Hydrogen from Microalgae and the Collection and Sensing Systems

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3 April 2015
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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 the microalgae strains *Chlamydomonas reinhardtii* and *Scendesmus sp.* can steadily create hydrogen gases. With a steady, self-sustainable hydrogen production, the hydrogen gases can be used in applications to create energy, such as fuel cells. This project seeks to improve microalgae cultivation and develop a sensor to accurately measure the amount of hydrogen production.

I. DESIGN FOR MANUFACTURING

The photobioreactor system assembled for this project is a continuation from 2012's Team 7 and 2013's Team 7 senior designs. Components for each team were adapted to develop a photobioreactor that would operate continuously and assist in the semi-continuous production of hydrogen gas. The list of components in the current design include:

1. Airlift Photobioreactor (Primary Component)
2. Algae concentration Sensor (Secondary Components)
3. Addition and Extraction ports
4. Air/CO_2 supply
5. H_2 purifier
6. H_2 concentration sensor
7. Photobioreactor stand

A. Airlift photobioreactor

The current design had the advantage of not needing machined parts. The photobioreactor itself (minus the secondary components listed above) was composed of schedule 40 clear PVC pipe. The diameters of pipe used were 1.0", 1.5", and 3.0". Appropriate sized PVC fittings were used to connect the photobioreactor together and to connect the secondary components. Even though the type of photobioreactor and over look of the design used this year came from 2013's Team 7, roughly 90% of the current design was assembled from scratch. Figure 1 shows the CAD drawing of the photobioreactor minus the secondary components. Note that the section enclosed in the dashed line represents the section of piping used from 2013's prototype while the other components labeled X-X were assembled this year. Using figure 1, the assembly process was as follows:

A. Component 1 from 2013's prototype was removed using a handsaw.
B. The pipes were cut slightly larger than design specs.
C. Components 1 – 11 were laid out in their appropriate locations.
D. Components 1 – 11 except for 3 and 4 were dry fitted and cut to size as needed.
E. Component 5 was then cut in order for 2 and 3 to fit without altering dimensions.

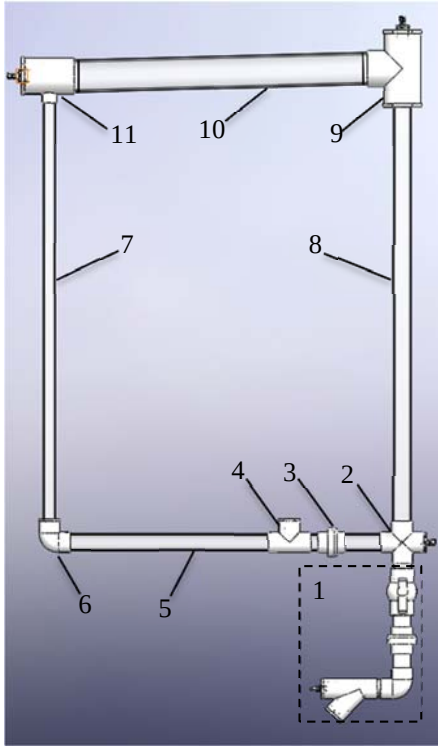


Figure 1: PBR drawing without secondary components

F. All components were dry fitted to check for final dimension accuracy. Then components were disassembled.
G. Included in components 2, 9, and 11 are reducing couplers and threaded male to Yor-lok fittings. These "sub components" were connected to 2, 9, and 11.
H. All components were dry fitted again to double checked for accuracy then disassembled.
I. Finally, using a specialized cleaning primer and glue, the components were connected together in order starting from 1.

The total time required to fully assemble the bioreactor (minus the secondary components) was roughly 7 hours spread throughout a two-week period. However, during testing, part of the section used from 2013's prototype fractured and had to be replace, which added an addition 1.5 hours. Overall, the time required to assemble the photobioreactor was slightly higher than anticipated due to unforeseen technical and scheduling issues.

B. Algae Concentration Sensor

The algae concentration sensor used was designed and built by 2012's team 7 and can be seen in figure 2. Even though the sensor was not assembled for this project, there were some minor issues that needed to be fixed. The first issue involved the alignment of the LEDs and LDR. The alignment was off by roughly 0.5 inches in the axial direction of the pipe, which meant lower light intensity hitting the LDR. This problem was fixed easily by removing then reattaching the LDR to assure full light intensity. The second issue with the sensor dealt with the programming, and wiring. Since this year's team did not build the prototype, time was needed to understand the wiring, and reprogram the sensor to better suit our purpose. For full assembly and specs, refer to [1].

