DESIGN, CONSTRUCTION AND TESTING OF PILOT SCALE
PHOTOBIOREACTOR SUBSYSTEMS

A thesis presented to

the faculty of

the Russ College of Engineering and Technology of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Benjamin M. Mears

June 2008
This thesis titled
DESIGN, CONSTRUCTION AND TESTING OF PILOT SCALE
PHOTOBIOREACTOR SUBSYSTEMS

by

BENJAMIN M. MEARS

has been approved for
the Department of Mechanical Engineering
and the Russ College of Engineering and Technology by

Ben J. Stuart
Associate Professor of Civil Engineering

Dennis Irwin
Dean, Russ College of Engineering and Technology
Abstract

MEARS, BENJAMIN M., M.S., June 2008, Mechanical Engineering

DESIGN, CONSTRUCTION AND TESTING OF PILOT SCALE

PHOTOBIOREACTOR SUBSYSTEMS (88 pp.)

Director of Thesis: Ben J. Stuart

Methodology of designing and testing pilot scale photobioreactor containment and gas circulation subsystems. Evaluation of containment subsystem seal surfaces based on testing of bench-top model with identical features. Gas circulation subsystem evaluated based on airflow distribution profile generated from air velocity data taken from full size photobioreactor. Considerations and recommendations for subsystem integration into complete pilot scale facility.

Approved: _____________________________________________________________

Ben J. Stuart

Associate Professor of Civil Engineering
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>3</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>6</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>7</td>
</tr>
<tr>
<td>1) INTRODUCTION</td>
<td>10</td>
</tr>
<tr>
<td>1.1) COAL AS AN ENERGY SOURCE</td>
<td>10</td>
</tr>
<tr>
<td>1.2) PHOTOBIOREACTORS</td>
<td>11</td>
</tr>
<tr>
<td>1.3) PROJECT OBJECTIVE</td>
<td>13</td>
</tr>
<tr>
<td>2) LITERATURE REVIEW</td>
<td>14</td>
</tr>
<tr>
<td>2.1) CARBON MITIGATION</td>
<td>14</td>
</tr>
<tr>
<td>2.2) PHOTOBIOREACTOR SUBSYSTEMS</td>
<td>16</td>
</tr>
<tr>
<td>2.3) PHOTOBIOREACTOR DESIGNS</td>
<td>18</td>
</tr>
<tr>
<td>3) DESIGN APPROACH</td>
<td>21</td>
</tr>
<tr>
<td>3.1) DESIGN RESTRICTIONS</td>
<td>21</td>
</tr>
<tr>
<td>3.2) SUBSYSTEM DESIGN</td>
<td>22</td>
</tr>
<tr>
<td>3.3) SUBSYSTEM INTEGRATION</td>
<td>26</td>
</tr>
<tr>
<td>4) TEST PLAN</td>
<td>27</td>
</tr>
<tr>
<td>4.1) INDIVIDUAL SUBSYSTEM TESTING</td>
<td>27</td>
</tr>
<tr>
<td>5) EXPERIMENTAL METHODS</td>
<td>30</td>
</tr>
<tr>
<td>5.1) CONTAINMENT SUBSYSTEM</td>
<td>30</td>
</tr>
<tr>
<td>5.1.1) DESIGN CRITERIA</td>
<td>30</td>
</tr>
<tr>
<td>5.1.2) INITIAL DESIGN</td>
<td>32</td>
</tr>
</tbody>
</table>
5.1.3) CRITICAL ELEMENT – SEAL SURFACE ........................................ 33
5.1.4) SEAL SURFACE CONFIGURATION ........................................... 34
5.1.5) SHEET METAL SEAL SURFACE ............................................. 36
5.1.6) EVALUATION OF SEAL DESIGN ............................................ 37
5.1.7) PRESSURE INCREASE INSIDE REACTOR ................................. 39
5.2) GAS CIRCULATION SUBSYSTEM .................................................. 42
  5.2.1) GAS CIRCULATION FAN BLADE ........................................... 42
  5.2.2) GAS CIRCULATION MOTOR ................................................. 43
  5.2.3) MOTOR CONTROLLER .......................................................... 44
  5.2.4) FAN ASSEMBLY ................................................................. 45
  5.2.5) FAN SHROUD ................................................................... 47
5.3) FULL SCALE REACTOR MOCK-UP ............................................... 48
  5.3.1) HEADER AND MEMBRANE FRAME MOCK-UPS ....................... 48
  5.3.2) LIGHT PANEL MOCK-UPS .................................................... 49
  5.3.3) INSTALLATION OF MOCK-UP COMPONENTS ......................... 50
5.4) METHOD FOR TAKING AIR VELOCITY READINGS ...................... 52
  5.4.1) INSTRUMENTATION FOR AIR VELOCITY READINGS ............... 52
  5.4.2) TEST PLAN FOR TAKING AIR VELOCITY READINGS .............. 53
  5.4.3) PROCEDURE FOR OPERATING FAN ...................................... 55
6) RESULTS AND DISCUSSION ......................................................... 57
  6.1) CONTAINMENT SUBSYSTEMS .................................................... 57
    6.1.1) FEA OF CORNER SEAL SURFACE ...................................... 57
    6.1.2) FEA OF SHEET METAL SURFACE ....................................... 60
6.1.3) PRESSURE TEST OF BENCH-TOP MODEL.................................61

6.2) GAS CIRCULATION SUBSYSTEM..............................................67
   6.2.1) INITIAL RESULTS – NO FLOW MODIFICATIONS...............67
   6.2.2) FLOW MODIFICATIONS – VANES....................................71
   6.2.3) FLOW MODIFICATIONS – SCREENS...............................74

7) CONCLUSIONS.................................................................................82
   7.1) CONTAINMENT SUBSYSTEM..............................................82
   7.2) GAS CIRCULATION SUBSYSTEM............................................83
   7.3) PILOT PROJECT STATUS...................................................83

8) RECOMMENDATIONS AND FUTURE WORK.................................84

REFERENCES..................................................................................86

APPENDIX A: CORNER SEAL SURFACE ASSEMBLY.............................88
## List of Tables

