Preliminary Feasibility Study of a Bubble Column CO_2 Capture Unit Utilizing Microalgae

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Abstract

In recent years, governments have become increasingly aware of their country's carbon dioxide (CO_2) emissions. This awareness has resulted in an increase of government regulations in industry, leading to the need for a carbon capture system (CCS) to keep up with the ever-increasing government standards. This report focuses on the use of photobioreactors, a much less explored, more environmentally friendly approach to managing the issue and reducing industrial CO_2 emissions. The contents of this paper include research conducted in the field of photobioreactor (PBR) and their effectiveness at using micro-algae to absorb CO_2. Time was spent determining the feasibility of creating a small scale PBR with the goal of experimentation in mind.Different types of PBRs were researched and compared to determine which one would be more promising to work with throughout the course of this project. The PBRs compared were vertical column, flat panel, tubular, and internally illuminated. Comparing these types of reactors to one another resulted in the choice of a vertical column PBR. It was found that though reactors such as the tubular were more efficient at absorbing CO_2, they are typically more complex and require more input power than vertical column or flat panel. Also, compared were different types of algae, a main component with biophysical properties needed in this project. This was originally more challenging than expected because of the limited knowledge in microbiology. Two well-researched genus of algae were then compared: Spirulina, and Chlorella. It was determined that they are both easily acquired, and generally undemanding with respect to the environment. These factors made them ideal for use in the desired system. A decision-making matrix was therefore used to determine that Chlorella would be the appropriate genus. Similar processes were applied to evaluate different types of materials that will be used in the PBRs main structure and pinpoint a manufacturing process best suited to project requirements. A 3D printer

will be used to produce PBR components, irregular parts, and hardware housings for temperature and CO_2 sensors.

Introduction

Information about CO_2 emission and their effects on the planet are often neglected, both by the public media and the general public. The Environmental Protection Agency (EPA) determines values for the amounts of greenhouse gasses released annually by both mankind and the environment. Carbon dioxide has been the primary greenhouse gas pollutant for recent years. Due to this a number of solutions have been exercised to minimize the effects of CO_2 pollution on the planet. Each year, millions of tons of CO_2 are emitted into the atmosphere through different man-made pollutants. The accumulation of this product in nature has a negative effect on the health of living things. According to the Canadian Center for Occupational Health and Safety, Carbon Dioxide (CO_2) in small quantities in a room or in the environment is not necessarily harmful. However, a large amount can cause suffocation after displacing oxygen in the air [1]. While a few governments and international organizations work to encourage the use of CO_2 capture and storage systems in the industrial world, others are reluctant to invest. This is partially because the installation of such units is expensive and not necessarily helpful for companies in advancing their productivity [2]. To illustrate, NRG Energy, a large power provider, is spending $1 billion to reduce its CO_2 released from Fort Bend County power plant, in Texas. Arun Banskota, the president and CEO said "this will basically be extremely clean emission from a coal plant – which we've never seen – at low coal prices." When it comes to CO_2, this is by far the largest CO_2 capture project a power company will undergo [3].

In order for humans to continue thriving on the Earth for many years to come, our generation will have to better understand the environment and its problems. The next step will be to change our lifestyle to meet the resources available. The goal of this project is to first study known methods of CO_2 capture, following this by designing and manufacturing of a PBR. In the future we will perform experiments to determine the effectiveness of this PBR at capturing and storing CO_2 compared to other methods of CO_2 capture.

Information on the subject of CO_2 capture was researched to gain a better understanding of how CO_2 capture is done and why it is applicable. These will be compared below to demonstrate multiple methods of capture. This information will be followed by an explanation of our system's needs, showing the components chosen and decision matrixes comparing each of the options we considered. A model created in SolidWorks will be provided with dimensions to show the size of our reactor.

How CO_2 is generally captured

There are three primary methods for the sequestration of carbon dioxide (CO_2), and a fourth method that has only recently been implemented for the purpose of capturing and storing CO_2. The primary methods have all been used extensively for the past sixty years, in many areas and industries, however the fourth is still very much in the experimental stages of development. The four methods include: pre-combustion method, which allows a coal power plant to transform the coal into a clean, usable gas by removing the CO_2 in the gas before combustion. The second method is the post-combustion method, which involves scrubbing the plant's exhaust system with chemicals to collect the CO_2. The third method requires the burning of coal using a high concentration of pure oxygen, yielding approximately pure CO_2 to be collected. The fourth and final method is the most recently implemented and the focus of this project is the sequestration of

CO_2 using photobioreactors, which utilizes microalgae's ability to absorb CO_2 from the flue gas produced by the power plant [4]. All four methods are further explained in the following paragraphs.

Pre-combustion CO_2 capture uses a process called "gasification" for solid fuels such as coal. So far, gasification is the cleanest known way to produce energy from coal, yet only a handful of plants around the world use this method to produce power [5]. In this process, the coal is crushed and made into slurry. The coal slurry is then essentially preheated to a gaseous state. After pre-heating, the yielded synthesis gas (syngas) is mostly H2 and CO, leaving other impurities to be separated out (CO_2 and Sulfur). The syngas is passed through a scrubber unit, which will pick up the CO_2 and Sulfur, producing a purified syngas. The purified syngas can then be used for power generation, while the filtered out CO_2 and sulfur can be transported away for sequestering. This method has many environmental benefits including: lowered emission levels, less solid waste production, and less water consumption [5]. Some cons of this method, are the gasification process in which the syngas is produced is very expensive and less effective at extracting energy from the coal as compared to other methods.