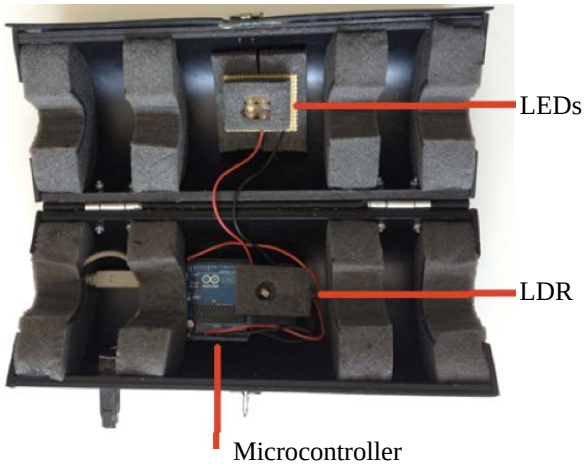


Figure 2: 2012's algae concentration sensor. **Picture taken from Design for Manufacturing by Team 7*

C. Addition and Extraction Ports

The purpose of the ports is to extract dead algae and add new algae in order to semi-continuously produce H_2. Figure 3 shows the wiring schematic of the addition and extraction ports. The system's components include:

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

2013's team 7 purchased the motor driver and microcontroller used in the current design. In order to make sure there were no wiring issues, the wiring done by 2013's team was removed and then rewired according to figure 3. Yor-lok fittings were then added to the inlet and outlet sides of both valves, and testing was done to assure the valves were functioning properly. The total assembly time for the addition and extraction system was roughly 4 hours spread throughout a one-week period. Again, the time overall time required to assemble the system was higher due to a lack of knowledge with electrical components.

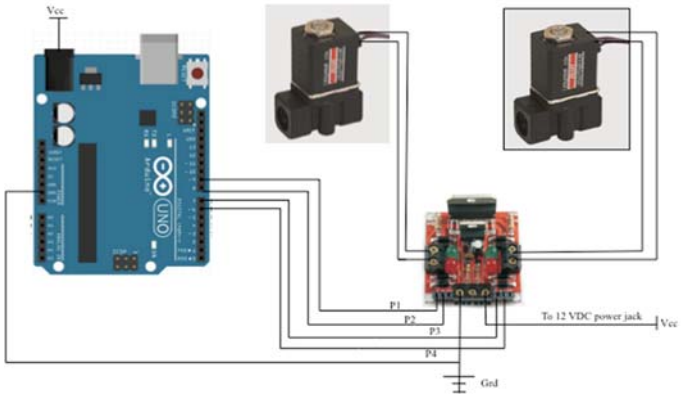
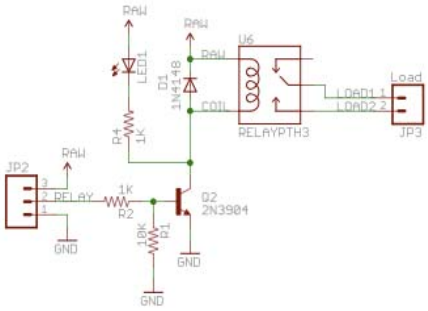


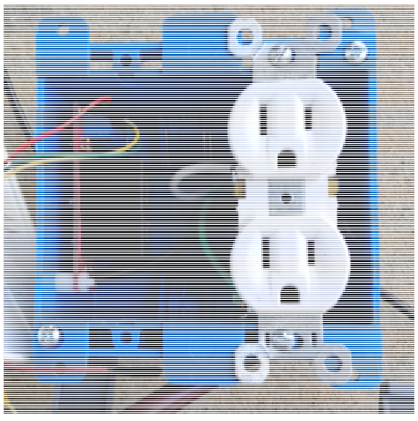
Figure 3: Wiring schematic of addition / extraction ports.

