}^{p_1} PdV = (p_1 v_1 - p_2 v_2)(r-1)^{-1} = R(T_1 - T_2)(\gamma - 1)^{-1} \quad (8)$$

Where:

- R is the gas constant
- P_1 is the pressure before compression, P_2 is the pressure after compression
- V_1 is the volume before compression, V_2 is the volume after compression
- T_1 is the temperature before compression, T_2 is the temperature after compression
- γ is the specific heat ratio: $\frac{C_p}{C_v}$

Treating hydrogen as an ideal gas will lead to error in volumetric calculations. In order for accurate solutions, hydrogen must be treated like a real gas. The discrepancy between the volume of ideal and real gas is solved using the compressibility factor Z [13]. The solution to this discrepancy is shown by adding Z in equation (9).

$$PV = nZRT \quad (9)$$

The compressibility factor Z is essential as the pressure increases and temperature decreases. The compressibility factor can be found by solving equation (10).

$$Z = 1 + p[A + BT^{-1} + CT^{-2} + DT^{-3} + ET^{-4}] \quad (10)$$

Where:

- p is the pressure
- T is the temperature
- A = $4.93482*10^{-5}$
- B = 2.04036
- C = 81.5334
- D = $-65561*10^{4}$
- E = $4.56516*10^{6}$

C. Evaluation of Designs

Hydrogen Storage

The final design selection was based on the following criteria: economic feasibility, safety, hydrogen storage capacity, minimal weight and size, ease of use, and the ability to undergo multiple charge and discharge cycles. The scoring breakdown for each criteria can be seen in the design matrix in table 1. Affordability, size, and storage capacity can be very closely related if there is a need for a mass amount of storage. For example, liquid storage in cryogenic tanks was given the highest score in affordability mostly because of its ability to store hydrogen with respect to its size. Even though compressed gaseous tanks of the same size are cheaper, they are not able to store the same amount of hydrogen as cryogenic tanks. For this project, large amounts of hydrogen are not expected so a gaseous compressed tank would be sufficient. Safety plays a huge role in determination of an appropriate hydrogen gas storage tank. Hydrogen is an extremely combustible gas so precautions must be made when handling it. The bioreactor design has been sized down for use in an indoor lab. Because of this, a hydrogen storage tank of a smaller size and weight would be most ideal. Another important determining factor is the ability of the storage system to undergo multiple charge and discharge cycles. The tank should be able to handle taking in hydrogen as well as releasing it an unlimited number of times. Additionally, the tank should be easy to use and require minimal operation in order to avoid additional maintenance.

Table 1: *Hydrogen Storage Decision Matrix*

Criteria	Hydrogen Storage Options		
	Gaseous	*Liquid*	*Solid*
Affordability	6	7	5
Safety	8	4	10
Storage Capacity	6	8	10
Small Size	7	7	9
Lightweight	6	8	3
Lifetime (number of cycles)	8	8	5
Ease of Use	10	5	4
Weighted Sum	**51**	**47**	**46**

Hydrogen Gas Sensor

One of the changes that will be made from the beginning of the semester is the sensor selection. At UFPR, the sensor currently being used is the MQ-4, which is able to detect several natural gases. The decision to change to the MQ-8 sensor was made by the fact that the new sensor only

detects hydrogen gas. We hope this will lead to clearer and more precise readings. Challenges encountered so far will be with the lab production of hydrogen. The first strain used, scenedesmus, yielded no results and was unable to produce hydrogen. Once switching to the *Chlamydomonas reinhardtii* algae species, hydrogen was successfully produced.

D. Programming Needs and Control

Because this project focuses on the production of hydrogen, a hydrogen sensor is essential for determining if hydrogen is being produced. As stated previously, a MQ-8 sensor is being used because of its ability to detect concentrations of hydrogen gas. The hydrogen sensor will be located immediately after the gas purifier outlet. Algae only produces hydrogen under specific conditions such as depriving it of nutrients like sulfur. The use of a hydrogen gas sensor will be helpful in determining how well the growth mediums are working and if any other options should be explored. The bioreactor is also in need of an automated continuous addition and extraction unit. This unit will replenish the bioreactor with nutrients and water as needed. It will also remove any dead algae. Without this addition and extraction unit, the bioreactor must be completely drained in order to remove dead algae and replace the bioreactor with a new growth medium and water. Completely draining the bioreactor could be very costly. An automated addition and extraction unit will increase the efficiency of the bioreactor and make it more marketable for large scale commercial use.

2. Final Design

A. Photobioreactor

The photobioreactor used for this project is an external loop airlift photobioreactor with a tube separator [5]. Figure 7 shows the CAD drawing of the photobioreactor. The photobioreactor is constructed from schedule 40 clear PVC pipe and standard PVC pipe fittings. Clear pipe should be used to allow sunlight utilization by the algae. Clear PVC schedule 40 is manufactured from a type I, grade I Polyvinyl Chloride (PVC) compound with a cell classification of 12,454 per ASTM D1784. This class of pipe offers high impact strength, long life when exposed to weather, and low cost. Specs of the photobioreactor are as follows:

- Total length of piping = 16 feet (9 ft of 1.5" pipe, 3 ft of 3" pipe, and 12 ft of 1" pipe)
- Total volume = 2.09 gal (7.91 L)
- Total volume w/ headspace = 1.31 gal (4.95 L)
- Weight = 25 lbs
- Max height = 6 ft
- Max width = 3 feet 5 inch

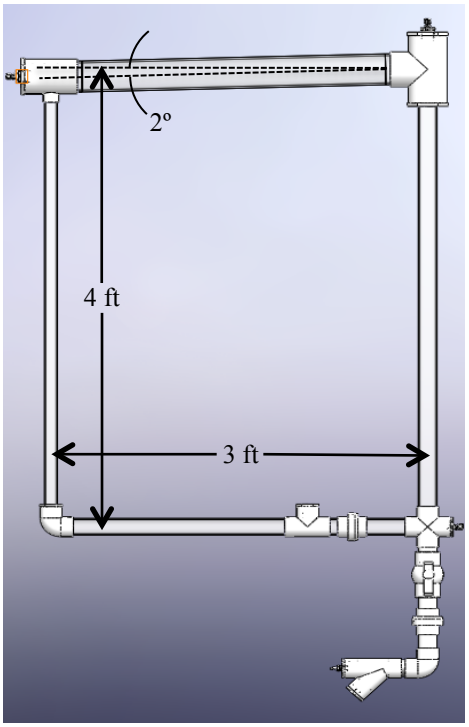


Figure 7: PBR drawing without components

Two crucial components of the photobioreactor are the gas separator and the downcomer tube, which can be seen in Fig. 8. The gas separator allows for liquid circulation and gas disengagement. The downcomer tube is also important, in terms of it's cross sectional area. A 60 percent area reduction was used in order to maintain a pressure similar to that in the riser tube. Reducing the cross-sectional area of the downcomer will help with gas holdup, mass transfer of CO_2, and other important fluid flow patterns [5].