Post-Combustion CO_2 capture functions much like any other power plant, but with an added scrubber unit to process the exhaust gasses through. This is the easiest method available to retrofit many existing fuel burning power production facilities. This process starts after the power generation cycle of a coal plant, where the exhaust is then put through a scrubber unit containing an amine solution, which will capture the CO_2. The CO_2 rich amine solution is then put through a stripper unit, which removes and contains CO_2 so it can be transported offsite and stored. Here, the amine solution can be put back into the cycle for re-use. This process does consume more energy and decreases efficiency by 20 to 30% on average, but benefits the environment [6]. This method seems to be the most viable method for existing power generation plants to incorporate a CO_2 capture and storage method [6].

Oxyfuel-Combustion starts with Oxygen being separated from air so that the required concentration can be met. The fuel is then combusted in the Oxygen, which is diluted with flue-gas rather than air to control concentrations. The Nitrogen-free environment then results in final flue-gas that primarily consists of H_2O and CO_2. This allows for an easy separation process of the CO_2 in a scrubber unit, then transportation, and finally storage of the CO_2. This method is essentially a highly refined version of post-combustion CO_2 capture, in being so that it also requires more equipment and more capital investment [7].

Photobioreactors utilizes a microalgal biomass to absorb CO_2 through the process of photosynthesis [4]. Microalgae is suspended in a mineral media within a transparent housing, this mineral media provides a source of nourishment for the algae allowing the biomass to grow, while the clear housing allows for light penetration for the process of photosynthesis to occur [4]. The photobioreactor is positioned vertically or inclined at an angle relative to incoming light, then a CO_2 rich flue gas, and atmospheric air mixture is introduced at the bottom of the reactor. This gaseous mixture flows quickly to the top because the air is much less dense than the surrounding liquid. As the CO_2 rich gas mixture ascends to the top of the reactor, the gas dissolves into the liquid; at this point the CO_2 can be utilized by the suspended microalgae [8]. The microalgae absorbs the dissolved CO_2, water, and collects solar radiation with the use of photoreceptors to produce useable carbohydrates, through the process of photosynthesis [8]. The chemistry behind photosynthesis is shown by the following reaction:

$$6CO_2 + 12H_2O + \text{Light} \rightarrow C_6H12O6 + 6O2 + 6H2O$$

Using photobioreactors is a relatively inexpensive system to maintain. It also provides a steady growth of algal biomass, which can be used in a number of different applications in uses such as: food supplement, alternative food, crops, and lipid production for use in biofuels [4]. This system is cleaner, simpler and more environmentally friendly than any other method of capturing CO_2.
Many contemporary facilities can integrate these capture methods. New facilities on the other hand, with the option to capture CO_2 for power generation have higher capital and operational costs, as well as lower efficiencies than conventional power plant. An estimate of around 10-40% [4, 5] more energy is required with carbon capture system (CCS), this is mostly to separate and compress the carbon dioxide.
Transportation can then be done through a pipeline for small distances, or super-compressed into a liquid and transported by highway or overseas as it is largely inert [3].Using an algae photobioreactor requires less energy than other CCS and eliminates the need for pressurizing the CO_2, and only requires transportation of the produced algal biomass [4].

Classification of photobioreactor

There are many different types of photobioreactors. The types of which include "Flat Panel", "Tubular", "Internally Illuminated", and "Vertical Column" photobioreactors [4]. Each type of PBR also has sub categories to further specify the details of the design of that specific PBR.
The “Flat Panel” photobioreactor (Figure 1.) is a rectangular prism-shaped PBR. It works by pumping compressed flue gas through a tube and into the bottom of the system where the diffuser is located to allow bubbling of the flue gas. The flue gas bubbles will then flow vertically through the algae media contained within the system. As the bubbles flow through the media, the algae absorb the carbon dioxide from the flue gas bubbles. Just as within other PBRs, as the algae absorbs the carbon dioxide from the flue gas, it produces oxygen, which then floats to the surface of the media and into the atmospheric air. As opposed to cylindrical shaped photo-bioreactors, the "Flat Panel" design only allows for a less-than-uniform flow of bubbles through the algae media. Also, the design allows more room for error in construction due to more corners and edges that need to be sealed.

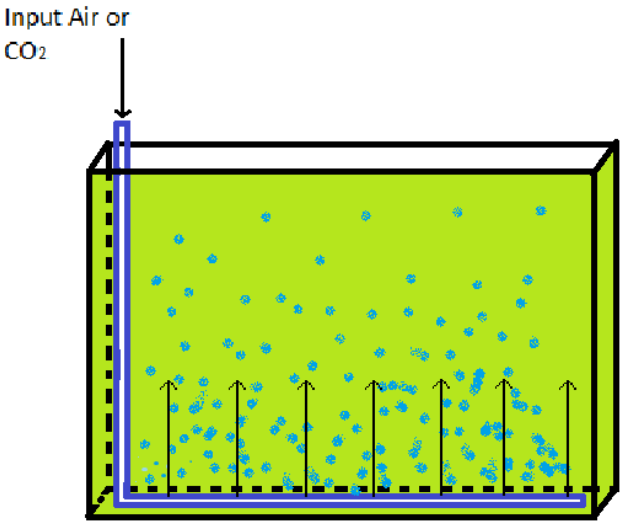

Figure 1. "Flat Panel" PBR

A "tubular" PBR (Figure 2.) is in the form of a tube, or series of tubes, that use the energy from the exhaust flowing through them to circulate the algae and media inside the tubes [4]. A fault of this design is that the pressure must be exerted in the opposite direction of the gas flow to force the algae and media through the tubes in the opposite direction of the original flow. This causes some energy to have to be spent on the tubular PBR in order for it to be used over and over again, thus making the overall system less efficient than other types of photo-bioreactors [4]. The following figure illustrates the tubular PBR.