D. Air/CO_2 supply

CO_2 supply to the algae was achieved using a one-gallon pancake air compressor, and a solid-state relay. The air compressor used in the current design was the same one used by 2013's team 7, and required very little set up time. The relay was purchased as a kit and required assembly. There were nine components to the relay kit, which included several resistors, a transistor, a LED, and the relay itself. Figure 4 (a) was used when soldering the components to the board. Upon completion, the relay kit was mounted inside an electrical box, and wired to a standard electrical outlet that can be seen in figure 4 (b). The total assembly time was roughly five hours due to complications with soldering the electrical components.



(a)



(b)

Figure 4: Schematic for relay (a), and completed assembly (b).

E. H_2 Concentration Sensor

The hydrogen concentration sensor was originally designed and assembled at UFPR, Brazil, which made the assembly easy. First, an LCD was connected to the microcontroller along with the MQ-8 gas sensor via a 4-wire jumper. Then, a wax mold of the 100 mL flask opening was made, which the sensor was fed through. The time required to assemble the sensor was 3 hours, however, the calibration took roughly 3 days to complete because several 100 trials were needed. The time required to assemble and calibrate the sensor was close to the anticipated time.

F. Photobioreactor Stand

A stand was needed to house the electrical components and the photobioreactor itself. The current design is closely related to 2013's design since some of the parts were reused. The process of assembly was as follows:

1. The stand built by 2013's team 7 was disassembled except for the base.
2. The vertical and cross beam section was assembled.
3. The housing box for the electrical components was assembled.
4. Roofing brackets were attached to the base then the vertical section.
5. The diagonal support beams were attached.
6. Finally, the electrical hosing box was attached to the stand.

<u>Photobioreactor System Assembly</u>

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 DAT and algae concentration sensor were set, and the components connected to their appropriate ports. Figures 5 and 6 shows the photobioreactor system and an exploded view, respectively. The total time required to assemble the system was roughly 5 hours, which was reasonable.

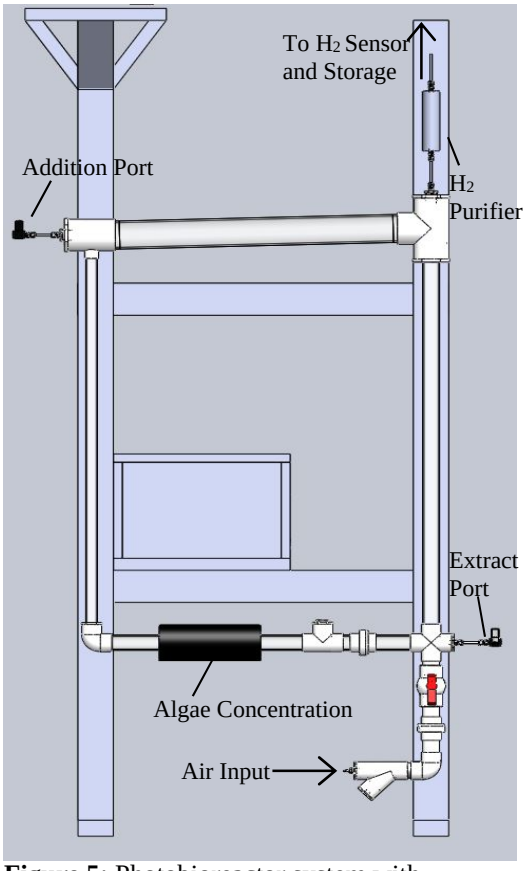


Figure 5: Photobioreactor system with secondary components.

All in all there were seven components to the photobioreactor system, including the photobioreactor itself. While it might seem that there are too many components in reality more components should be added to assure proper function of the pbr. For example, temperature sensors that would provide real time analysis of the temperature within the pbr, making sure it did not exceed the algae's max temp. Another component that was not added due to time issues was a CO_2 sensor. This sensor is also important because it would provide information on CO_2 utilization of the algae. Both the temperature and CO_2 sensors