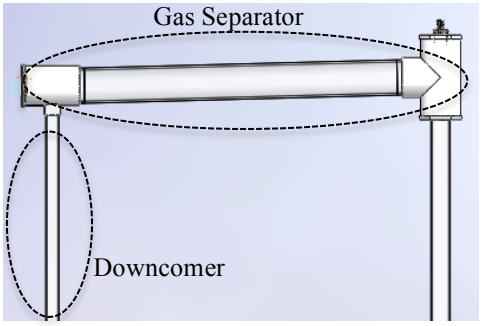


Figure 8: Downcomer and gas separator components of PBR

B. Concentration Sensor

The concentration sensor consists of a light dependent resister, 4 LEDs, a microcontroller, and an enclosure. The sensor was designed and built by 2012-2013's senior design team 7. Figure 9 shows the (a) finished concentration sensor and (b) function diagram developed by team 7 [20]. The sensor measures the concentration through light obscurity i.e. the higher the concentration of algae cells, the lower the amount of light will hit the LDR. The amount of light hitting the LDR is measured as a voltage, which is then converted to

an 8-bit value used in the programming of the sensor. Some of the specs of the concentration sensor include:

- Length = 11.5 inch
- Diameter = 4.5 inch
- Diameter of opening = 1.5 inch
- Arduino Uno microcontroller
- LDR max operating voltage of 100 VDC, 2 ~ 6 (10Lx) (KΩ)
- 5 mm LEDs with operating voltage of 3.2 VDC, and 20 mA

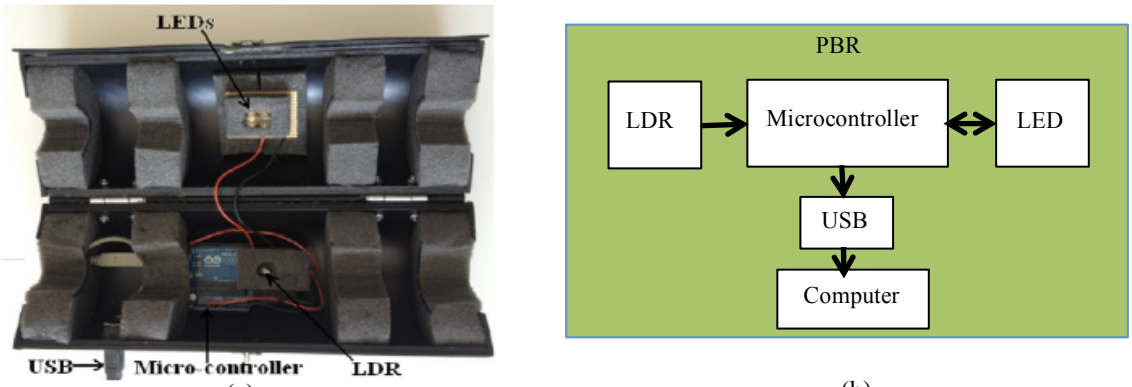


Figure 9: (a) Prototype and (b) function diagram of algae concentration sensor

C. Addition / Extraction ports

Both addition and extraction ports are necessary in order to achieve a continuously operating system. The components of the addition / extraction system include:

- 2 – solenoid valves
- A microcontroller
- A motor driver

The solenoid valves are powered through a motor driver and controlled by an Arduino Uno microcontroller. Figure 10 shows the wiring schematic of the addition and extraction system. Component specs of the addition / extraction system are:

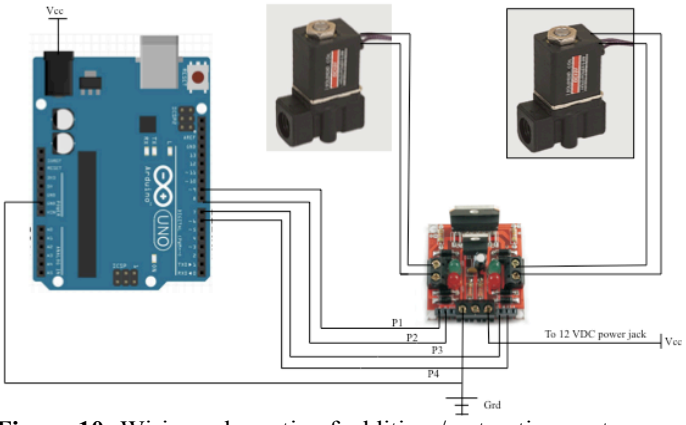


Figure 10: Wiring schematic of addition / extraction ports.

- Valves: 12 VDC, 2 way normally closed, Cv = 0.23, ¼" NPT port size, Operating power ~5 W
- Motor Driver: 5 – 26 VDC operating, 5 VDC control input, peak output current = 3 A

The addition and extraction are gravity fed systems, which requires a 6-liter container or bucket arranged so that the bottom outlet of the bucket is at least one foot higher than the addition port in order to provide an adequate flow rate.

D. Air/ CO_2 Input

To increase algae concentration in the pbr, air and CO_2 must be supplied. For this project, the CO_2 supplied comes from atmospheric air and not an external CO_2 tank. A compressor was used to supply the air, while the relay switches the compressor on and off at specific intervals. The specs for the compressor and relay are as follows:

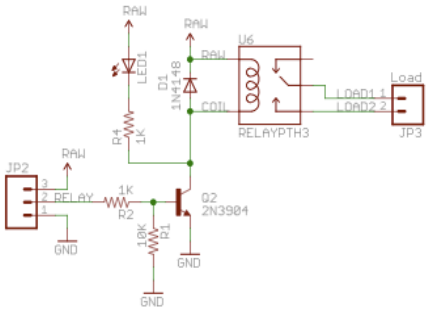
Air Compressor

- Capacity = 1 gal
- 0.51 SCFM at 40 PSI, 0.39 SCFM at 90 PSI
- Voltage = 120 VAC
- Amperage = 2 A
- Weight = 16 lbs.

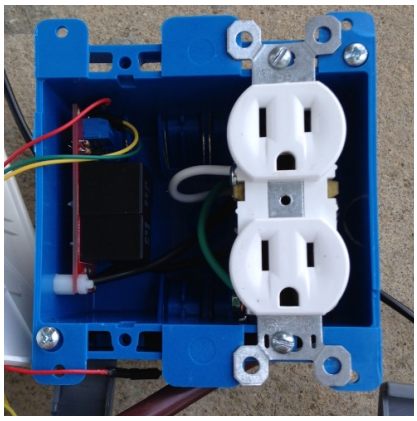
Relay

- JQX – 15F solid state relay
- Control voltage = 5 V
- Control amperage = 185 mA
- Rated load of 220 VAC, 20 A

The wiring schematic and completed assembly can be seen in Fig. 11 (a) and (b), respectively. Figure 7 (b) shows the relay housed in an electrical box and connected to a standard 120 VAC



(a)



(b)

Figure 11: Wiring schematic for relay (a), and completed assembly (b).

electrical outlet.

E. H_2 Purifier

A purifier was used in order to remove impurities from the produced hydrogen gas. It is important to purify the hydrogen as much as possible for gas storage, increased energy output,

and to prevent the release of pollutants. The purifier is a disposable OxiClear gas purifier and can be seen in figure 12. Some of the specs include:

- Length = 7 ½ inch,
- Diameter = 1 ½ inch
- Disposable when capacity ~ 1200 cubic ft. standard grade H_2 gas
- Min working pressure drop = 0.3 psi
- Reduces O_2, H_2O, and other impurities to < 15 ppb
- ¼ OD compression fittings

Figure 12: Hydrogen gas purifier used.

F. H_2 Concentration Sensor

The concentration of hydrogen gas produced can be measured using the assembled system seen in figure 13. The system includes a MQ-8 gas sensor, an Arduino Uno microcontroller, a LCD display, and a 100 mL Erlenmeyer flask. The specs of the hydrogen sensor are as follows:

- Sensitivity ≥ 100 ppm H_2
- Operating voltage = 5 VDC
- Working O_2 concentration between 2% and 21%
- Requires 24 hr. preheat time

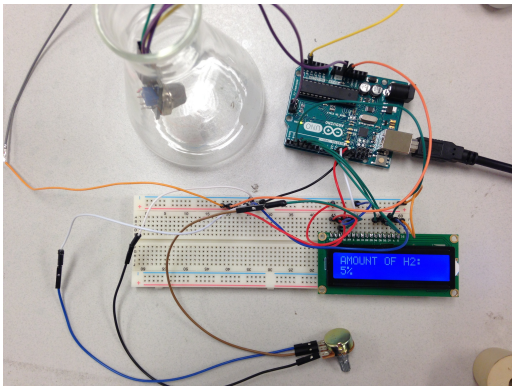


Figure 13: Current H_2 concentration sensor

G. Photobioreactor Stand

The photobioreactor stand was assembled using 2013's prototype and new materials. It is composed of pressure treated 2" x 4" and 2" x 6" wood, along with roofing brackets and galvanized wood screws. The purpose of the stand is to support the photobioreactor and the DAQ system, which is used to control the electrical components. Figure 10 shows a CAD drawing of the pbr stand. Some of the specs include:

- Height = 8 ft, Width = 3.5 ft.
- 41 ft of pressure treated wood
- Weight = 40 lbs
- Platform for addition solution storage

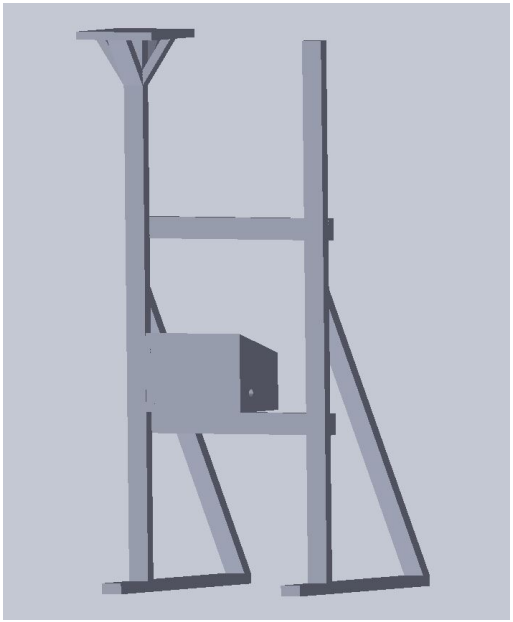


Figure 14: Photobioreactor stand.

G. Project Assembly

Upon assembling and testing each component mentioned above, the entire photobioreactor system was assembled. First, the photobioreactor was

connected to the stand via the upper supports and pipe clamps. Second, the H_2 purifier and addition/extraction valves were connected to the reactor using ¼" 304 stainless steel tubing. Next, the air compressor and hydrogen gas sensor were connected via plastic tubing. Finally, the algae concentration sensor was set, and the components connected to the their appropriate ports. Figures 15 shows the CAD drawing of the photobioreactor system assembly.

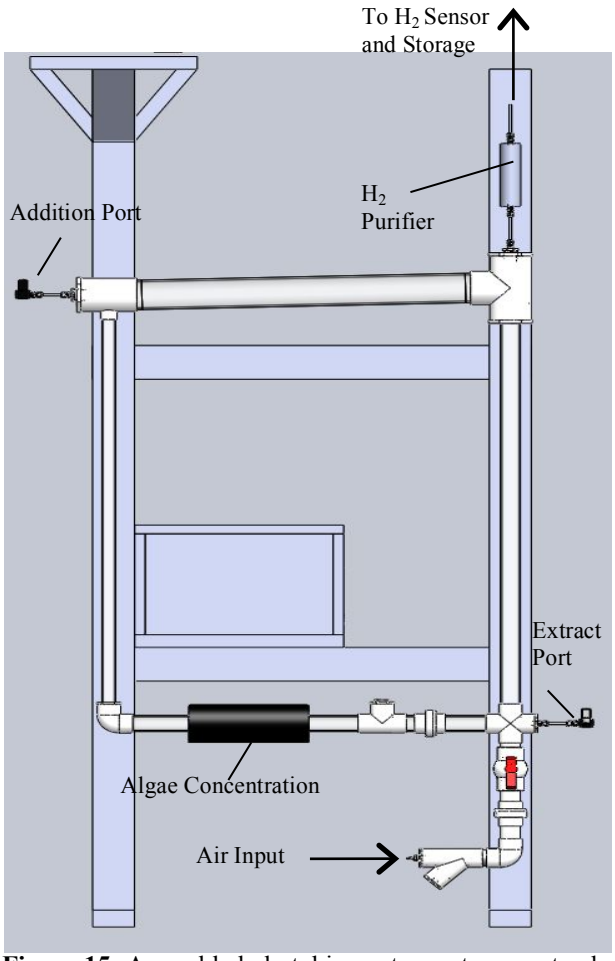


Figure 15: Assembled photobioreactor system on stand.

3. Design of Experiment

The main function of this project involves the semi-continuous production of H_2 from algae in a continuously operated photobioreactor (pbr). A second function of this project is the concentration measurement of H_2 being produced by the algae in the pbr. The production of H_2 is made possible by several components of the pbr, which include:

A. Airlift Photobioreactor
B. Algae concentration sensor
C. Addition/Extraction ports
D. Air/CO_2 input

The secondary components serve the purpose of purification and analyzing the system's functionality. These components include:

E. H_2 purifier
F. H_2 % concentration sensor

Figure 16 shows the overall system diagram, which includes the components listed above. Components A-D function to assist H_2 production while components E and F help in analyzing the system. As can be seen in figure 16, the main component is the photobioreactor, and the secondary components are attached.

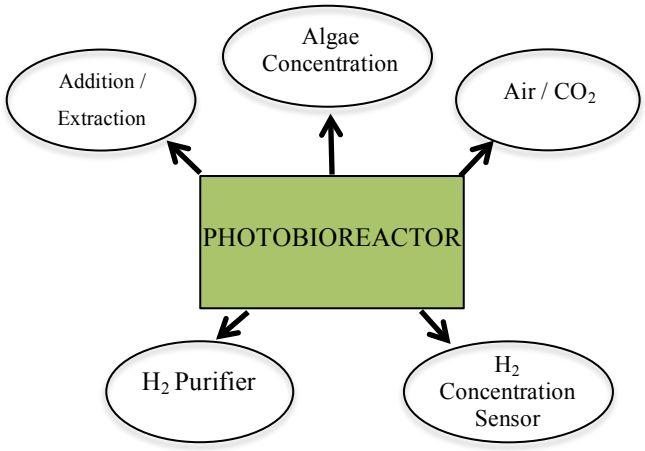


Figure 16: Overall system diagram showing all components

For the operation of the photobioreactor to be continuous and to work properly, there are several factors that need to be correctly connected and checked to make sure they are functioning. Once the components are assembled as stated previously, the code for the master controller and the code for the slave controller are to be uploaded to the two Arduino boards. The master controller controls the solenoid valves and the relay, while the slave controller controls the concentration sensor. Both of the controllers work together to maintain the continuous process seen in figure 17.

The way the code is written for the master controller board is that once it is initially manually filled with algae, the master controller will then send a signal to the relay, which powers the air compressor. The air compressor will be

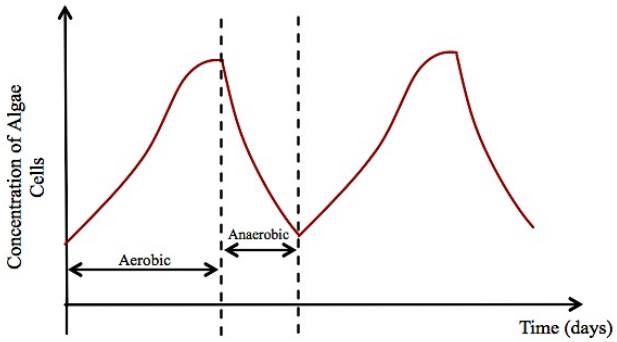


Figure 17: Correlation between hydrogen output and sequence of operation.

on during the entirety of the aerobic cycle. Simultaneously, via serial ports, the master controller will be obtaining values from the slave controller, which will be storing values read by the concentration sensor until a maximum concentration is detected. This value will be the peak of algae growth and is the point in which the air pump will be shut off. Once the air compressor shuts off, the anaerobic cycle begins and hydrogen production will take place. The slave controller will continue reading values from the concentration sensor until a minimal value is detected. This is when much of the algae cells are dead, and the extraction port opens until the pbr is emptied. After the extraction valve closes the addition valve opens until the photobioreactor is filled to the appropriate level. There will be a slight delay between the extraction port being closed and the addition port to be opened. It must be noted that the amount of time it takes for the bioreactor to be emptied and filled should be determined experimentally. At this point, the cycle will begin again and will be continued until the compressor's power source is shut off. Any hydrogen that is produced will go through the hydrogen purifier. A storage unit should be added above the purifier to collect the hydrogen to be used in an energy production application.