<table>
<thead>
<tr>
<th>Table Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1 – Model Pressure versus Time</td>
<td>63</td>
</tr>
<tr>
<td>Table 2 – Acceptable Average Air Velocities for Initial Test</td>
<td>70</td>
</tr>
<tr>
<td>Table 3 – Air Velocity Averages at 6 in. Above Bottom of Membrane with Airflow Vanes</td>
<td>73</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Conceptual Photobioreactor</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Skeleton Framework after Assembly</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Overall Dimensions of Pilot Bioreactor</td>
<td>33</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Portion of Seal Surface Members</td>
<td>34</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Loads and Constraints on Sheet Metal Seal Surface</td>
<td>37</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Bench-top Model of Seal Surfaces</td>
<td>38</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Pressure Increase Example Calculation</td>
<td>40</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Pilot Pressure Increase vs. Time</td>
<td>41</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Gas Circulation Fan Assembly</td>
<td>42</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Gas Circulation Motor</td>
<td>44</td>
</tr>
<tr>
<td>Figure 11</td>
<td>GS1 AC Drive for Fan Motor Speed Control</td>
<td>45</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Fan Assembly Installed on Pilot Reactor</td>
<td>46</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Milled Slots on Motor Plate for Belt Tensioning</td>
<td>47</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Installed Fan from Inside Reactor</td>
<td>48</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Installed Fan with Fan Shroud</td>
<td>48</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Header and Membrane Frame Mock-up</td>
<td>49</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Header Support Hooks</td>
<td>51</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Mock Membrane Frame and Light Panel Setup</td>
<td>52</td>
</tr>
<tr>
<td>Figure 19</td>
<td>AirData Multimeter ADM-850L</td>
<td>53</td>
</tr>
<tr>
<td>Figure 20</td>
<td>160 Series Pitot Tube</td>
<td>53</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Particle Board Door for Air Velocity Readings</td>
<td>54</td>
</tr>
</tbody>
</table>
Figure 22 – Horizontal View of Channels for Data Points

Figure 23 – Location of Data Points in terms of Height and Depth

Figure 24 – ALGOR Results Window of Stress Distribution for Four Inch Bolt Spacing

Figure 25 – Close-up View of Compressive Forces on Corner Seal

Figure 26 – ALGOR Results of Sheet Metal Seal

Figure 27 – Close-up View of Compressive Forces

Figure 28 – Average and Greatest Pressure Decrease of Bench-top Model

Figure 29 – Net Pressure of Pilot Reactor Considering Burner Operation

Figure 30 – Top View of Reactor Displaying Velocity Profile Area in Red

Figure 31 – MATLAB Plot of Velocities at 6 in. Below top of Membrane

Figure 32 – MATLAB Plot of Velocities at Midpoint of Membrane

Figure 33 – MATLAB Plot of Velocities at 6 in. Above bottom of Membrane

Figure 34 – Vane Flow Modifiers

Figure 35 – Vane Flow Modifier Variables

Figure 36 – Air Modifying Vanes in 90° Position. H = 8 in

Figure 37 – Flow Modification with Screen Material Under Middle Five Membranes

Figure 38 – Screen Airflow Modifier Drawing

Figure 39 – Installed Screen Modifiers

Figure 40 – Rotated View of Screen Modifiers

Figure 41 – Mock Screen Flow Modifier Installed Between Two Membrane Frames

Figure 42 – MATLAB Plot of Velocities with Screen Airflow Modifiers

Figure 43 – Modified Area for Air Velocity Readings
1. Introduction

1.1 Coal as an Energy Source

The most abundant resource within the United States is coal. The United States possesses over one fourth of the world’s coal supply. This amount contains more energy content than all of the world’s known recoverable oil. The United States uses coal as its primary fuel source for electricity. Coal-fired electrical power plants generate more than half of electricity consumed by Americans (U.S. Department of Energy, 2007). The vast abundance of coal makes it a very attractive energy source.

While coal is abundant and provides the majority of the electrical power in the United States, there are a number of negative aspects of coal which make it a less attractive energy source. The first negative aspect of coal is apparent with the extraction process. Underground mining for coal is a historically dangerous process. There was an average of 51 deaths annually in underground coal mines between the period of 1990 to 1999 (U.S. Department of Labor, 2007). Other forms of extraction such as strip and long wall mining are less dangerous but leave nearby wildlife and landscapes decimated.

The extraction of coal contributes a small fraction of the negative attributes of coal. Once coal has been collected, problems arise. Coal is less convenient to store, transport and use in comparison with oil and gas. Also, coal produces twice the amount of the greenhouse gas carbon dioxide ($\text{CO}_2$) for the same amount of heat as the other two fuel sources (Boyle et al, 2003).

The primary negative attribute of coal utilization is due to what is released into the atmosphere when the fuel is burned. Coal-fired electrical power plants release many potentially harmful substances into the atmosphere during the combustion process. A
large coal fired power plant generates enough ash in a single year to cover an acre of
ground up to six stories high (Boyle et al, 2003). If this ash is not properly treated and
contained it can spread into nearby lakes, damage wildlife, and contaminate ground
water.

Due to coal’s complex nature, the combustion process produces NO\textsubscript{x} and SO\textsubscript{2};
however the main combustion products are CO\textsubscript{2} and water. A modern 660 MW coal-fired
power station produces 700 tons of CO\textsubscript{2} in one hour of operation (Boyle et al. 2003).
Because CO\textsubscript{2} is a known constituent of air, it is not thought to be harmful to nearby
wildlife in the concentrations being outputted from power stations. The main concern
with CO\textsubscript{2} is the cumulative effect on the climate from all of the world’s power stations
(Boyle et al. 2003).

The effect of greenhouse gases such as CO\textsubscript{2} on the world’s climate is a
documented problem. High concentrations of these gases cause the radiated heat of the
sun to stay within the atmosphere for an extended period of time, thus producing the
greenhouse effect. In 2000, the global mean temperature was estimated to be
approximately 0.35\textdegree C above the average of the four previous decades (Boyle et al,
2003).

1.2 Photobioreactors

Because CO\textsubscript{2} is an inherent product of the coal combustion process, removing it
has become the focus of much recent attention. Many methods of capturing the gas and
sequestering it beneath the earth’s surface have been proposed, and some have been
implemented. The main drawback to these methods is the cost associated with the process
of sequestration. Capturing, transporting, and storing CO$_2$ before sequestering can be very expensive. An appealing method of sequestration is biological sequestration by means of photosynthesis. One method of utilizing photosynthesis to reduce CO$_2$ levels is to circulate flue gas through a photobioreactor containing algae. The photobioreactor introduces light into the system allowing the algae to grow. Excess algae can be harvested and processed into a profitable product.