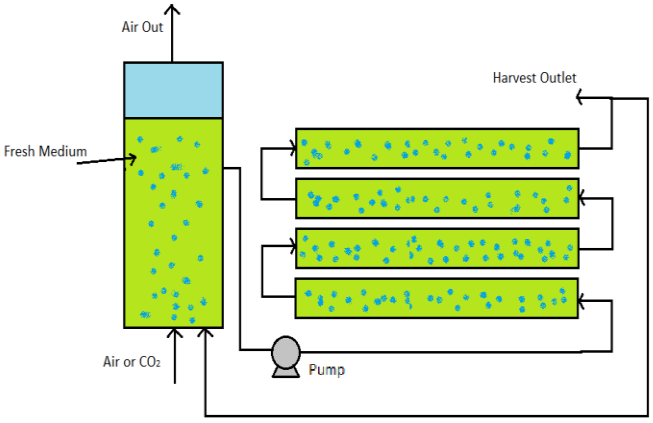

Figure 2. "Tubular" PBR

The "Internally Illuminated" photobioreactor (Figure 3.) differs from other designs due to its light source being provided from within the column as opposed to demanding light from an outside source. The particular internally illuminated PBR in the following figure has a light emitting tube in the center of the outer tube with a tube in the middle of the light tube as well [4]. In the centermost tube, a stirrer acts to circulate the algae and media within. Not all internally illuminated photobioreactors are the same, as some may have a helical tube around a center light or just a single outer tube encasing the illuminated tube inside.

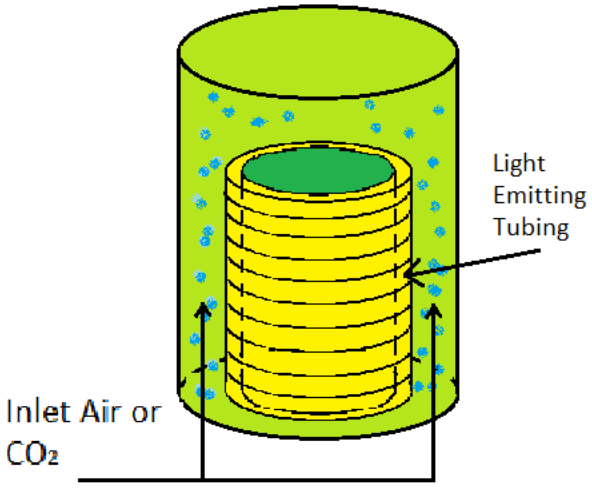

Figure 3. "Internally illuminated" PBR

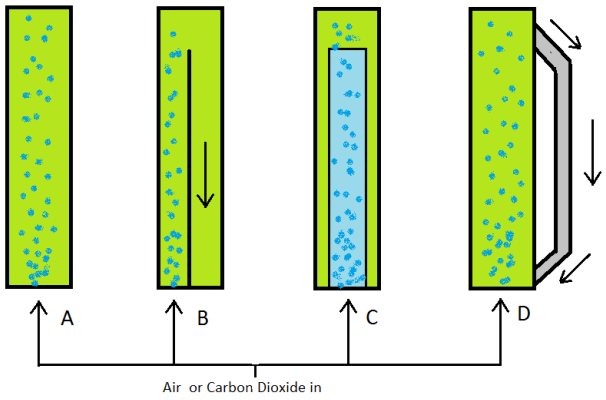

Figure 4. Vertical column PBRs

As it can be seen in Figure 4, the Bubble Column PBR is a simple conceptual design. The figure simply illustrates the basic flow in the column. The gas enters the bottom of the column through a diffuser causing the gas to break into thousands of small bubbles making it easier for the algae to absorb the carbon dioxide in the gas. Once the algae has consumed as much carbon dioxide as it can, it releases oxygen in the form of gas, which leaves the column through the opening in the top and returns to the atmosphere [4]. The three illustrations following the Bubble Column show the other three types of Vertical Column PBRs. Illustration "B" shows an example of a "Split-Column Airlift" PBR [4]. This PBR works in the same way that the Internal Loop Airlift PBR does, except that the vertical flow is on one side of the column, divided by a flat wall of the column [4]. Illustration "C" is an example of an "Internal Loop Airlift" PBR [4]. The "Internal Loop Airlift" PBR works similarly to the Bubble Column as the gas enters the column through the bottom and leaves through the top. However, unlike any other type of photobioreactor, it uses an internal column to house the upward gas flow. As the gas leaves the center column, it causes an upward flow in the algae and water that fills the column, allowing it to overflow the center column and return to the bottom to be circulated again as more gas enters the center column [4]. Illustration "D" is an example of an "External-Loop Airlift" PBR [4]. It works the same way as the Internal Loop Airlift with respect to the flow. However, the flow back down to the bottom of the column takes place in an external tube connecting from the top to the bottom of the column [4].