For the hydrogen sensor, it must be plugged in 24 hours before usage. This time is allotted for the sensor to preheat, which allows for more accurate readings. While the sensor is preheating, the connections made between the Arduino board and the LCD should be checked, as well as the code for the Arduino board should be uploaded. There is a code supplied in Appendix A to check that the connection of the LCD is functioning. Once the assembly is finished and the hydrogen sensor is preheated, it is ready for operation. The flask should be evacuated for accurate measurements. The air compressor can be used to evacuate the flask via a hose connected to the inlet side of compressor and the flask. This should only take a couple seconds and will create a vacuum within the flask. The tubing should be connected to the connection found above the hydrogen purifier. Once the valve is switched to open, the vacuum in the flask will cause the gases to move into the Erlenmeyer flask. This is the point in which the sensor will begin working and the LCD will output the percent of hydrogen contained within the flask. The valve should be closed after the flask is filled, which should only take a couple seconds.

4. Consideration for Environment, Safety, and Ethics

A. *Hydrogen*

Hydrogen is a flammable gas that can ignite over a very wide range of combustible concentrations in air, between 4% to 75%. Compared to gasoline, propane, and natural gases this is a very wide range as shown in figure 18 [14]. Furthermore, this gas requires very low ignition energy to ignite − about one-tenth of the energy needed to ignite gasoline vapors − so a lit cigarette, or even a spark released from a person with an excess of static electricity, can cause hydrogen gas to ignite at its stoichiometric fuel-air mixture of 29% [15]. Hydrogen gas burns at a

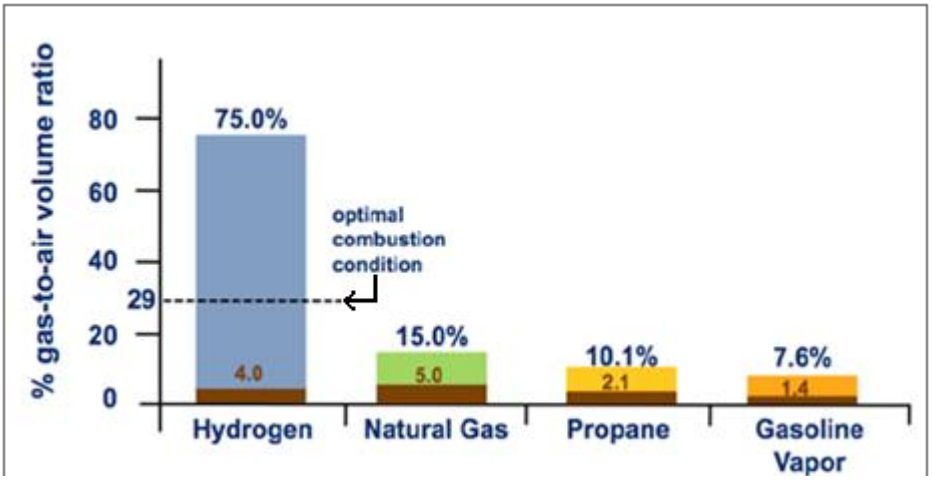


Fig 18: *Gas to Air Volume Ratio*

temperature of 3,713 ºF (verses 2,276 ºF for gasoline) but radiates little infrared heat, and no smoke, making inadvertent contact with the flame a strong possibility [16]. It does, however, emit significant amounts of ultraviolet radiation which can be dangerous should overexposure occur [14]. Also, the flame is almost undetectable by the human eye making detection measures a high priority to avoid the hazard presented by the ignited gas.

Not only is hydrogen gas flammable, like any other gas it has the potential to explode as well. A hydrogen cloud that grows as a result of a leak in a confined space, or the accumulation of gas in a covered area outdoors, produces an explosion hazard. Flames can spread through the cloud at a velocity of several meters per second, and when the fuel is detonated in a closed area it can create an increase, of almost eight times, in the pre-explosion pressure [14] [15]. Should the detonation occur in a tank of hydrogen the pressure increase would happen so quickly that devices designed to relieve pressure become obsolete [15]. Furthermore, the pressure could increase to a point that is high enough to explode buildings which could cause even more catastrophic damage. Detonation of hydrogen gas can also occur over a wide variety of mixtures, ranging from 18.3% - 59% [15].

Due to the low viscosity, buoyancy, diffusivity, and molecular size of hydrogen gas it is difficult to contain, therefore, this gas is prone to leaks [15]. Not only can these leaks create a combustible situation, it can also create an environment that is harmful to respiration. In a

smaller confined space, all gases (except oxygen of course) may cause asphyxiation, and even though this may be rare due to its physical properties, it is still a possibility [15]. The possibility of a jet stream forming that extends meters poses an even greater threat; should the stream ignite it could cause serious damage to anything in the path of the jet flame or in the blast radius should an explosion occur [14].

B. *Microalgae and Constituents*

When growing microalgae a media rich in various nutrients must be used; these nutrients include, nitrogen, potassium, and phosphorous, among many others. The photobioreactor must be expunged of this media (and the microalgae) at the end of the organism's life cycle. Casually disposing of the algae and the nutrient rich water that it grows in, into the sewage or other aquatic outlets can have negative effects on the environment. Disposing of the growth media into other waterways can create nutrient dense marine environments that promote the growth of other strains of algae [16].

This "algae bloom" can have several effects on the biodiversity such as the increase in toxicity of the water. Various types of algae produce toxins that harm the water supply so human and animal exposure to these toxins is dangerous and can lead to various health problems or even death; more and more incidents of the effects of this algae toxicity are being reported [16]. Not only is the toxicity a major issues when it comes to environmental and safety issues, but so is the chemical reactions that occur as a result of the presence of dying algae or the components of the media that is grew in. For instance, as algae decays they release nitrogen and phosphorous, but also consume oxygen from the water source [17]. Nitrogen and phosphorous assist in the growth of new algae and can lead to undesirable levels of toxins that may poison people, wildlife, and other creatures of the environment. The low levels of oxygen lead to fish kills in which large amounts of fish die due to a lack of oxygen supply in the water [17]. Also, depending on the solution, if it is copper enriched, the copper in the solution will form a new toxin in the water (copper carbonate) that will interfere with certain bacteria decomposition, which could negatively affect the breakdown of sewage [17]. Furthermore, parasites may grow in the water where the algae is disposed of due to a spike in pH levels caused by the growth of algae in an unnatural and uncontrolled environment [18]. In order to counteract the environmental and safety issues associated with the disposal of dead microalgae close attention must be paid to how and where it is discarded.

5. Project Management

A. Gantt Chart

Please refer to Appendix B for full Gantt Chart.

B. Budget

The list of materials and cost of each components is seen below in Tables 2-4. The first table briefly outlines the materials used for algae growth and cultivation. Roughly $130.42 was wasted on the purchase of incorrect growth media and faulty algae solutions. The first sets of algae ordered were dead when they arrived. The initial solutions ordered also contained sulfur while our team needed a sulfur-free solution for our specific needs. Because of this mix up, our team ordered an algae cultivation kit from the University of Minnesota. This kit was more useful since it included all the necessary materials for successful algae cultivation. This kit included two chlamydomonas algae cultures, sulfur-deficient media, and medical grade pipettes. In total, algae growth materials should have only cost $75.00 where as we spent a total of $205.02. Our team was able to save additional money by using equipment available in the CAPs building and equipment leftover from last year's design project. This "donated" equipment includes microscopes, microscope slides, hand-counter, Erlenmeyer flasks in various sizes, artificial lighting, air chamber, distilled water, and cleaning products. Because of the availability of equipment, future teams will only need to purchase algae cultures and growth media. Our recommendation for future teams is to purchase an algae culture kit that is all-inclusive. This will save money and ensure that they have all necessary materials.