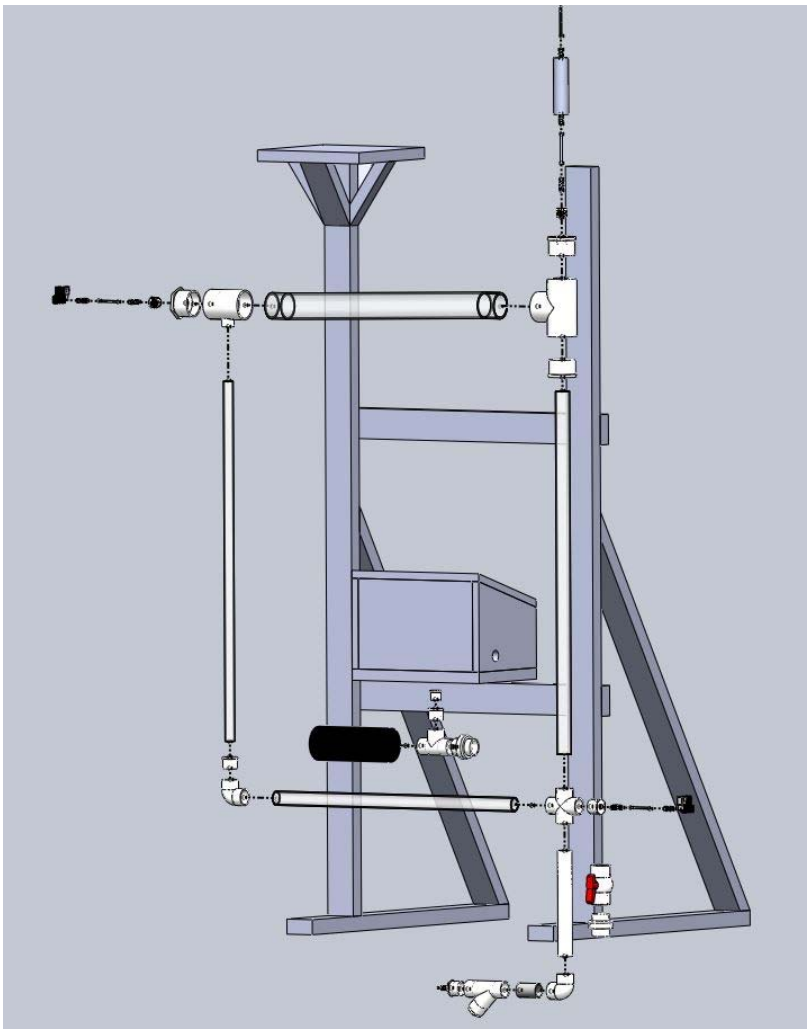


Figure 6: Exploded view of photobioreactor system.

could also have an impact on the addition/extraction process i.e. a small of mount of extraction and addition would occur if the temperature of CO_2 levels were too high. Other components that should be included in the system include; a H_2 mass flow sensor, storage tanks, and/or a sunlight tracking system.

II. Design for Reliability

All of the main components included in our prototype performed well during the initial testing. The addition and extraction ports opened and closed according, by command of our Arduino code, allowing us to fill and empty the photobioreactor as desired. The pump was also successfully run and stopped with the use of our code and performs well when circulating the test fluid. A leak was experienced when testing this system initially but has since been fixed so that no fluid escapes the system. The hydrogen and concentration sensors that will be incorporated into our system are also working but need to be calibrated before they can be added to the system. Therefore, the photobioreactor prototype performed well when used once, and subsequently about 4 more times.

When used 100, or even 1000, times we believe the system should perform just as well as it performed during the initial testing. The system is relatively simple with only a few major components. Also, the reputation of the vendors that the parts were ordered from were researched and found to be reputable sources for the materials we needed. Furthermore, the photobioreactor system is stationary and is not put under any stress besides the weight of the fluid in the system when filled. The photobioreactor will be used to sustain the semi-continuous production of hydrogen through the cultivation of microalgae and is a very delicate process and an even more delicate organism, respectively. Therefore, a large amount of wear and tear on the system is not present. The hydrogen purifier will need to be replaced, however. The tank is disposable and once it is filled with contaminates it can no longer be used in the system. If the system is properly maintained during its lifetime there is no reason why the photobioreactor should not perform perfectly when used 100 or 1000 times.