The "Vertical Column" PBR is the selected design to be applied to this project. As it can be seen in Table 1, the Vertical Column PBR scored significantly higher based on the core design requirements decided upon by the group. More specifically, the "Bubble Column" is to be utilized as the base concept for the photobioreactor to be tested [4]. The "Bubble Column" PBR design we have chosen to work with can be illustrated under "A" in Figure 4. The "Bubble Column" design concept was chosen for this project for multiple reasons. The first reason being that of all of the different types of photo-bioreactors, the "Bubble Column" is the most basic in design and the most economical design to construct. The different parts needed for construction are listed in the budget section of this report. The basic design of the "Bubble Column" will allow for the feasibility of the system to be determined with the least amount of parts for construction. Secondly, vertical column photobioreactors have been proven to be a sturdy design as well as having the ability to allow the maximum amount of light per surface area [4]. This allows for optimal algal growth, which in turn leads to optimal amounts of carbon dioxide being

absorbed by the algae. Also, the design of the "Bubble Column" PBR eliminates Algae-damaging shear force that can be created when using impellers or pumps such as in different types of PBRs [4].

Table 1. Decision matrix for photobioreactor

		Types of Photo-Bioreactors			
Design Requirements	Weight Factor	Vertical Column	Flat Panel	Tubular	Internally Illuminated
Power Efficiency	2	8	8	2	4
Volume Capability	4	5	2	8	5
Cost to Build	3	8	7	1	1
Ease of Maintenance	3	7	6	2	2
Carbon Dioxide Removal	5	6	3	8	6
Ease of Construction	4	7	8	2	1
Raw Score	413	139	110	93	71
Relative Weight %		33.66	26.63	22.52	17.19
Rank Order		1	2	3	4

Using algae in photobioreactors

"Algae are a fully aquatic, plant-like organisms" [12]. They have a number of different structures, from simple single-cells, to large multi-celled structures [12]. Algae are amazing creatures, one can find anywhere on planet earth with even the slightest presence of water. Some environments algae are commonly found in: oceans, lakes, rivers, puddle and even in snow [12].

Algae can be very difficult to classify, this fact is mostly impart due to the many different structures that an algae can occur as: single-celled, filamentous, and plant like structures [12]. An easier way to classify algae, and the way they are most commonly classified is by their primary color; these primary color groups are broken up into red, green and brown [12]. To further complicate the nomenclature, single-celled algae mostly fall under the broad category of phytoplankton [12]. Phytoplankton are microorganisms that drift about freely in water, they can be found in a variety of structures: cyanobacteria, diatoms, din flagellate, and green algae. For algae to truly be considered a phytoplankton, the algae need to use chlorophyll A in photosynthesis, be single-celled or colonial, and live its entire life cycle floating in the water never attaching to any substrate [12].

Phytoplankton are the primary organisms that are used to absorb CO_2 in photobioreactors. For our project we will be focusing on the green algae variety of phytoplankton. They have the same pigments (chlorophyll A, B, and carotenoids), chemical in their cell walls (cellulose) and same storage product as plants (starch) [12].

Choosing a type of algae to work with

Mentioned in the above section is the fact that phytoplankton is the most commonly used organism in photo bioreactors. This fact proved a good starting point when researching different types of algae to use in our photo bioreactor. After some research, we found two types of algae

that we believed would serve the purposes needed for our experiments. The two genes selected for use in the experiment were Spirulina and Chlorella; these were selected above other phytoplankton because of their relatively undemanding growth conditions. Further research was conducted to better determine which of these two algae would be better suited for use in our system.

Table 2. Algae comparison decision matrix

		Algae Being Compared	
Design Factors	Weight Factor	Spirulina	Chlorella
Cost of Acquisition	1	3	3
Acquisition Difficulties	2	5	5
Medium Needs	3	2	8
Growth Rate	5	6	8
Life Span	4	4	4
Lighting Requirements	4	7	8
PH Requirements	2	6	7
Potential Environmental Impact	3	5	3
Raw Score	268	120	148
Relative Weight %		44.78	55.22
Rank Order		2	1

Table 2 lists the design factors we took into consideration when making a choice between the genes of algae being considered. It was determined that Chlorella would best fit the needs and capabilities of the system being constructed.

Algae cultivation and CO_2 capture

Commercial and industrial cultivation of algae has numerous uses, and for that reason finding a way to reduce CO_2 and also produce a viable product has been a large focal point for companies in recent years. This algae produced have many uses such as: food supplements, food additives, bio plastics, fertilizers, dyes, colorants and the potential application of algal fuel.

Water, carbon dioxide, minerals, and light are quintessential factors in play during the cultivation of algae, but some algae have different preferences when it comes to mineral composition when compared to others. Regardless of these preferences they all share a basic means of producing energy [7].

The use of photobioreactors provides a more advantageous method, by combining an aqueous absorption liquid for capturing CO_2 with a growth medium normally used to cultivate algae to produce a more efficient combination of capturing CO_2 from flue gas and bioconversion thereof by algae. Existent absorption liquids capable of removing CO_2 from flue gas are widely known and used. It is performed with an absorption-stripping process using different types of solvent such as amines and amino acids. The regeneration of the solvent loaded with CO_2 is done by heating the solvents, which consumes a lot of energy and costs a lot of money. Therefore, combining algae growth with CO_2 capture is expected to be more efficient and reduces operational expenditure [7].