Research completed over the past few decades has focused on the use of algae as a renewable clean energy source. Hydrogen produced via photobioproduction has been studied as a clean fuel source for fuel cells. Similar studies have shown the potential for algae as a high yield, low cost liquid biofuel. The idea of growing algae for economic profit is the main motivation which pushes to development of larger and more efficient photobioreactors.

Current bioreactors in research and in practice work in similar fashions. Hot flue gas is introduced into the system. The gas is directed into an environment which contains an algae rich medium and the presence of a light source. The gases are circulated for a period of time to allow for photosynthesis to take place. Once the potential for algal growth has been maximized the gases and algae are removed and the process is repeated.

While carbon mitigation is a key benefit of photobioreactors, the main motivation behind their development is the production of algae. Algae produced from photobioreactors have many industrial and scientific applications which can offset the cost of fabricating and operating a reactor as well as potentially generate a profit. These applications include, but are not limited to: industrial biofilters, production of human
food, production of useful compounds including transportation fuels, water quality
testing, and environmental change indicators (Graham and Wilcox, 1999).

1.3 Project Objective

The goal of the Pilot Photobiorector project is to design, construct and test a
photobioreactor that maximizes algae growth. The pilot scale photobioreactor will
incorporate a number of subsystems which must interact efficiently to maximize algae
growth. Subsystems will be designed, constructed, and tested prior to full scale reactor
operation. These subsystems will include gas, light, and nutrient delivery, harvesting, and
containment.

Successful completion of the project will result in a “shakedown” run of the
reactor with all systems operational. The desired outcome of the shakedown run is to
demonstrate an accumulation of algae in the system. It is anticipated that the shakedown
run will not be at the system’s full capacity; however it should identify any shortcomings
in subsystem design which can be addressed prior to full-scale operation.

The objective of this thesis is the design and testing of the containment and gas
circulation subsystems. Each subsystem has criteria which will be used to evaluate the
success of the designs. Countermeasures and modifications may be implemented in order
to meet the set design criteria. Upon completion of this objective preliminary work in the
design and construction of the remaining subsystems will be documented and
incorporated into a final system that will be available to students continuing work on the
Pilot project.
2. Literature Review

2.1 Carbon Mitigation

Various methods of carbon sequestration have been researched and practiced in the past decades. Costs, length of sequestration, and transportation and storage of CO₂ are all issues which must be addressed by any proposed method. Carbon sequestration methods in practice today include Enhanced Oil Recovery (EOR) and sequestering the gas beneath the Earth’s surface (Boyle et al, 2003).

Each of the methods share one main disadvantage: the CO₂ must be captured and separated from combustion flue gas. Methods for capturing CO₂ exist, however they are costly and not necessarily efficient (Boyle et al, 2003). Not taking into account government subsidies, the only sequestration method which has the potential to turn a profit is EOR. EOR is a sequestration method which works by taking CO₂ and injecting it into depleted oil fields. By injecting the gas into the well, remaining oil can be extracted and sold. As of 2000, oil prices were in the range of $20-25/barrel of oil (bbl) and CO₂ was priced in the $1-2/thousand cubic feet (Mcf). These prices indicate that with a successful capture and transportation strategy, the market for CO₂ EOR exists. Up to 10% of the CO₂ from the power plants could be captured, sold and sequestered for an extended period of time. However, the potential for CO₂ EOR in Texas was estimated to exist for a period of 12 to 20 years (Holtz et al, 1999).

A more attractive method for sequestering CO₂ is to use biological sequestration. Biological sequestration can mitigate CO₂ while producing a marketable product. One such product is bio-oil. Bio-oil production from microalgae not only mitigates CO₂ but it also produces a renewable energy source. High yield bio-oil methods have been
researched and tested. High temperature pyrolysis of microalgae biomass has shown a product yield of up to 57.9%. (X. Miao and W. Qu, 2004)

Energy conversion processes pertaining to the liquefaction of algae have been performed in recent years (Yang et al, 2004). The accumulation of large amounts of storage lipids in algae, combined with the organism’s ability to reproduce rapidly led to the development of processes for the extraction of biomass lipids. One such process involves introducing a catalyst into a slurry of algae biomass under high temperature and pressure. This results in the liquefaction of the algae and evolved gases, which are removed and sampled. The liquefied algae are then extracted with chloroform to recover the remaining bio-oil. This liquefaction process yielded oil fractions of up to 39.5% (Yang et al, 2004).

Algae have also shown potential to create hydrogen via photobioproduction. When algae are placed under stress conditions, there has been evidence of a hydrogen path metabolism (Dante et al, 2004). Stress conditions included varying the algae’s exposure to air and light. Algae were shown to provide nearly 5 ml of hydrogen per liter of algae culture (Dante et al, 2004). The main advantage to hydrogen production is that hydrogen is a desired energy source for fuel cells. Current hydrogen production requires large amounts of energy which is usually derived from fossil fuels. By producing hydrogen from algae, the energy derived from fuel cells would come from a renewable source.

Concerns arise when considering algae for use in a bioreactor system. The first concern is that of flue gas temperature. Algae typically do not grow in high temperature environments such as those of flue gas (~120 C) (Ono and Cuello 2006). However,
certain strains of algae have shown the ability to survive and grow at elevated temperatures (Bayless et al, 2001). A second concern is that algae will not be able to grow at optimal rates in the CO₂ rich environment of the flue gas (~ 14% v/v) (Bayless et al, 2001). However, experiments where algae were placed in elevated CO₂ environments (5% v/v) showed improved algae growth (Ono and Cuello, 2006).

2.2 Photobioreactor Subsystems

The many subsystems of photobioreactors lead to an array of possible designs. Some important subsystems of a bioreactor include gas, nutrient, and light delivery. Variations on subsystem design each have their own advantages and disadvantages. The gas delivery system of a bioreactor must circulate simulated flue gases throughout the reaction area of the system. A main goal in designing a gas delivery system is to keep the gases in the reactor in constant motion so the algae can complete the photosynthesis process. One method is to suspend the algae in a fluid and then pump the gas through the fluid, creating a “bubbling” effect. Pockets of gas can mix the algal fluid by creating turbulent flow. When implementing this method high pressures are often required in order for the gases to move through an entire column of fluid. This requires compressing the gas which can become costly due to the power requirements of a compressor.