However, while that may be the case, the same does not apply to this system after being used 10,000 times. This is a very large amount of times for this system to be run. Before the system can be used and perform at the optimum standards this many times it will most likely need to have components replaced, and/or elements reattached. This may include wires, solenoid valves, electrical components of the hydrogen and concentration sensor, the hydrogen purifier, and any piping that may need to be reattached to each other. After a certain amount of uses (to be determined) the useful lifetime of the wires and electrical components of this system will have been reached and they will have needed to be replaced for the system to be able to operate automatically. Furthermore, the solenoid valves may need to be replaced after a certain amount of uses as well due to the light wear and tear experienced by these components over a long period of time causing it to become fatigued. As stated previously, the hydrogen sensor will need to be replaced on a regular basis in order for the system to serve its purpose. Otherwise, the tank will become filled with contaminates and the hydrogen will no longer be separated from the other gases present throughout the system. Also, since this system will be placed outside, the natural elements will cause some wear on the system with respect to the piping. The system needs light which means it will experience the direct heat from the sun which can cause the adhesive used on the piping to become brittle and corroded. This can be taken care of relatively easily by reapplying the epoxy that adheres the piping together. One thing that

may cause the most amount of distress when getting the system to last for an extended period of time will be changing out the actual pipes themselves. This process may be necessary in order to optimize the performance and efficiency of the system. As we've noticed from the photobioreactor constructed during the 2013-2014 senior design project, the pipes we're severely stained due to the chlorophyll present in the microalgae and the heat from the sunlight. This stain hinders the amount of light that can enter the system and lowers the efficiency of our photobioreactor (PBR) system. Therefore, the piping will eventually need to be replaced unless consistent maintenance (which should include the cleaning of the system) will be enough to stop the piping from becoming stained. As the system is run and cleaned the state of the system needs to be monitored to keep track of which components may need to be replaced in order to keep the system performing as desired.

The concerns listed above with respect to long term use are also some of the main reliability concerns that can arise currently and may need to be taken care of accordingly. However, further reliability concerns may arise and need to be documented in the event that the malfunction does occur. These concerns are categorized below by the major component of the system.

A. PBR Base

For the purpose of this report, the PBR base will include all piping and the addition and extraction ports. As noted earlier, the PBR system has a potential to leak fluids out of the system. This is the primary concern of this component since it essentially acts as a containment device (as well as a connection for the rest of the components for the system). Any leaks present in the system can be due to a variety of reasons that include:

1. Mishandling (including, but not limited to, dropping) the PBR system causing the epoxy bond to break and the pipes to separate or no longer be sealed air tight.
2. Degradation of the epoxy due to the elements and/or consistent handling of the system when cleaning the PBR or transporting the system to and from its stand.
3. Malfunction of the addition and extraction ports; this condition would more than likely be caused by an issue with the electronics or coding of the system.

In either of these cases, a leak can be detrimental to the goal of the project. If the leak is minor enough to amend while the system is running it will affect the system to an extent that allows the system to continue to run and perform, almost as desired, as the problem is being fixed during while the system continues to run. If a major leak is present it will lead to a major setback that involves a loss of viable algae. With this loss comes a loss of potential hydrogen production which is the sole purpose of the PBR system.

Should a leak occur upon filling or emptying the system that involves the PBR base, with the exception of a malfunction of the addition and extraction ports caused by issues with the coding of the system, Jonatan Elfi will be the one to perform the actions necessary to fix the leak(s). This includes applying any epoxy to the pipes and rejoining any of the piping. This may also include any rewiring of the system that needs to be done. Should a malfunction of the addition and extraction ports arise due to the coding of the system, Nicole Alvarez will amend the code and/or reset the system as necessary. If some

malfunction occurs during the run of the system that causes a leak it will be the responsibility of the team as a whole, or whoever is present or most readily available, to take the actions necessary to save the microalgae as well as PBR base.

B. Pump

The pump is needed to supply air and CO_2 to the system as necessary and so a reliability concern for this component is that it will not work and, therefore, will cause the microalgae to enter into the anaerobic respiration cycle prematurely. Another issue is that the pump is supplying too much air, or is supplying the air at a rate that is fast enough to shear the microalgae. As a result, the system will not produce the maximum amount of hydrogen that it would have had the potential to produce if the pump was working properly. In the event that the pump does not work at all then the microalgae will not receive the appropriate air supply and will enter into the stage during which hydrogen is produced prematurely. Under these circumstances the algae will not have cultivated to their maximum concentration before the anaerobic stage is reached. Also, supplying too much air will cause a decrease in the amount of microalgae that will be cultivated, which also affects how much hydrogen can be produced, if any should this reliability concern arise. Finally, if the algae is sheared as a result of rapid air addition then the algae can be damaged if not killed by the shear stress imposed upon them, which also decreases the amount of algae cultivated for the production of hydrogen.