Another obligatory step in this method is that the CO_2 be stored in the absorbent liquid solution. The CO_2 is chemically bound and will not be released to the atmosphere as easily when compared to CO_2 dissolved in water. For the project, it is preferred that the absorption of CO_2 by the absorbent liquid lead to chemically bound CO_2. It will thus have very high CO_2 capture efficiency as compared to CO_2 bubbled through an aqueous growth medium. A good advantage for the use of an absorbent liquid in a PBR is that when compared to using an absorbent liquid in an open pond, there would be a considerable loss of CO_2 from the open surface, using a PBR this is avoided. Also, using a PBR enables regeneration of the absorbent liquid solution without using high amounts of energy [7].

Both Spirulina and Chlorella respectively require ingredients (salts) to grow to its' optimum. The Table(s) 3 and 4 gives the ingredients the two algal species require.

Table 3. Required spirulina salts [13]

	Spirulina	
#	Chemical Name	Formula
1	Sodium BiCarbonate	$NaHCO_3$
2	Sodium Carbonate	Na_2CO_3
3	Dipotassium phosphate	K_2HPO_4
4	Sodium nitrate	$NaNO_3$
5	Potassium sulfate	K_2SO_4
6	Sodium chloride	NaCl
7	Magnesium Sulfate Heptahydrate	$MgSO_4\,7H_2O$
8	Calcium Chloride Dihydrate	$CaCl_2\,2H_2O$
9	Ferrous Sulfate Heptahydrate	$FeSO_4.7H_2O$

Table 4. Required chlorella salts [14]

	Chlorella	
#	Chemical Name	Formula
1	Di-potassium hydrogen orthophosphate	K_2HPO_4
2	Potassium di-hydrogen orthophosphate	KH_2PO_4
3	Magnesium Sulfate Heptahydrate	$MgSO_4\,.7H_2O$
4	Sodium Nitrate	$NaNO_3$
5	Calcium Chloride Dihydrate	$CaCl_2\,.2H_2O$
6	Sodium Chloride	NaCl

7	Zinc Sulfate Heptahydrate	ZnSO4.7H2O
8	Manganous Chloride Tetrahydrate	MnCl2 .4H2O

Table 3, and 4 lists the sustaining salts required for the efficient growth of Spirulina (Table 3) and Chlorella (Table 4).

Table 5. Decision matrix for required salts

		Algae Medium	
Required Salts	Weight Factor	Spirulina	Chlorella
K_2HPO_4	9	5	7
KH_2PO_4	7	3	7
$MgSO_4 .7H_2O$	6	1	1
$NaNO_3$	6	3	7
$CaCl2 .2H_2O$	3	1	2
NaCl	3	2	3
$NaHCO_3$	8	7	3
Na_2CO_3	5	4	1
$CaCl_2 2H_2O$	3	2	2
$FeSO_47H_2O$	3	1	2
K_2SO_4	4	0	0
MnCl2 .4H2O	3	0	2
CuSO4 .5H2O	4	1	3
Raw Score	422	188	234
Relative Weight %		44.55	55.45
Rank Order		2	1

Preferably the algal culture chemically converts the CO_2 from the absorbent liquid. Then a fixed amount of CO_2 is added to our reactor containing fixed amount of absorbent liquid, growth medium and algae, the carbon dioxide is allowed for a fixed period of time to be absorbed by this absorbent liquid and then converted by the algae, before harvesting the algae. A good way to operate this method is make use of different species of algae that can tolerate a high pH; a good example would be the one the group is using which is Chlorella. An absorbent liquid with high pH is able to absorb more CO_2 than an absorbent liquid with neutral or acidic pH. This is only because at an alkaline pH, for example 8 and higher, enables the equilibrium of gaseous CO_2 or HCO3 to shift which in turn will enable for more CO_2 to be taken up by the absorbent liquid at equal partial CO_2 pressure. In our preferred case of the absorbent liquid has a pH reading of 8 or more the most preferred choice would be 10 because the higher pH the more CO_2 our reactor can absorb. But for the group's algae culture to grow in an alkaline environment which is beneficial

for the absorption of CO_2, the algae must be able to tolerate such high alkaline pH which ours does [7].
A good integration of the algae cultivation to process on a large scale, different kinds of activators for the absorption process is used. Sodium Carbonate ($NaCO_3$) can be used to enhance the transfer of CO_2 from gas to liquid phase. In general, it is imperative to enhance the solubility and rate of uptake of CO_2 in the solvents, the algae cultivation at high pH most typically at a pH of 9, the amount of CO_2 that can be dissolved will increase [7].

Safety concerns when working with algae

When working with algae some safety concerns need to be taken into account, harmful chemicals can be released by a variety of different algae species this poses a particular concern to those working with algae. Disposal procedures are an important part of any experiment involving algae. Failing to follow disposal procedures can pose an extreme environmental concern. These two points will be covered in more depth.