A second method for circulating flue gas in systems where the bulk fluid is gas is to use a fan and create a circular path to blow the gas throughout the reaction chamber. Large industrial fans consume less electrical power than a compressor and keep the flue gas in constant motion in the areas surrounding the algae. Bioreactors with horizontally oriented fans have been tested, as in Ohio University’s second generation Carbon
Recycling Facility (CRF-II). Designs which do not efficiently use space for gas travel may result in large reactors with small reaction chambers.

The method of nutrient delivery can also have many variations. A common method is to suspend the algae in a fluid and circulate it through tubes or other structures (Tsygankov, 2001). This method is advantageous in that it is simple in concept and the tubes can be easily constructed and manipulated into various configurations. However, suspending algae in tubes can lead to a lack of photons reaching the algae. If algae attach themselves to the surface of the tubes they begin to block photons from reaching algae at the interior of the tubing. The absence of photons inhibits photosynthesis and decreases both algal growth and carbon mitigation.

A second method for nutrient delivery involves what is known as fixed film growth. Fixed film growth refers to flowing algae over a surface in order to get the individual organisms to attach; this is known as the loading phase. Nutrient rich fluid is then dripped over the medium throughout the photosynthetic process. Systems using fixed film membranes have been researched and tested in the past (Bayless et al, 2001). Fixed film growth systems can become complex because a method for creating an even coverage of algae across the film needs to be devised. Also, it can be difficult to detach the organisms from the material at harvesting time. Fixed film algae growth systems orient the organisms into a position to receive optimum amounts of both CO₂ and light.

A third subsystem of photobioreactors which has multiple possible designs is the light system. Light is vital to photosynthesis, as algae will not convert CO₂ to O₂ without it. One artificial option is to use electrically powered lights. Electric lights are beneficial in that the light intensity can be adjusted fairly easily and the light source is available 24
hours a day. However, electric lights are expensive to power over long periods of time. Also, the electric power is generally provided via coal power plants.

A second option is to use solar power. By using a solar collector to gather usable photons, light can be directed through fiber optic cables and into light emitting panels inside the reactor. The light source is available at zero cost however it is only available for a limited portion of the day. Solar light delivery systems with limited light/dark or photoperiods can be advantageous in photobioreactors. Research has shown that certain strains of algae reach optimum growth when light and dark periods are varied. Photoperiods of 16:8 and 15:9 (hours of light: hours of dark) have shown maximum growth in algae strains used for bioproducts. (Bouterfas et al, 2002; Huang and Rorrer, 2002). These periods approximately coincide with natural daylight photoperiods.

2.3 Photobioreactor Designs

Numerous benefits of large scale algae growth have been researched, but the main issue lies in designing a reactor capable of large scale growth. Several types of reactors have been researched and designed (Tsygankov 2001). One such reactor is called a Flat Parallel-Sided Cuvette. In this reactor the algae medium is a liquid which is held in a vessel. A gas mixture is bubbled through the vessel and light is illuminated on either one or both sides. A drawback to this design is that because the culture volume is not controlled continuous cultivation is difficult to implement.

Tube based reactors are very popular because of their simplicity and scalability. In such a reactor, suspended algae flows through a tube which is externally illuminated. A gas-mass exchanger introduces gas into the culture and a pump provides liquid
circulation. A key disadvantage of this system is the spatial separation of certain portions of algae and the gas-mass exchanger. This means that not all of the algae are exposed to both gas and light at the same time, making photosynthesis less effective (Tsygankov, 2001).

A more innovative reactor design is a Coaxial Cylinder Reactor. In such a reactor two coaxial tubes are placed one inside the other. The algae fluid is located in the annular space between the surfaces of both tubes. A light emitting source is introduced through the axis of the tube. The gas inlet is the same as for the tube based reactor. A key advantage to this reactor is that a metal ring can be placed in the section containing the algae. If a magnetic field is applied the ring can be moved back and forth, mixing the algae liquid. The main drawback here is the complexity of the system. These reactors can be difficult to assemble and are limited in size to laboratory applications (Tsygankov, 2001).

A practical bioreactor which allows algae maximum exposure to flue gas and light has been conceptualized and built. A Carbon Recycling Facility (CRF) was developed at Ohio University using fixed film membranes to support algal growth. The algae are introduced to the reactor by flow over membranes from a header system. The membranes are suspended vertically in a reaction chamber which has a constant circulation of flue gases. Solar light is collected and run through fiber optic cables, illuminating panels which are positioned between membranes. Once mature algae have maximized their growth a harvesting system is activated. The harvesting system is designed to force the algae off the membranes by increasing the volumetric flow down the membranes to
generate a high shearing force. After harvesting is completed the process can be repeated (Bayless et al, 2001)

An important difference between the CRF and the previously mentioned reactors is the use of solar light. Solar light is ideal for photobioreactors because it consumes less electricity (by not powering lights) and it provides efficient light distribution over the entire visible spectrum (Tsygankov, 2001). The main drawback to using solar light is the difficulties present in distributing light uniformly throughout the reactor. Solar concentrating systems have been shown to exceed 45% efficiency in recent years, but once photons are collected, difficulties arise in evenly distributing them. Fiber optic cables can transmit light from the solar collector to the reactor, but non-uniform light emissions are observed in the materials present inside the reactor. Research into various light-emitting materials such as woven optical pads, light pipes, and silica and polymer optical cable has been conducted. Light-emitting fibers appeared to show the most promise for large scale use and they also provide adaptability for a hybrid system of natural and artificial light.

Solar power collection is only viable during daylight hours. This poses a problem for photobioreactors because photosynthesis only occurs in the presence of light. In order to maximize the algae production of photobioreactors, the implementation of hybrid light sources has been researched (Ogbonna et al, 1999). An innovative system which implements a control box has been designed to counter this problem. Inside the control box are light intensity sensors and solar collectors provide light during the day. Once light intensity falls below a preset limit, artificial light is turned on via a metal halide lamp. The research showed that on cloudy and rainy days almost no cell growth occurred
when only natural light was used. This lead to the hypothesis that prolonged periods of
poor sunshine could lead to complete failure of a photobioreactor relying solely on solar
light. Once artificial light was used, the system was able to sustain cell growth during
periods when solar power was not available (Ogbonna et al, 1999).