The air pump used in our system is the same pump used from the previous year. It is not a new pump so any malfunction of the pump more than likely comes from the fact that it is wore and/or has not been taken care of in the past. Another reason for any malfunction of the pump could arise to a malfunction in the coding of the system that is meant to control the operation of the sensor.

Should the pump malfunction due to technical issues that have nothing to do with operator error it will be taken to a professional for repair – or Jonatan Elfi, he's or designated handy man. If repairs cannot be made then an alternative pump will have to be found or purchased if funds allow. If the pump malfunctions and it is suspected that it is an issue with the programming, Nicole Alvarez will amend any coding pertaining to the operation of the pump or reset the system as necessary.

C. Hydrogen (H_2) Sensor

Reliability issues that involve the sensor include it measuring the hydrogen output of the system and displaying a concentration that is incorrect or not displaying a concentration at all. Either occurrence does not necessarily affect the efficiency of our system with respect to the production of hydrogen, but it does affect our ability to adequate measure the effectiveness and efficiency at which hydrogen is being produced from our system.

In the event that the sensor is yielding a misreading, or no reading at all, it is an issue pertaining to the coding, calibration, and/or the connection of the hydrogen sensor to the system and Nicole Alvarez will make the necessary adjustments to the code, recalibrate the sensor, and/or reset the system as necessary.

D. H_2 Purify

A reliability concern for the H_2 purifier is that it will not filter the hydrogen gas from the rest of the contaminants present in the system, therefore, yielding gas that is not readily available for direct use and/or demonstrative testing. The hydrogen gas stored that has not been purified must then go through a separate step at a different time in order to be purified so that the photobioreactor system can continue to run once a working purifier has been acquired. Again, like the sensor, the H_2 purifier does not directly affect the efficiency of the system with respect to producing as much hydrogen as possible from the microalgae.

Should the purifier not work at filtering the gas, either due to a malfunction with the device, or simply because the tank is already full of contaminants, then it is the responsibility of Ariel Johnson or Angeline Lenz to order a new purifier (budget permitting) and ship the filled canister to the appropriate location for correct and safe disposable. Since it is a gas canister the necessary safety precautions must be taken when being rid of this waste. The same can be said for any dead microalgae accumulated during the hydrogen production process.

E. Concentration Sensor

The concentration sensor is used to determine the concentration of microalgae present in the PBR while the system is running. This component is very important and allows the system to optimize the maximum amount of hydrogen that can be produced per batch. A reliability concern that arises from the concentration sensor is that it will not function at all when turned on, or that it will sense the wrong concentration.

Should a malfunction arise with the concentration sensor it can have a significant impact on the amount of hydrogen that will be produced. If the sensor does not function at all then there will be no readings to drive the operation of the pump, addition, and extraction values whose code depends on the amount of microalgae present in the photobioreactor. Therefore, once the algae is in the system it will receive no air supply and enter into the anaerobic cycle prematurely. This negatively affects the amount of hydrogen gas produced which decreases the efficiency of our system. The sensor could also read a concentration that is incorrect which will also negatively affect the amount of hydrogen produced. Should the concentration sensor sense a concentration that is two high then the system will cut off the air supply prematurely as stated before. If the sensor reads a concentration that is too high, relative to the amount of algae present, then the system will cut off the air supply after the maximum amount of algae has been reached. Therefore, the amount of microalgae present after the optimum concentration is reached will be lower than the optimum concentration due to the death of microalgae that naturally occurs. This too yields an amount of H_2 gas that will be lower than the optimum amount that could have been produced.

Should any malfunction occur with the concentration sensor it is the responsibility of Ariel Johnson or Angeline Lenz to amend the code accordingly, recalibrate the system, reconnect the system to the PBR base, and/or reset the system as needed.

F. PBR Stand

The PBR stand is a wooden stand that will be used to hold the photobioreactor, making it a freestanding system. This stand holds the photobioreactor about a foot off of the ground to allow room for the pump and for the system to drain when needed. It provides a stand for the fill bucket (or tank) to be placed so that an operator does not need to hold it when the PBR is being filled. It also has a box for the electronics to be placed with cutouts that allow the electrical wires to be connected to the PBR system and the electronics system of the design. This box protects the electronics from water and other components of the environment.