Algae handling procedures

When working with algae there are important factors that should be noted. Some species of algae in particular demand special handling procedures be followed when working with them. In nature algae only poses a concern when it is present in high concentrations, such as those present in algae bloom. Blooms of algae have been reported in marine and freshwater bodies throughout the world [15]. Many of these booms simply appear as an aesthetic nuisance, some species of algae produce toxins that kill fish, shellfish, humans, livestock and wildlife [15].
Some dinoflagellates and cyanobacteria produce toxins that can affect domestic animals and humans [15]. These toxins such as domoic acid, saxitoxin (paralytic shellfish poisoning or PSP toxin), brevetoxin, and cyanobacterial toxins (including anatoxins, microcystins, and nodularins [15]. Marine algal toxins such as saxitoxin, domoic acid, and brevetoxin that bioaccumulate or are magnified in the food chain by fish and shellfish, and anatoxins from freshwater cyanobacteria, affect the nervous system; cyanobacteria that contain microcystins or nodularin cause liver damage [15].
The toxins shown above represent the inherent potential dangers that are present when working with different types of algae. These are provided simply to stress the importance of gathering background information on the particular species of algae one could work with. Though most red tide and toxic freshwater cyanobacteria are not harmful unless they are ingested, some organisms irritate the skin and others release toxic compounds into the water, and if aerosolized by wave action (environment) or by bubbles bursting at the water's surface of the PBR, these compounds may cause problems when people inhale them [15].
Depending on the type of algae being observed in the PBR a risk of potential exposure to hazardous chemicals that can be harmful to one's health are a possibility. The use of rubber or latex gloves are recommended when handling any species of algae, and masks should be worn when the cap is removed and the surface of the algae is exposed to the air to prevent potential inhalation of aerosolized toxins.

Disposal of Algae

Throughout the course of this project algae will be cultivated, this algae may not be native to the region in which the experiment is being conducted. It is imperative that precautions be taken to prevent the release of non-native species into local waterways.

Instruction proved for the disposal of native and non-native species of algae. For most filamentous and unicellular microalgae the chlorine in most municipal tap water will be sufficient to kill the entire culture. Pour the culture down the drain, then followed by flushing the line with 1 gallon of water [16]. If your tap water is from a well and isn't chlorinated, add 1 mL of household bleach or isopropyl alcohol to the culture and let stand for 30 minutes before flushing down a sink [16].
Alternatively, if you wish to keep the algae alive after removing it from the PBR, place it in an aquarium established for the exclusive purpose of containing algae. If alternative disposal instruction relating to the disposal of organisms is provided by your lab protocols, school district, or other responsible authority these take precedence over the disposal instructions mentioned in this report [16].

Selecting aspects and requirements

Before implementing the design, a few aspects of the design must be identified. Aspects such as selecting the material to buy and methods of manufacturing to use require identifying the needs and requirements of our system. Other points that will need to be researched are sensors to be used to take concentration and flow readings. These sensors will have to follow certain key criteria to meet the needs of the project:

- Measure temperature
- Measure pressure
- Measure level of CO_2 (at the input and output)
- Waterproof/Water-resistant quality's
- Easy integration into the design

Other points that need to be researched are how we will supply CO_2 to the algae within the reactor, different lighting option to implement and how to make them efficient.

Photobioreactor Design

The design of the base for our photo bioreactor while at first seemed to be simple creating a base in which to set a clear cylinder quickly turned into a long in depth project. We reviewed many different factors we felt should be involved with the construction and design of the photobioreactor. To list a few of the design factors: material, size, shape, location and size of hole, potential reactions with medium and materials, and a long list of other factors.
After much thought, design and redesign, we finally came up with a design that meets all of our design requirements, the drawing of our PBR is shown in Figures 5 - 8. Also included is a schematic drawing of our PBR at the end of this report.
Moving on with the design of the PBR, details and dimensions were determined in order to further the design process. Below are the constraints determined for the structure of the photobioreactor. These "limiting factors" pushed the project into the next phase in which a more detailed design was determined.
Limiting factors that affect our PBR design:

- 8in X 8in X 6in limited dimensions for parts due to 3D printers printing plate
- Material must be waterproof, to ensure no leaking through the base
- Must be able to withstand forces imposed from bolts to create a seal
- Must be able to be fabricated to the appropriate dimension
- Non-reactive with medium composition

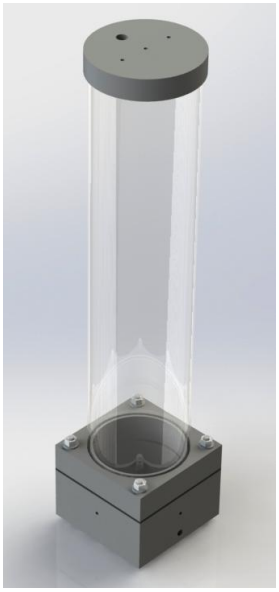

Figure 5. Photobioreactor complete assembly

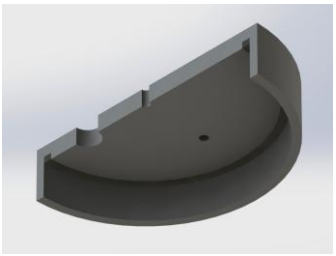

Figure 6. Photobioreactor cap cross section

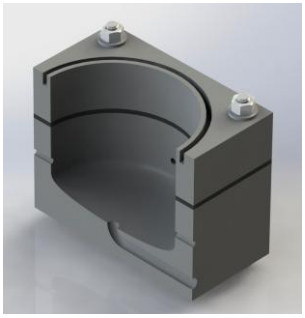

Figure 7. Photobioreactor base cross section

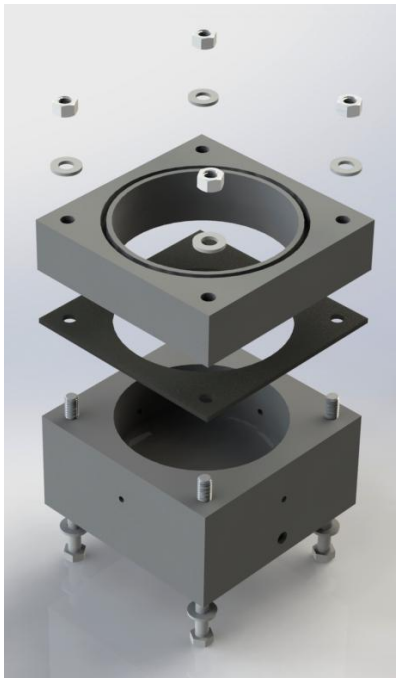

Figure 8. Photobioreactor base exploded view

An FEA analysis will be used to determine if the forces resulting from tightening the bolts would be enough to fracture the ABS plastic, and will be added to a later version of this report.