Table 2: *Microalgae Materials*

Part	Vendor	Cost	Qty.
Scenedesmus Algae	Carolina Biological Supply	$21.66	3
Chlamydomonas Algae	Carolina Biological Supply	$32.36	3
Bold Basal Solution	Sigma-Aldrich	$38.90	1
TAP Solution	Life Tehcnologies	$37.50	1
Hydrogen Evolution Kit	Unv. Of Minnesota	$42.50	1
Hydrogen Evolution Supplement	Unv. Of Minnesota	$32.50	1
	Total Cost	**205.42**	

The airlift photo bioreactor and frame were built with cost effective materials that would also meet our performance standards. The breakdown and cost of each component can be found in Table 3. The photobioreactor was made of standard-wall clear PVC unthreaded pipe purchased from McMaster-Carr. The piping is very strong and corrosion resistant which allows the photobioreactor to have more versatile use. The piping's ability to withstand corrosion allows the bioreactor to be outdoors if artificial lighting is not an option. All fittings and elbows were also purchased from McMaster-Carr. Parts were ordered to size in order to minimize machining. Our team tried to use a piece of piping from the previous team's photobioreactor to minimize costs. However, because the last year's photobioreactor was left outdoors for an extensive period of time the piping became very brittle. When incorporated into our design, the old piping cracked after a single use during testing. Because we had extra piping, we were able to easily replace this section without any added cost. The frame for the photobioreactor was donated so it came to no extra cost. The frame was built simply using prime pressure treated lumber, nails, screws, and hooks. The total cost of the photobioreactor was $456.17.

Table 3: *Photobioreactor Materials*

Part	Vendor	Cost	Qty.
1” Clear PVC Pipe 4 feet	McMaster-Carr	$17.99	1
3” Clear PVC Pipe 4 feet	McMaster-Carr	$68.60	1
3x1x3 Pipe Size, Reducing Tee	McMaster-Carr	$8.34	1
1.5” 90 Degree Elbow	McMaster-Carr	$1.16	1
3” PVC TEE	McMaster-Carr	$7.66	1
3” Male to 1.5” Female Bushing	McMaster-Carr	$4.37	1
1.5” Male to 1” Female Bushing	McMaster-Carr	$1.90	2
3” Male to 1” NPT Female Bushing	McMaster-Carr	$6.46	2
1” Male to 0.25” Female NPT Bushing	McMaster-Carr	$2.88	2
Adapter ¼” OD to ¼” NPT Male	McMaster-Carr	$11.66	1
Abrasive Nylon Tube Brush	McMaster-Carr	$7.81	1
3” Square-Head Plug, NPT Male 40	McMaster-Carr	$7.08	2
Hydrogen Gas Purifier	Sigma-Aldrich	$206.00	1
1.5” Clear PVC Pipe	McMaster-Carr	$16.38	1
1.5” to 0.25” Bushing	McMaster-Carr	$3.32	2

0.25” OD to 0.25” NPT Tube Fitting	McMaster-Carr	$20.12	4
3ft. Length ¼” OD Steel Tube	McMaster-Carr	$22.62	2
1.5” Clear PVC Pipe	McMaster-Carr	$27.45	1
Pipe Union	McMaster-Carr	$9.23	1
1.5” PVC Cross	McMaster-Carr	$3.60	1
1.5” PVC Tee	McMaster-Carr	$1.54	1
	Total Cost	**$456.17**	

Because many items were out of stock, the sensors and controls system took the longest to complete. A breakdown of the components used for constructing the hydrogen sensor and addition and extraction units is shown in Table 4. Most of the sensor components were purchased through SparkFun. Once all components were purchased, the hydrogen sensor was assembled quickly. Again, because many items were donated by the previous year's design team, our total cost was minimized. Our team was able to use the concentration sensor from the previous year and only had to make minor changes. The air pump used to circulate the algae and nutrients was also donated. The National High Magnetic Field Laboratory donated hydrogen to our team which allowed us to successfully calibrate the completed hydrogen sensor. The total cost of sensor components came to $150.96.

Table 4: Sensor and Controls Materials

Part	Vendor	Cost	Qty.
Arduino Uno R3 Microcontroller	Sparkfun Electronics	$24.90	1
4-Wire Jumper Assembly	Sparkfun Electronics	$3.00	2
Arduino Uno Starter Kit	SainSmart	$36.79	1
Relay (for air pump)	Sparkfun Electronics	$7.95	1
MQ-8 Hydrogen Gas Sensor	SainSmart	$18.20	2
Cytron LCD Keypad Shielf	RobotShop Inc	$11.26	1
12 VDC Solenoid Valve	Sizto Tech Corp	$48.86	2
	Total Cost	**$150.96**	

The total cost of our prototype including algae experiments came to $812.55, which was $187.45 under budget. Not including algae experiments, the constructed photobioreactor equipped with sensors only cost $607.13. This was possible due to the amount of donations and resources we

received which allowed us to make better use of our budget. Although we picked the best combination of shipping rates and shipping times, shipping costs for many of the components were still very high. Donations allowed us to remain under budget while successfully constructing the photobioreactor and necessary sensors. Because the constructed photobioreactor is only a prototype, cheaper materials were used in its construction. Once the photobioreactor undergoes adequate testing to prove that it works, it can be upgraded using more expensive and durable materials for long-term use.

As stated previously, the total cost of the photobioreactor equipped with the hydrogen sensor and concentration sensor was $607.13. Most photobioreactors have been constructed for high-volume output. There are very few photobioreactors available that are smaller scale. This makes it difficult to provide an accurate assessment of product cost. However, in comparison to the few smaller scale photobioreactors that are on the market, this photobioreactor is very affordable. Table 5 below shows a comparison of our prototype with 3 commercially available photobioreactors and a graphical display is shown in Figure 19.

Table 5: *Commercially Available Photobioreactor Comparison*

	Team 9	Alga4	Alga5	Alga 6
Volume (L)	4.95	500	2,000	12,500
Cost	$607.13	$2,175	$2,475	$3,375

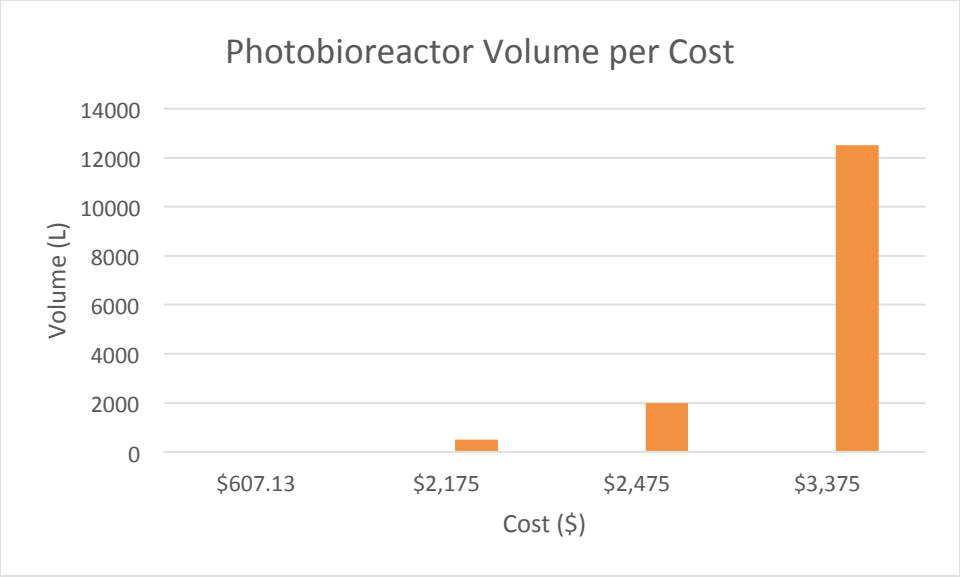


Figure 19*:* Commercially Available Photobioreactor Comparison

The only small-scale commercially available photobioreactors our team found came from AlgaSol. However, the information regarding their photobioreactors was very limited. There was no indication of what types or if any sensors are included in their design. Implementation of sensors would increase the overall cost of the photobioreactor. In terms of cost per liter, our

design is roughly $122 per liter whereas the Alga4 has a cost of $4.35 and is the most expensive AlgaSol design in terms of price per liter. This information tells us that we may need to explore further options when it comes to the actual photobioreactor components. However, the limited information given about AlgaSol products makes it difficult to reach a concrete conclusion.