A reliability concern of the system is that it may tip over in the event of strong winds or a storm since it is so tall. In the event that the stand, and therefore, the system, tips over precautions must be taken with respect for safety and not the PBR. If an operator(s) is around when the stand is falling over then he/she/they must quickly move out of the way. No attempt should be made to stop the PBR from tipping over unless the device only shows signs of being slightly off balance. Any attempt to save the photobioreactor while it is falling over may result in personal injury which is highly undesirable. If it appears that there will be weather that may lead to unsafe environments for the PBR then the system should be moved indoors where it will be unaffected by the weather.

Although the PBR and stand could tip over from rough weather it could also tip over from carelessness displayed around the PBR. If someone is not paying attention for example, and they bump or fall onto the system causing it to sway or come off balance, it could tip over and fall. Furthermore, if caution is not taken when filling up the PBR then the bucket at the top of the PBR could fall and lead to a serious injury or a hazard if the contents of the bucket spill onto the floor…which they will.

In the event that the photobioreactor falls it can severely damage any and/or every component of the device. This can be detrimental to future functions of the system so operators and bystanders must take precaution when in the vicinity of the PBR.

To prevent these types of hazards from occurring caution signs should be placed near the PBR. Hazard signs should also be present in the area in case of a spill. To keep the PBR from falling over the sand bags that were implemented for last year's design will be used this year at the base of the stand to anchor it to the ground. To prevent poor weather conditions (which should be monitored) from adversely affecting the PBR system it will be moved to a safe location in the event that rough winds or a storm will approach.

Should the precautionary measures fail and the stand and PBR system fall, it will be the responsibility of the team as a whole to fix any components that have become damaged. This ensures that the PBR is running again in a timely manner.

In order to prevent a vast majority of the reliability concerns from happening it is necessary to periodically monitor the PBR and document the status of the system. This allows the operators to be aware of when it is time to make the necessary adjustments or

replacements to the system. Furthermore, all sensor systems should be calibrated every so often to ensure that they are sensing the proper values. The system must also be routinely cleaned to ensure it will run properly with future uses. This cleaning also lessens the possibility for contamination which can negatively affect the concentration of algae present in the system. A failure mode effects analysis (FMEA) is presented on the following page in Table 1 to further organize the failure modes and the consequences and actions taken to amend these issues.

III. Design for Economics

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 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
OxiClear In-line Disposable 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/20-011-960	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. The table below shows a comparison of our prototype with 3 commercially available photobioreactors and a graphical display is shown in Figure 7.

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

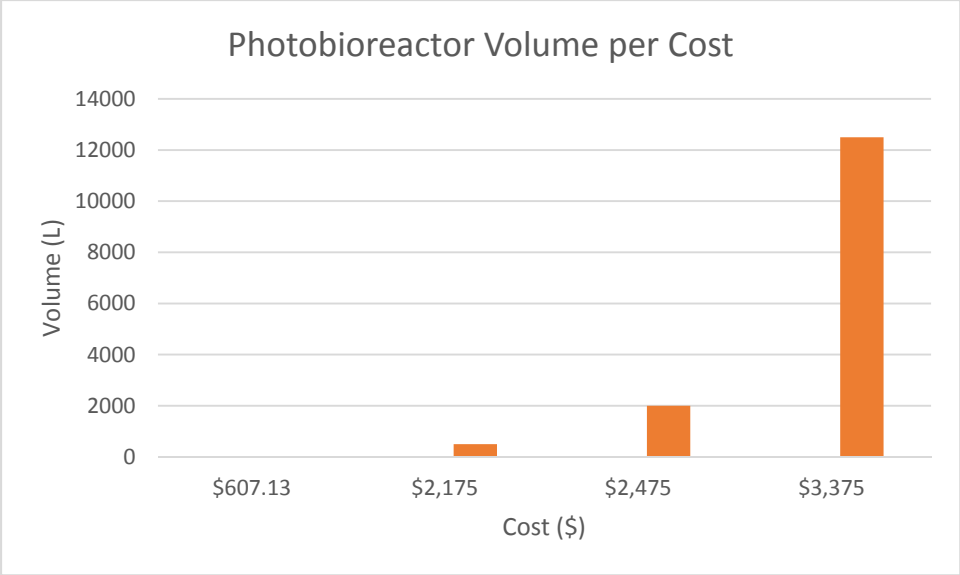


Figure 7: *Commercially Available Photobioreactor Comparison*

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.