3. Design Approach

3.1 Design Restrictions

The pilot scale photobioreactor will require new designs, the use of previously
designed systems and their components, as well as designs delegated to other researchers.
Before outlining the design approach for each subsystem it should be noted that a number
of constraints were placed on designs for the pilot reactor due to previous experiences
with photobioreactors at Ohio University’s Coal Research Center (OCRC). First, stainless
steel was mandated for all structural components of the reactor. Previous experience with
corrosion problems superseded the cost reduction of using less expensive materials with
corrosion resistant after-treatments.

Second, the header design was to be the same as that used for the CRF-II. These
headers have shown good flow distribution in previous reactors and are in the process of
being patented. The Omnisil material used for the growth membranes was also
predetermined.

Final restrictions were based on the location of the pilot reactor. Room
dimensions, access to utilities and roof access were all critical in the reactor design.
3.2 Subsystem Design

The first component designed and constructed for the pilot reactor was the frame. The frame material must be specified in order to withstand the corrosive environment inside the reactor. A key design criterion of the frame is that it is transportable. Therefore a “knockdown” style frame will be employed. The knockdown style frame needs to provide a well sealed reactor which can be disassembled and transported in the future. The frame needs to provide adequate structural support for all subsystems of the pilot reactor while accommodating each subsystems unique dimensions and characteristics (i.e. removable, replaceable, and accessible for maintenance). This will require two doors on the front and back of the reactor in order to provide access to the reaction chamber.

Computer Aided Design (CAD) was a key tool in the design of the reactor frame. Designing a frame in CAD allowed for Finite Element Analysis (FEA). FEA was used to analyze stress distributions along seal surfaces and joints of the frame. FEA was used to validate the sizes and strengths of specified support member materials. A major benefit of CAD is the ability to check for interferences and fit of subsystems and their parts throughout the reactor. The programs used for CAD and FEA on the Pilot Reactor are Solid Edge and ALGOR, respectively.

The initial concept of the pilot reactor incorporates a large industrial fan to induce a draft inside of the reactor. An image of the conceptual pilot reactor is provided below in Figure 2. The vertical circulation design allows for a compact system with a large reaction chamber. The belt driven fan will draw air upwards through the center compartment of the reactor. This air is then pushed back down the compartments on the sides of the reactor, flutes, creating a constant flow throughout the reactor. A number of
vanes may be installed to help keep equal amounts of air moving towards all membranes. Previous bioreactors similar to the Pilot Reactor such as the CRF-II require an air/gas velocity of 1 m/s. The fan and motor for the pilot reactor will be designed to achieve a minimum fluid velocity of 1 m/s with the potential for higher and lower velocities should these be desired in future experiments.

![Image](image.png)

**Figure 1.** Conceptual Photobioreactor.

In order to introduce CO₂ into the reaction chamber, natural gas will be combusted inside both of the side flutes. Two burners, mounted through the side walls of the flutes will burn natural gas creating CO₂ and heat. The design criterion for the burners is that they can maintain a temperature of 140° F inside the reactor. By burning natural gas to heat the reactor the CO₂ level inside the reactor will stabilize at a constant level, at which point the flame on the burner may become unstable. The CRF-II targets a CO₂ level of approximately 10%. This value has been observed to minimize the disruptive impact of flame instability and will be targeted during testing of the burner system in the pilot bioreactor.
A system for delivering the nutrient solution to the headers is a key component of the pilot bioreactor. The system serves to move the nutrient solution from the growth tank into the headers and will require a few specific characteristics. First, the growth lines will need to enter the reactor (pass through the exterior walls) in such a manner as to not disrupt the airflow. This may be problematic due to the number of headers inside the system, which will require a large flow rate. These lines cannot pass through the top of the reactor due to the location of the fan.

The second characteristic is the flow rate of the growth solution. The CRF-II maintained a solution flow rate of 0.8 gallons per minute per linear foot of membrane. This value will serve as a target for specifying adequate pumps. However the membranes inside the CRF-II were much shorter than the membranes which will be installed inside the pilot reactor. A system capable of delivering quantities of growth solution higher than 0.8 gpm may need to be specified. Flow characteristics will be observed on full scale membranes outside of the bioreactor prior to final assembly to determine the appropriate required flow rate.

The final subsystem of the pilot reactor requiring a complete design is the lighting system. Current literature suggests that the algae strain *Chlorogeopsis* has optimum growth at light levels of 200 μmol m\(^{-2}\) s\(^{-1}\) (Ono and Cuello, 2007). This light intensity will be the maximum target for light inside the reactor. While it may be possible to achieve this light level at given points in the reactor, the lighting system will be designed to operate continuously at lower light intensities (~ 40-80 μmol m\(^{-2}\) s\(^{-1}\)) over the majority of the area of the membranes. The light panels will be mounted inside the reactor and
fiber optic cables will need to be fed into the reactor to each light panel, similar to the growth lines.

Because the main feature of the pilot reactor is the use of natural light, the fiber optic cables will need to be routed from the exterior of the bioreactor, outside of the building, and ultimately onto the roof where the solar collector will be located. The exact location of the pilot reactor will dictate how to route the cables outside. Consideration will have to be made to keep the overall length of the cables as short as possible in order to minimize the loss of usable light during transmission.

Interest at the OCRC in using light panels for various applications led to the delegation of this subsystem’s design. The complexity of designing a light panel capable of dispersing light evenly coupled with the integration of a solar collection system is substantial. In the absence of a solar lighting system, light levels will be artificially simulated inside of the reactor. This will allow for the testing of algae growth inside of the reactor should the solar lighting system still be in the design or construction phase prior to completing the shakedown test.

The header and membrane system from the CRF-II will be used in the pilot reactor with some modifications. The CRF-II headers used high flow “harvest” lines to flush the algae off of the membranes. The pilot reactor headers will have only small lines inputting the growth solution. A second modification to the system will be to strengthen the membrane supports. The increased height of the membranes along with the tension of the membranes could cause bowing of the frames. A more robust frame will need to be designed to prevent this effect. The membranes will be made of Omnisil fabric, the same material from the CRF-II.
3.3 Subsystem Integration

The integration of all subsystems within the pilot bioreactor is critical for the production of algae. An understanding of how each subsystem interacts with one another was necessary before completing the conceptual design. With solar lighting being the key feature of the pilot bioreactor, it was important to select subsystems which complemented its features.