Photobioreactor base manufacturing options

While designing the base, we compared a number of different options for materials. We finally determined that to aid in the simplification of construction it would be easier to make the entire base out of two pieces of ABS plastic. After determining the material we wished to work with, we needed only determine with method of manufacturing necessary to give our concept constructed in SolidWorks shape. The two methods with which to work with ABS plastic are 3D printing our design utilizing the 3D printer supplied by West Virginia University Institute of Technology, or purchasing blocks ABS plastic and outsources the milling of our PBR base to an outside company with the appropriate C&C mill. Table 6 compares the manufacturing methods with the desired characteristics of our PBR base.

Table 6. Photobioreactor manufacturing method decision matrix

		Manufacturing Methods	
Design Requirements	Weight Factor	3D Printed ABS Plastic	Milled ABS Plastic
Cost of Material	2	+	-
Strength of Finished Product	4	-	+
Water Resistance	5	S	S
Design Limitations	3	+	-
Precision of Product	3	S	S
Time to Manufacture Product	1	+	-
	Score	+2	-2
	Rank Order	1	2

We determined with the above decision matrix that 3D Printing would yield a preferred outcome. It has substantial benefits over the option of milling the base, most notably we will be able to create some of the complex shapes and channels we have sketched in our SolidWorks models shown in Figure 7.

Capturing data from the experiment

The most effective means to collect data from a system by installing measuring instruments within it. Factors of interest are CO_2 concentration at inlet and outlet, temperature of the medium solution, and inlet flowrate of gas into the PBR. Research was conducted and a decision matrix was used to aid in choosing a CO_2 sensor that would be most effective for meeting the needs required for the application in the PBR. Ideally a sensor with the capabilities to provide readings on the amount of CO_2 as well as temperature would be advantageous to the team's goals. An additional sensor will be required to monitor the inlet flow of gas. The inlet gas line shown in Figure 9 provides CO_2 artificially to the reactor in the place of a true flue gas product seen by the reactor in real world applications. Once the CO_2 leaves its' holding canister it will pass through a length of line, long enough to allow the compressed gas to reach room temperature. In a true system the flue gas will be at a very high temperature and will need to be cooled in a heat exchanger before injection into the reactor during the summer but may be used to heat the PBR during the winter.

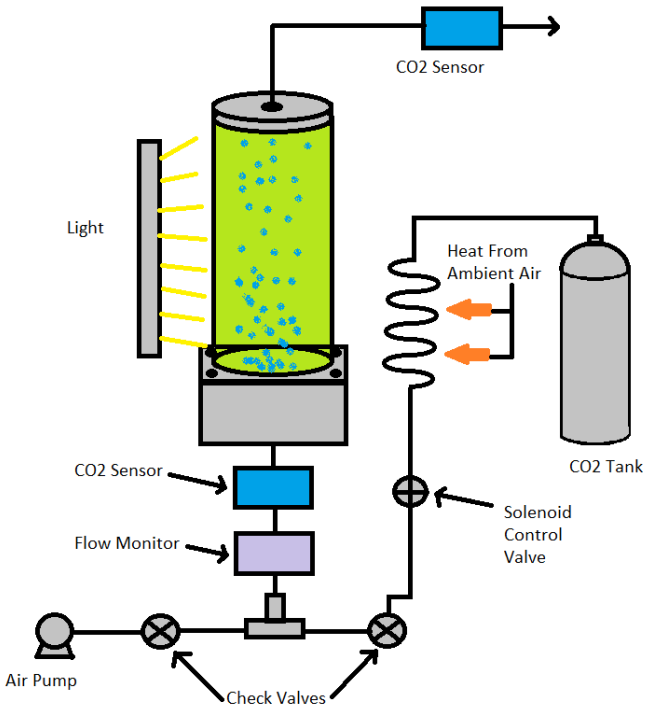

Figure 9. Proposed system blueprint

After heating the CO_2, it is passed throw a solenoid control value to control the flow rate into the PBR. This flow passes through a check value where it connects to a T-connector. This T-connector joins the two inlet flows from the air pump and the CO_2 input system previously mentioned. The outlet flow from the T-connector passes through a flowrate sensor so that the flow rate can be monitored and controlled. After passing through the flow rate sensor the air CO_2 mixture passes through a CO_2 sensor where the concentration of CO_2 is measured. Knowing the concentration of CO_2 allows us to vary it input concentration to match real world conditions. Another CO_2 sensor will be placed at the outlet of the PBR to monitor the outlet concentration of CO_2 this will allow for an accurate measurement of the amount of CO_2 absorbed by the algae within the PBR. All of these components are represented in Figure 9.