There are very few hydrogen gas sensors available on the market. The few sensors that we found were developed for use in large industry plants to detected gas leaks. These sensors are very expensive, ranging from $300-$1000. Overall, this type of sensor would not be suitable for our application so it is difficult to make an effective cost comparison. The cost of our hydrogen sensor was roughly $90. We have been unable to determine whether this product is cost-effective based on limited availability of similar sensors. The same issue arose with the concentration sensor. We have been unable to locate any commercially available sensors of this type. Because this item was donated by the previous team, we don't have an accurate reflection of product cost. Based on typical costs of the components used in creating the concentration sensor, the cost should be somewhere between $80 and $100.

6. Conclusion

The continuous development of renewable energy sources like that of hydrogen can make a positive impact on society. Decreasing society's dependency on fossil fuels will not only create a cleaner atmosphere by reducing greenhouse gas emission, but it is also an economically viable energy option. This design project was focused on developing a continuously operating photobioreactor that will assist in the semi-continuous production of hydrogen. The final design incorporates several components to accomplish these tasks. The components included were an algae concentration sensor, air input system, addition/extraction system, H_2 percent concentration sensor, and H_2 purifier. Due to budget and time constraints it was necessary to use the prototype from the 2013-2014 senior design team. This design was chosen because of its simplicity and the fact that it is an airlift bioreactor, which has the advantages of good mixing, effective mass transfer of CO_2, high S/V ratio, and good removal of O_2. However, several modifications had to be made so that the photobioreactor could be optimized for hydrogen gas output. Two important characteristics of the proposed design include the surface area to volume ratio and the cross sectional area ratio between the down-comer and riser with values of 2.67 in^{-1} and 0.36, respectively. A gas separator region was also added in order to improve H_2 gas exchange. It was also necessary to calculate the maximum velocity of the gas bubbles produced by the air input system so that the shear stress the algae are subjected to does not break them up apart. The max mean bubble velocity calculated in this case was 0.0316 m/s.

After designing and building the photobioreactor system it was evident that there were some issues with the function of the system. First, the circulation of CO_2 bubbles within the reactor was not adequate. One of the biggest factors of this problem was due to the air compressor used. The pressure and volume flow rate of air delivered from the air compressor was too large, which caused the bubbles to burst once they reached the top of the riser tube. A smaller air pump with a higher degree of pressure control should be used in order achieve the desired superficial gas bubble velocity and circulation of algae. Another issue was the implementation of the concentration sensor with the current design. The biggest factor was writing code in order to combine all of the components to the concentration sensor. More time should have spent to solve this problem. Overall, the basic scientific principles and ideas used to develop the system are sound so the finished prototype should function to assist hydrogen production if minor changes are made.

Future Recommendations

It is important for future teams to improve the current system proposed in order to maximize hydrogen production. Some key areas for improvement include:

- Experiment with mutant strains of algae, which might yield higher amounts of hydrogen gas.
- Reduce input power to system for greater net energy output.
- Improve air input system by implementing an air pump and not an air compressor. The air pump should have a higher degree of pressure control, which would improve algae and CO_2 circulation.
- Develop a H_2 mass flow censor instead of percent concentration sensor.

- Develop ideas for large scale implementation of proposed design.

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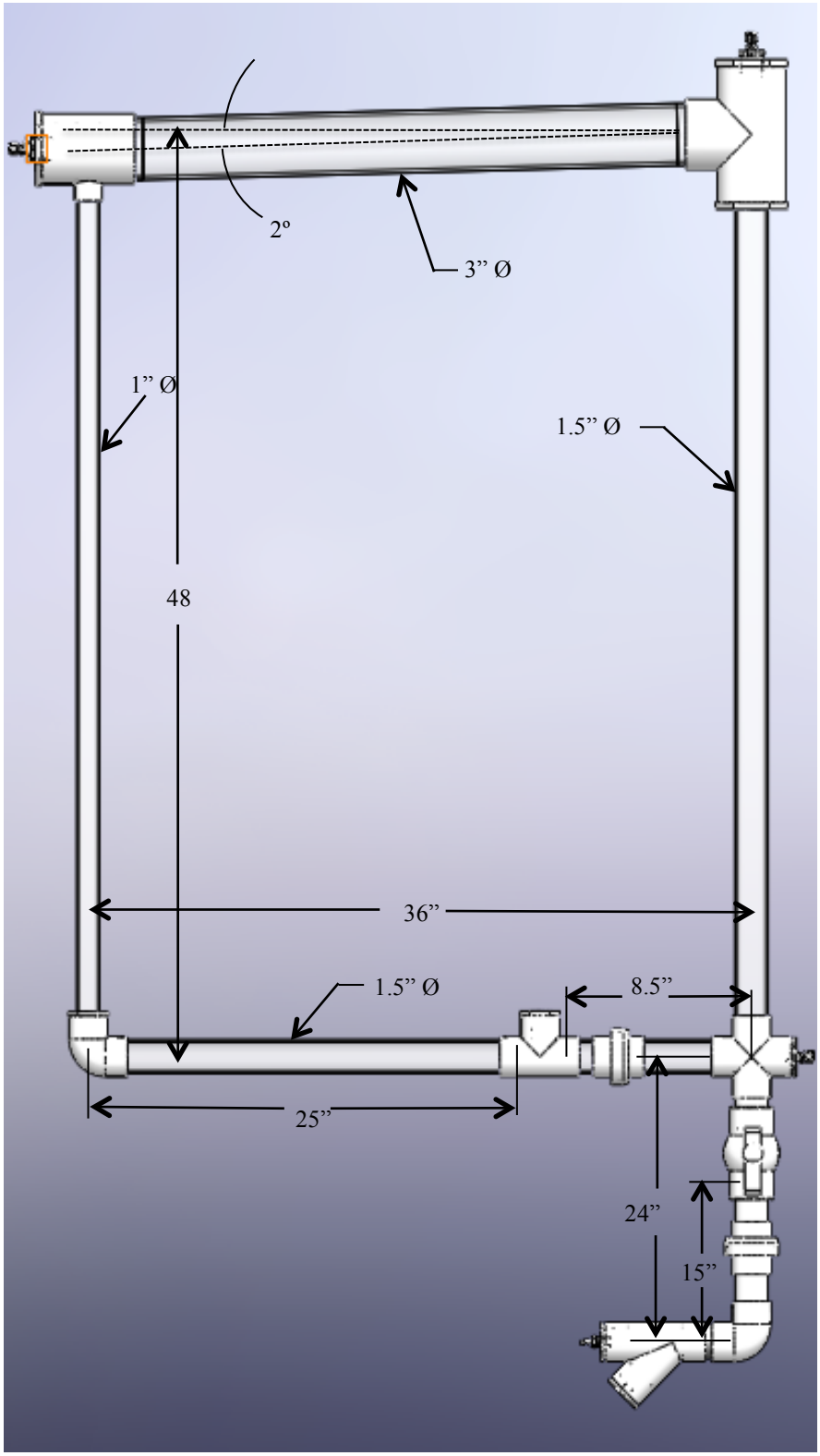
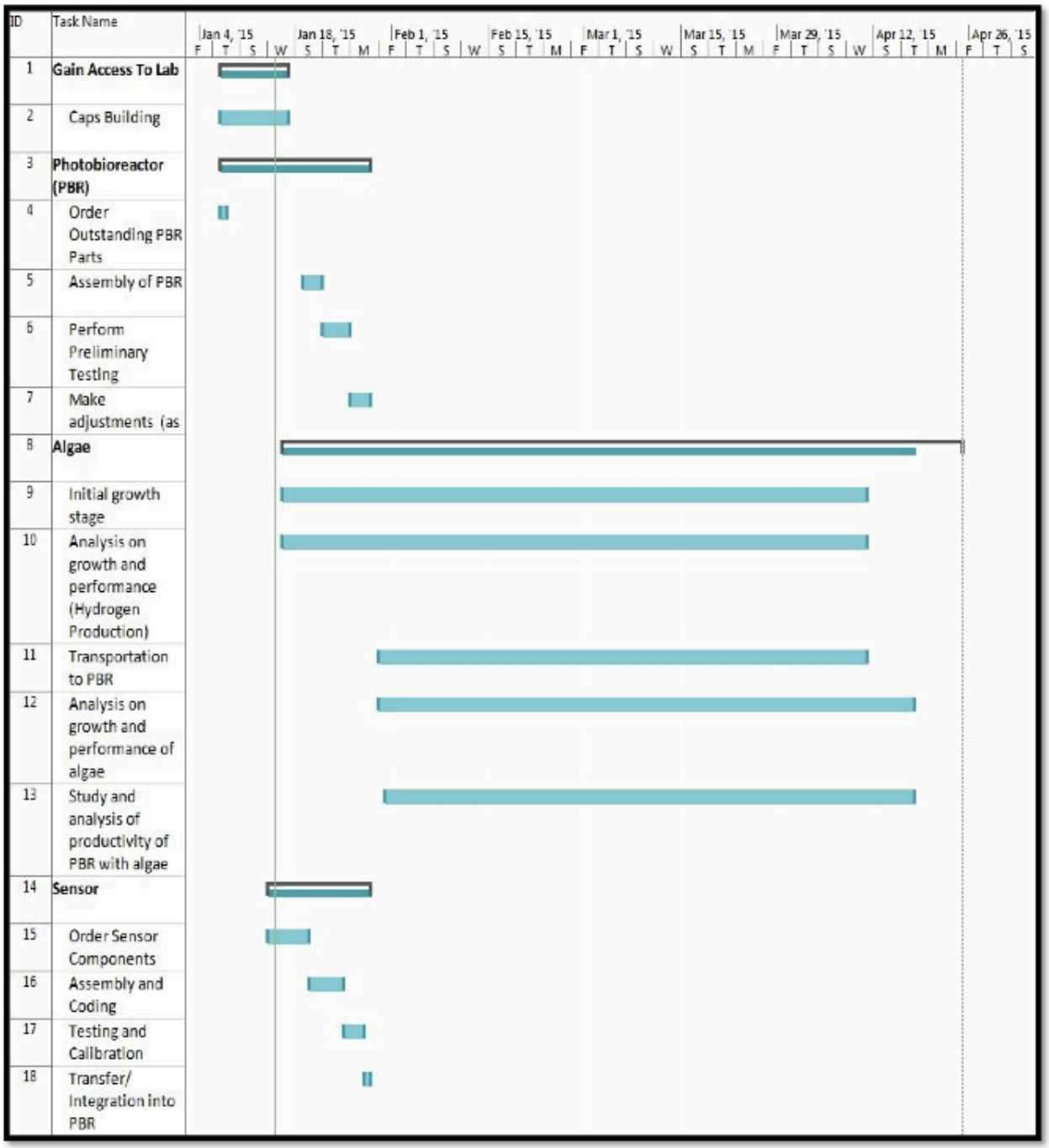
Appendix A