The solar collector functions to gather light and transmit it down fiber optic cables. In order to disperse light into the reactor evenly these cables attach to light panels inside the reactor, as described above. Using a light source such as this leads to the implementation of fixed film algae growth on the membranes. By using these systems in tandem the maximum amount of photons can be delivered to a large amount algae at all times.

The gas delivery system had to fit the conceptual design as well. In order to draw the flue gas continuously across the membranes the fan driven circulation design was chosen. The fan promotes circulation throughout the system without depriving any algae attached to the membranes of CO₂. A vertically oriented system allowed for an increase in the ratio of surface feet of membranes to volume of the facility in comparison to the CRF-II. The integration of these subsystems led to the final conceptual design presented in Figure 2.
4. Test Plan

4.1 Individual Subsystem Testing

Each component and subsystem for the pilot reactor needs to be tested under a variety of conditions. While design work was completed for many of the subsystems previously described the test plan for this thesis will only address the frame and air circulation subsystems.

In order to test and validate the containment, or frame design, a smaller bench-top model of the Pilot Bioreactor’s seal surfaces was constructed. The model was designed to incorporate key components of the seal surface which identified possible leak points. The assumption was made that if the seal surface can maintain gas pressure then the seal surface will contain fluids as well. Therefore the model was pressurized with air and this pressure was monitored with a pressure gage.

Once the seal maintained a minimum pressure then the pressure was monitored for an extended period of time, approximately one hour. To determine if the seal surface leaked air at an accelerated rate, the model was “snooped” for leaks. Snoop is a term that refers to a mixture of soap and water. This mixture was placed on surfaces which were designed to hold pressurized air. The presence of bubbles indicates a leak. Countermeasures were taken to address any leak points discovered during the snooping process.

In order to calculate any leak rate in the Pilot’s seal surface, it was necessary to develop an understanding of the pressure which would build up inside the chamber due to the combustion of natural gas from the burner. Thermodynamic calculations were conducted in order to quantify the amount of pressure which would accumulate inside the
reactor. Also, any leak rate from the bench-top model was correlated to the full size Pilot Reactor. These two values were compared in order to validate the frame design of the Pilot Bioreactor.

The test plan for the gas circulation subsystem began by installing the fan, motor, electrical controller, and all necessary structural components and then testing their operation. Being a very dynamic system in comparison to the containment system, there were a number of safety considerations which were identified and addressed before any testing of the system was conducted.

Once safe operation of the circulation system was achieved airflow testing was conducted. The instrument used for taking air velocity readings was an AirData Multimeter, Model ADM-850L. The AirData Multimeter is an electronic micromanometer capable of taking readings for a variety of data related to air. A pitot tube was attached to the AirData and inserted into the reaction chamber of the Pilot Reactor. Air velocity measurements were taken at numerous locations throughout the reaction chamber in order to establish the airflow profile for the Pilot.

The air velocity measurements were compared to the target value of 1 m/s. It is anticipated that this target may be modified due to inconsistencies in the velocity profile. The potential for an inconsistent velocity profile comes from the changes in cross sectional area that air moving through the reactor will experience. After initial testing, the criterion was modified to only achieve the target value at 75% of the data points.

In order to address a velocity profile with a wide range of air velocities flow modifiers were implemented. These modifiers consisted of vanes and screens placed to direct air to different portions of the reactor, or as devices to block too much air from
entering other parts of the reaction chamber. A subset of the total number of data points were taken in order to allow sufficient time for experimenting with different geometries, configurations, and types of airflow modifiers. The symmetry of the Pilot Bioreactor allows for this reduced data set to describe the entire system based on the assumption that air velocities should be symmetrical throughout the reactor.
5. Experimental Methods

5.1. Containment Subsystem

The method for evaluating the containment subsystem design consisted of a number of steps. The design process began by identifying the criteria the subsystem needed to meet. Next, the initial design could be laid out including dimensions and materials. The next step was to perform analyses of any critical areas or features which may compromise the functionality of the frame. The last step was to build a bench top model of the frame which contained the critical elements. This model was used in tests to evaluate the integrity of the containment system.

5.1.1. Design Criteria

The ultimate design criterion of the Pilot bioreactor containment subsystem was that the reactor be both gas and liquid tight. During operation, concentrations of gases will be accumulating inside the reactor. In order to operate the system efficiently and safely these gases need to be contained within the reactor. Similarly it is crucial that the system contain liquids. Electrical systems will be operating adjacent to the reactor and loss of water could become a hazard.

In addition to gas and liquid containment, the Pilot Reactor also had to resist corrosion. Previous bioreactors researched and operated in the OCRC have experienced issues with corrosion. Therefore materials with corrosion resistant properties needed to be specified for the containment system. A number of cost effective alternatives do exist, such as powder coating and epoxy painting the materials, however stainless steel was
mandated for the Pilot bioreactor because of the OCRC’s previous experiences with these alternative methods.

Type 304 stainless was the material of choice for the external frame, and is the most common grade of stainless steel. The material can be easily welded in comparison to other types of stainless steel. Type 304 stainless also exhibits excellent corrosion resistance due to a minimum chromium content of 18% (Lenntech). The metal is also readily available through distributors who are within proximity of the OCRC.

A key requirement of the Pilot bioreactor was that the entire system had to be transportable. The final location of the reactor was not known when the project first began. This led to a “knockdown” style frame design. A knockdown style frame is one in which sections are not permanently fastened together. Because the characteristics and layout of the final location were not known, each section or piece of the frame had to be able to fit through a doorway. This requirement led to a frame design consisting of four sections which could be transported and then bolted together to form the exterior frame. The skeletal structure of the frame is shown in Figure 2, after assembly.

Figure 2. Skeleton Framework after Assembly
5.1.2 Initial Design

The primary structural shape of the reactor frame metal is 2 inch by 2 inch angle. Angle was chosen because it provides long flat surfaces for sealing sections of the reactor together. One-quarter inch thick members were used for horizontal pieces of the front and back sections, as well as the four corner posts where the sections attach. The remaining members were each 1/8 inch thick.