Control system for monitoring CO_2

The decision matrix for CO_2 sensors shown in Table 7 compares five sensors for monitoring CO_2 concentration. Research was conducted to determine advantages and disadvantages of each. The Vernier sensor is preferred because it not only can be used as an educational device built for the classroom, meaning an easier setup and application to different systems, but unlike many other measuring devices it doesn't need calibration. The disadvantage to this devise is its price. Next, the NeuLog sensor offers some similar properties, but must be calibrated often to ensure accurate measurements. The COZIR sensor is promising, due to a low cost and its ability to measure temperature and oxygen level. Integration may prove difficult due to multiple inlet ports that would need to be added to the design, thus increasing the system's complexity. The sensor that meets all requirements of the project and offers more than expected is the NODE sensor. It provides a live reading of the CO_2 level in a graphic way on a mobile phone using Bluetooth. The device is also wireless and could easily be integrated into the system with minimal effort.

The only problem that exists is it being a Kickstarter project and does not have a price yet. Lastly, research was conducted into building a CO_2 sensor using an Arduino board and source code found online. At this time this appears to be the most viable and affordable method of monitoring CO_2.

Shown in Table 7, the NODE sensor would be the best and provide everything desired for this project, however at this point in the project being able to generate readings is a primary goal. This point causes the Arduino Sensor Build to be the most desirable option for use in this project at its current stage. At a later point when more funding is available, another sensor will be purchased to replace the currently chosen Arduino Sensor due to the sensor's capability and reduce complexity.

Table 7. CO_2 sensor decision making matrix

		Characteristics of CO_2 Sensors				
Design Requirements	Weight Factor	Vernier CO_2 Gas Sensor	NeuLog CO_2 Sensor	COZIR Ambient CO_2 Sensor Kit	NODE + CO_2 Sensor	Build Arduino Sensor
Waterproof	2	0	5	0	5	0
Initial Costs	5	5	5	5	8	9
Measures CO_2 Levels	5	8	4	8	9	6
Accuracy	4	8	6	7	9	6
Can Be Integrated	3	8	6	7	7	8
Has Own interface	5	5	8	7	9	6
Ease to use	4	9	7	7	9	5
Calibration need	4	9	0	4	9	4
Raw Score	1034	218	165	193	269	189
Relative Weight %		21.1	16.0	18.7	26.0	18.3
Rank Order		2	5	3	1	4

System for controlled light application

The algae selected determines the lighting requirements for the system. As previously mentioned above using a decision matrix it was determined that the genus Chlorella would best be suited.

Information provided by the seller with which we acquired that algae included specific lighting requirements that were to be followed to allow for optimal growth. The Chlorella should be provided with a minimum of 200 foot-candles (1.39 lumens/in^2) to a maximum of 400 foot-candles (2.78 lumens/in^2), located at a minimum distance of 18 inches (46 cm) to a maximum distance of 24 inches (61 cm) from the specimen [15]. The amount of light mentioned, should be

applied to the specimen continuously for 12-hours a day, followed by a 12-hour dark period [15]. The requirements are summarized in Table 9 in the Appendix.

How to meet the lighting requirements

A light was chosen based off the specific requirements shown in Table 9. A light was found to meet the specific need required to grow Chlorella. The fixture chosen was a Finnex Ray 2.This lighting fixture implements 144 LEDs. These LEDs were each 3014 type; each produces 10 to 13 lumens each. This produces a total lumen output between 1440-1872 lumens per lighting fixture.Running some calculations using the projected lumen output for fixture and the exposed surface area of our PBR shown by the equation.

$$S_{PBR} = (2\pi * r * h) + (2\pi * r^2) \quad = (2\pi * (\frac{7(in)}{2}) * 30(in)) + (2\pi * (\frac{7(in)}{2})^2)$$

$$= 736.70in^2$$

$$\frac{Lumens}{Exposed\ Surface}(Min) = \frac{1440(Lumens)}{736.70(in^2)} = 1.95(\frac{Lumens}{in^2})$$

$$\frac{Lumens}{Exposed\ Surface}(Max) = \frac{1872(Lumens)}{736.70(in^2)} = 2.54(\frac{Lumens}{in^2})$$

We find that one light would deliver between 1.95-2.54 lumens/in^2. Comparing that output to the required amount of light required to grow the algae effectively 1.39-2.78 lumens/in^2 (200 – 400 foot-candles) we can see that one fixture should be able to supply enough light, assuming one is able to disperse that volume of light evenly across the total exposed surface of the PBR. For this reason research is being conducted to find different methods for ensuring equal light distribution with the aid of mirrors or the addition of a second lighting fixture.

Table 9. Chlorella environmental requirements

Lighting Requirements	Full Spectrum
Lighting Hours Per Day	12 (hr)
Light Distance Min/Max	18 - 24 (in)
Light Level Min/Max	1.39 / 2.78 (Lumen/in^2)

Conclusion

Through extensive research on our topic, comparing the many different potential solutions, a PBR system was designed. This system was designed with the ability to be in conducted on a small scale testing for the coming semester. The system designed consists of a vertical column photobioreactor, utilizing the genus of algae Chlorella to capture CO_2. A medium was chosen based on the requirements of Chlorella, these needs are laid out in Table 5 in the algae cultivation section of this report. Important aspects of design were laid out and chosen based on important characteristics and limitations set by necessary and 3D printing capabilities. 3D printing was chosen over milling because of price concerns and ease of access to a 3D printer. A light was chosen based off the specific requirements.It was found that a Finnex Ray 2 would meet these requirements as well. An Arduino board will be chosen as the basis for CO_2 sensors to be used in the project.

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