PBR dimensions



Gantt Chart


ID
Task Name
Jan 4, '15
Jan 18, '15
Feb 1, '15
Feb 15, '15
Mar 1, '15
Mar 15, '15
Mar 29, '15
Apr 12, '15
Apr 26, '15
1 Gain Access To Lab
2 Caps Building
3 Photobioreactor (PBR)
4 Order Outstanding PBR Parts
5 Assembly of PBR
6 Perform Preliminary Testing
7 Make adjustments (as
8 Algae
9 Initial growth stage
10 Analysis on growth and performance (Hydrogen Production)
11 Transportation to PBR
12 Analysis on growth and performance of algae
13 Study and analysis of productivity of PBR with algae
14 Sensor
15 Order Sensor Components
16 Assembly and Coding
17 Testing and Calibration
18 Transfer/ Integration into PBR

HYDROGEN SENSOR CODE

```
//Code to sense hydrogen levels
// Arduino Board UNO
// MQ-8 Hydrogen Gas Sensor that uses 5V
// websites to look at:
// arduino.cc/en/Tutorial/LiquidCrystal
// youtube.com/watch?v=HLivlogyNhs

#include <LiquidCrystal.h> // must call out the LCD library
LiquidCrystal lcd(12, 11, 5, 4, 3, 2); // pins where the LCD should be hooked up
int sensor = A0; // port in which the sensor is hooked into
int SensorValue = 0; // this is the number the sensor will output
float h; // this will be the percent of hydrogen number to be calculated

void setup() {
  lcd.begin(16,2);
  lcd.setCursor(0,1); // will write to second line
  //lcd.print("testing 1 2 3 ");  //use this to check lcd is set up correctly

}
void loop() {
   SensorValue = analogRead(sensor);
   lcd.setCursor(0,0); // will write to first line
   lcd.print("AMOUNT OF H2:");

   h = (0.97*(SensorValue/50)); // hydrogen conversion equation – still being calibrated
   lcd.setCursor(0,1); // print percent of hydrogen to second line
   lcd.print(h);
   lcd.setCursor(5,1);
   lcd.print("%");


  delay(500);
  lcd.clear();
 }
```

SOLENOID VALVES AND RELAY CODE

```
//Runs Solenoids and Relay

const int SolA = 8; //define pin for add solenoid (green and yellow)
const int SolA2 = 9; //define pin for add solenoid backward
const int SolE = 6; //define pin for extract solenoid (white and brown)
const int SolE2 = 7; //define pin for extract solenoid backward
const int soldel = 750; //delay for solenoid in ms
const int soldelA = 15000; //duration for addition solenoid operation in ms
const int soldelE = 5000; //duration for extraction solenoid operation in ms
const int MPolF = 5; //define pin for "forward" motor pole (HIGH = forward, LOW = backward)
const int pumpdel = 150; //delay for the pump in ms
const int pumpdur = 10000; //duration of pump operation in ms

void setup()
{
  Serial.begin(9600);
  // initialize the digital pin as an output.
  pinMode(SolA, OUTPUT); //set solenoid pin to output
  pinMode(SolE, OUTPUT); //set solenoid pin to output
  pinMode(SolA2, OUTPUT); //set pump forward pole pin to output
  pinMode(SolE2, OUTPUT); //set pump backwawrd pole pin to output
  pinMode(MPolF, OUTPUT); //set pump forward pole pin to output

  //Start all devices in off position
  digitalWrite(SolA, LOW); //start add solenoid off
  digitalWrite(SolE, LOW); //start ext solenoid off
  digitalWrite(SolA2, LOW); //start forward pump pole off
  digitalWrite(SolE2, LOW); //start backward pump pole off
  digitalWrite(MPolF, LOW); //start forward pump pole off
}
void loop()
{
//*Pump on
digitalWrite(MPolF, HIGH); //activate forward pumping
```

```
  delay(pumpdur);

  //turn off pump and allow for short time lapse (pumpdel)
  digitalWrite(MPolF, LOW); //stop forward pumping
  delay(pumpdel);

  delay(5000); //delay ten seconds between addition and pump turning on (arbitrary)

//*Extraction Routine
  //set solenoids in position for extraction (avoid delay in program)
  digitalWrite(SolA, LOW); //leave addition solenoid closed
  digitalWrite(SolE, HIGH); //open extraction solenoid
  delay(soldelE); // time for fluid to be extracted

  //close extraction solenoid (both solenoids closed) w/ small time lapse
  digitalWrite(SolA, LOW); //keep addition solenoid closed
  digitalWrite(SolE, LOW); //close extraction solenoid
  delay(soldel);

//*Addition Routine
  //open addition solenoid only w/ specificed time lapse = soldelA
  digitalWrite(SolA, HIGH);
  delay(soldelA);

  //close addition solenoid
  digitalWrite(SolA, LOW);
  delay(soldel);

  //delay before next round of concentration measurements
  delay(10000);
}
```