The last step of the initial design was to determine the overall dimensions. The pilot bioreactor needed to accommodate 14 membrane frames positioned in two rows of seven. The width of each membrane as well as any necessary support members was taken into account to determine the depth of the reactor. The spacing of the membrane frame from each light panel was derived from examining previous work conducted on the CRF-II. This spacing determined the width of the reaction chamber. Additional width for the side compartments was determined from measurements of standard doorways in the OCRC. The height of the Pilot Reactor was determined from estimated ceiling heights at some proposed future locations. Figure 3, gives the overall dimensions of the Pilot Reactor. This figure includes the completed frame sections and the fan subsystem, which were taken into account when determining dimensions.
5.1.3 Critical Element – Seal Surface

Upon completing the initial frame design, the seal surfaces of the frame sections were identified to be the critical areas of the containment subsystem. The length of the seal surfaces (56 linear feet – 2 surfaces at each corner) provides many leak points for gas and liquid to escape. Due to the knockdown style frame, these surfaces could not be welded to make a tight seal. In order to assemble the four sections, bolts were fastened along each of the eight seal surfaces.

Proper bolt spacing ensured a positive compressive force between the two pieces of angle being bolted together at each corner. Although some gasket products claim to maintain their ability to seal an exposed area under pressure, these products were specified only for the purpose of filling in any imperfections in the materials. In order to
understand the stress distribution throughout the fastened materials and to properly space
the bolts Finite Element Analysis (FEA) was implemented.

5.1.4. Seal Surface Configuration

Before performing an analysis, the complete description of the seal surface
needed to be determined. Each seal surface consisted of a 1/8 inch thick piece of 2 by 2
inch angle iron mating with a 1/4 inch thick piece, as shown in Figure 4. A rubber gasket
maker was applied between each mating surface. The modulus of elasticity of the gasket
maker was deemed negligible for the purpose of modeling the seal surface. Each piece
had a series of 1/4 inch holes drilled down the length of the seal surface, centered
longitudinally down the piece. The pieces were connected using 1/4-20 stainless steel
nuts and bolts with a 0.029 inch thick, 1/2 inch OD washer on both sides.

![Figure 4. Portion of Seal Surface Members](image)
Determining the torque applied to the bolts required consideration of a few factors. First, a very large torque was not desired. Transportation and reassembly of the Pilot Reactor may not be in a location with access to pneumatic tools. Also, large torques may not be obtainable by hand for some fabricators and could potentially shear the hex cap from the bolt. A brief experiment was conducted to determine a torque which was obtainable repeatedly without straining a fabricator. This torque was determined to be 10 ft-lbs. The corresponding compressive force between the two pieces of angle is determined by Equation 1 (Mischke and Shigley, 2001) as:

$$ T = K F_i d $$

(1)

where $T$ is the applied torque in foot-pounds, $F_i$ is the compressive force of the bolts in pounds, $d$ is the diameter of the bolt in feet, and $K$ is the frictional coefficient between the bolt and the material surface (estimated to be 0.2). Solving Equation 1 for the system as described above yields a compressive force of 2400 pounds for the torque and bolt diameter of the seal surface.

The seal surface was analyzed for a number of bolt configurations with changes to bolt spacing as well as washer size and hardness. Solution of Equation 2 (Engineer's Edge) below for the current system gives estimated bolt spacing for a gasket lined seal surface of four inches. This estimate was used as a guideline for determining the bolt spacing to analyze using FEA. The bolt spacings analyzed were four and eight inches. These spacings were chosen based on Equation 2 and the overall length of the members. In addition to changes in the bolt spacing, FEA models using large washers made of high-strength steel were also analyzed in an attempt to reduce the number of bolt holes by increasing the rigidity of the members.
36

\[ C = \left[ \frac{480 \left( \frac{a}{b} \right) E t^3 \Delta H}{13 P_{\text{min}} + 2 P_{\text{max}}} \right]^{\frac{1}{4}} \]  

(2)

Where:

- \( a \) = width of top (inches)
- \( b \) = width of gasket (inches)
- \( C \) = bolt spacing (inches)
- \( E \) = modulus of elasticity of top (psi)
- \( \Delta H = H_1 - H_2 \)
- \( H_1 \) = minimum gasket deflection (inches)
- \( H_2 \) = maximum gasket deflection (inches)
- \( P_{\text{min}} \) = minimum gasket pressure (psi)
- \( P_{\text{max}} \) = maximum gasket pressure (psi)
- \( t \) = thickness of top (inches)

5.1.5 Sheet Metal Seal Surface

The initial seal surface design work was only focused on the corner surfaces. This is because the sheet metal fan box and growth tank had not been specified. The design plan gave priority to designing and constructing the skeletal frame before proceeding with additional components. Therefore, the seal integrity also needed to be examined at these surfaces.

A CAD assembly of the surface was completed. This assembly consisted of four inch bolt spacing, the same fasteners as the corner seal, as well as the gasket material. In addition to the tensile load from the bolt torque, a force was added to the top of the sheet metal flange to simulate the forces from the weight of the fan box. The force was directed at an angle from the principal axis to simulate sag. Figure 5 shows the loading and constraining of the sheet metal seal surface.
**Figure 5.** Loads and Constraints on the Sheet Metal Seal Surface

### 5.1.6 Evaluation of Seal Design

In order to evaluate the design of the seal surface, a bench-top model of the Pilot Reactor’s containment system was constructed as shown in Figure 6. The model incorporated the eight corner seal surfaces of the full scale reactor. Also included in the model were the stainless steel panels which make up the majority of the walls of the containment subsystem. The panels were TIG (Tungsten Inert Gas) welded to the angle iron in the same manner as the Pilot Reactor.
In addition to the seal surfaces at the corners, the model also simulated the seal surfaces of the fan box on top of the reactor, as well as the growth tank beneath the reactor. These members are sealed to the model using the same method as the corner connections (i.e. same bolt spacing and gasket material). A pressure gage and air input valve were also installed on the model. The Magnehelic® differential pressure gage has a range of 0 – 20 in. H₂O, with an accuracy of ±0.4 in. H₂O.

The seal surface test began by attaching a compressed airline with a pressure control valve (set to the off position) to the air input valve on the model. Air was charged into the model until a pressure of 15 inches of water was read on the pressure gage and then the pressure control valve was shut. If the system maintained pressure, the test would be carried out by measuring pressure loss versus time. If the system lost pressure quickly then a snoop test would be conducted.