MASTER CONTROLLER CODE

```
const int chipSelect=4; //define pin for SD chip communication (4 for e-shield)
const int SolA = 8; //define pin for add solenoid (green and yellow)
const int SolA2 = 9; //define pin for add solenoid backward const
int SolE = 6; //define pin for extract solenoid (white and brown)
```

```
const int SolE2 = 7; //define pin for extract solenoid backward
const int soldel = 750; //delay for solenoid in ms
const int soldelA = 15000; //duration for addition solenoid operation in ms
const int soldelE = 5000; //duration for extraction solenoid operation in ms
const int MPolF = 5; //define pin for "forward" motor pole (HIGH = forward, LOW = backward)

const int pumpdel = 150; //delay for the pump in ms
const int pumpdur = 10000; //duration of pump operation in ms

int i=0; //initiliaze counter in for loop
int conc; //instantaneous conc reading from slave
float rconc; //real concentration value
long stallcnt =30000; //set time that indicates potential stall in program
int cnt=0; //initialize counter to 0
long sum=0; //initialize sum to 0
int avg; //initialize average
int mode=0; //arduino mode, initialize to 0
unsigned long previousMillis; //intitialize previous millis
String readString; //initialize string variable, "readString"
char rd; //initliaze "read" character variable for receiving char from slave

int c_min=0; //minimum concentration
int c_max=0; // maximum concentration
int p=0; //counter

void setup()
{
Serial.begin(9600);
// initialize the digital pin as an output.
pinMode(SolA, OUTPUT); //set solenoid pin to output
pinMode(SolE, OUTPUT); //set solenoid pin to output
pinMode(SolA2, OUTPUT); //set pump forward pole pin to output
pinMode(SolE2, OUTPUT); //set pump backwawrd pole pin to output
pinMode(MPolF, OUTPUT); //set pump forward pole pin to output

//Start all devices in off position
```

```
digitalWrite(SolA, LOW); //start add solenoid off
digitalWrite(SolE, LOW); //start ext solenoid off
digitalWrite(SolA2, LOW); //start forward pump pole off
digitalWrite(SolE2, LOW); //start backward pump pole off
digitalWrite(MPolF, LOW); //start forward pump pole off
}
void loop() {
//*Pump on
digitalWrite(MPolF, HIGH); //activate forward pumping delay(pumpdur);
//delay(5000); //delay ten seconds between addition and pump turning on (arbitrary)
Serial.println('b'); //send "b" character (begin) to slave for handshake
 previousMillis = millis(); //create a time stamp for later comparison
 rd = Serial.read(); //read any characters sent back from slave
 //remain in this while loop until rd = 'b'
 while(rd != 'b') {
 rd = Serial.read(); //keep checking serial
 //if 30 seconds of inactivity, resend 'b' command
 if (millis() - previousMillis >= stallcnt) { //current time - reference time
 Serial.println('b');
 previousMillis = millis(); //reset time stamp for reference
 } //if (millis() - previousMillis >= 30000)
 } //while(rd != 'b')
 if (rd == 'b') {
 rd = 'a'; //reset rd to != 'b'

 //Enter Data Acquisition Routine (mode = 0)
 previousMillis = millis(); //create time stamp for later reference
 while (mode == 0) {
 char c = Serial.read(); //stores current byte from serial buffer as char

 //if data acquisition exceeds 30s, assume no activity and break loop
 if (millis() - previousMillis >= stallcnt) {
 cnt = 0; //reset count
 sum = 0; //reset sum
 mode = 2;
 break; //break the "while (mode == 0)" loop
```

```
}
 //data acquisition sequence
if (c == '<') { //check for command that preceeds one measurement
delay(2); //short delay before reading next char
previousMillis = millis(); //time stamp for later reference

//gather data
while(Serial.available()) {
char c = Serial.read(); //read next byte sent from slave
if (c == '>') { //check for command that follows one measurement
break; //break the "while(Serial.available())" loop
} //if (c == '>')
else { //if no '>' then continue reading bits
readString += c; //adds current bit value to the readString
delay(2); //slow looping to allow buffer to fill with next character
} //else

//if 30 s pass, assume glitch in program and start at void loop()
if (millis() - previousMillis >= stallcnt){
mode = 2; //change mode value to leave "while (mode == 0)" loop
break; //leave "while(Serial.available())" loop
} //if (millis() - previousMillis >= 20000)
} //while(Serial.available())
} //if (c == '<')

//break data logging routine if end command received ('<e>')
if (readString == "e") {
readString = ""; //reset readString
mode = 1; //set new mode to enter add/ext section
break; //breaks "while (mode == 0)"
} //if (readString == "e")

//log data information if measurement received
if (readString.length() > 0) {
cnt = cnt + 1; //counter
conc = readString.toInt(); //convert readString into a number
```

```
sum = sum + conc; //add new raw data to sum for later averaging
readString = ""; //reset readString to no information
} //if (readString.length() > 0)
} //while (mode == 0)
} //if (rd == 'b')

//if mode == 1 calculate avg & rconc, decide if add/ext needed
if (mode == 1) {
//If cnt > 25 there will be calculation problems because sum cannot > 32767
avg = sum/cnt; //calculate average of measurements taken
rconc = -10.289*conc + 10789; //calibration equation to calculate real conc
sum = 0; //reset sum to 0
cnt = 0; //reset count to 0

for(int i=0; i<1; i++)
{
 c_min=rconc; //store initial concentration value
}
//----------------------
//CHECK MAX ALGAE GROWTH
//----------------------
if(rconc>=c_max)//if algae is continuing to grow
{
 c_max=rconc; //replace c_max with new max. concentration
}
else if(rconc<c_max) //algae is beginning to die
{
 c_max=c_max; //set max concentration to last maximum value

 //turn off compressor
 if(p>8) //set estimated value based on how fast algae dies
 {
  digitalWrite(MPolF, LOW); //stop forward pumping
 delay(pumpdel);
 }
```

```
   p++; //count up to 8 cycles to ensure that rconc<c_max isn't a random fluctuation in growth
 }
//------------------------
//CHECK MIN ALGAE GROWTH
//----------------------
if (rconc<=c_min)   //maybe set a counter to ensure a drop in concentration isn't due to fluctuation
{ //begin extraction
  digitalWrite(SolA, LOW); //leave addition unit closed
  digitalWrite(SolE, HIGH); //open extraction unit
  delay(soldelE); //time for fluid to be extracted
 //close extraction valve
 digitalWrite(SolA, LOW); //keep addition closed
 digitalWrite(SolE, LOW); //close extraction
 delay(soldel);
 //begin addition
 digitalWrite(SolA, HIGH);
 delay(soldelA);
 //close addition
 digitalWrite(SolA, LOW);
 delay(soldel);

 //delay before next round of measurements
 delay(10000);

 /*for troubleshooting
 Serial.print("cnt,");
 Serial.print(cnt);
 Serial.print(",a,");
 Serial.print(avg);
 Serial.print(",rconc,");
 Serial.println(rconc);
 */



//delay before next round of concentration measurements
```

```
 delay(10000); //delay before requesting for more data from slave ('b')
 } //if (rconc >= 700)
 else { //reset mode and delay if average routine not executed
 mode = 0;
 delay(10000); //delay in-between sending b's to slave
 } //else
 } //if (mode == 1)
} //void loop ()
```