In the case that the model maintains pressure the time elapsed test was conducted as follows. The model was pressured to 15 inches of water and pressure readings were
taken every five minutes for one hour. This process was repeated five times and the average leak rate for the model was established.

In the case that the model loses pressure quickly, a snoop test was conducted. Using the pressure control valve, air was continuously charged into the model until a steady state pressure was achieved. Then snoop was applied to each seal surface of the model to expose leak points. Countermeasures were taken to achieve a quality of seal such that the time elapsed test could be conducted.

5.1.7 Pressure Increase inside Reactor

A preliminary thermodynamic analysis of the Pilot Reactor was performed in order to calculate the pressure increase inside the reactor due to burning natural gas. The Pilot Reactor requires about 21,500 BTU’s per hour in order to maintain an internal temperature of 140°F. This calculation took into account heat loss through the sheet metal and acrylic which make up the containment subsystem. In order to keep the required BTU’s applied at a minimal value, one inch insulation on the sheet metal surfaces was included. Based on the heating value of natural gas (1000 BTU/ft³) the Pilot would need 21.5 ft³ per hour. This is equivalent to 0.00751 Moles of natural gas per second.

In order to simplify the calculations the following assumptions were made:

- Natural Gas would be calculated as 100% methane
- Complete combustion of the methane
- No excess air used for combustion
- The products would act as ideal gases
These assumptions give the full combustion equation shown in Equation 3.

\[
CH_4 + 9.52(0.79N_2 + 0.21O_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{3}
\]

Equation 3 shows the relationship between the reactants and the products of combustion. This relationship shows that each mole of CH₄ combusted requires 9.52 moles of air and produces 1 mole CO₂, 2 moles of H₂O, and 7.52 moles of N₂.

The calculations were performed to find the worst case scenario or greatest pressure increase in the reactor. This occurs at the highest temperature of 140°F (333K). The pressure increase of the Pilot can be calculated by taking into account the temperature and volume of the reactor (8.36 m³), with the combustion relationship. An example of the pressure calculations is presented in Figure 7, where the resulting pressure increase has units of Pascals (Pa).

\[
P = \frac{nRT}{V} = \left[n \left(\frac{8.314}{\text{mol K}} \right) (333 \text{ K}) \right] = n \left(331.09 \frac{N}{m^2}\right)
\]

Where \(n\) is the number of moles and \(R\) is the universal gas constant.

**Figure 7. Pressure Increase Example Calculation**

The combined pressure increase from the three product gases totals 26.17 Pa/sec, equal to 0.004 in. H₂O/sec. Figure 8 shows this pressure increase versus time.
The plot is linear due to the constant temperature of 140°F, the highest temperature or worst case scenario for pressure increase.

The estimated pressure increase of the Pilot Reactor is only valid if the facility incorporates a natural gas compressor. Natural gas supplied to OCRC’s labs is only at a pressure of approximately 11 in. H₂O. As the pressure inside the reactor approaches this level the fuel flow rate will decrease. If the pressure exceeds 11 in. H₂O a backflow will occur across the burner, causing the flame to go out and the burner’s premix safety valve to shut close.

After testing the bench-top model of the Pilot Reactor’s seal surface, a comparison was drawn between the potential pressure build up in the reactor and any leak rate in the seal surface. Should the containment subsystem show no leakage then a pressure release system will be incorporated into the system.
5.2 Gas Circulation Subsystem

Designing and installing the gas circulation subsystem required consideration of a number of issues. The design of the system incorporated a large industrial fan blade, an electric motor, a structure for supporting the motor and fan during operation, a motor controller, and a method for taking air velocity readings inside of the bioreactor. Once each of these components of the subsystem were designed and specified the entire subsystem could be constructed and installed into the pilot frame. Figure 9 below shows a schematic of the fan assembly.

Figure 9. Gas Circulation Fan Assembly

5.2.1 Gas Circulation Fan Blade

Selection of a fan blade for the subsystem was based on airflow capacity, corrosion resistance, size, and cost. The required capacity of the fan blade was based on
the target value of 1 m/s, the cross sectional area of the reaction chamber inside the Pilot Reactor, as well as allowance for any future desire to increase or decrease airflow. Equation 4 shows the required capacity for the gas circulation subsystem fan.

\[
\text{CFM} = V \cdot A = \left(3.28 \frac{ft}{s}\right) \left(60 \frac{s}{min}\right) \left(23.25 ft^2\right) = 4576.6 \frac{ft^3}{min}
\]

(4)

Where V is velocity in feet per second and A is the cross sectional area of the Pilot’s reaction chamber in square feet.

To address corrosion of the fan blade, type 304 stainless steel was chosen as the material due to its availability with preferred distributors. Taking size and price into consideration led to the decision of a 48” four blade unit with a maximum airflow capacity of ~25,000 CFM at 525 rpm. The maximum capacity for this particular blade resulted in the ability to deliver the required airflow at low fan speeds and an opportunity to increase airflow if desired in the future.

The fan blade selected had additional impacts on the airflow inside the react due to its size and capacity. During operation the fan blade was running at a speed of ~250 rpm. This relatively low speed caused a pulsing effect on the air velocity because the blades pulled larger quantities of air with each turn, resulting in turbulent flow.

5.2.2 Gas Circulation Motor

The next component in the design of the gas circulation system was the electric motor which is used to drive the fan. Due to the corrosive environment inside the reaction chamber, it was decided that the motor needed to be externally mounted. This requirement led to a belt driven design for transferring power to the fan blade.
A 1 horsepower, 3-phase AC motor was selected for the system. Single phase power was investigated, however concerns arose with using voltage regulation to control the speed. The concern was that reducing voltage with a regulator would increase current to a dangerous or destructive level. With a 3-phase motor, the motor speed can be controlled by frequency using a frequency regulator. The motor for the Pilot Reactor (see Figure 10) has a maximum speed of 1725 rpm and a full load current of four amps.

![Gas Circulation Motor](image)

**Figure 10.** Gas Circulation Motor

### 5.2.3 Motor Controller

In order to control the speed of the motor a GS1 AC Drive was wired into the electrical circuit for the fan motor. The GS1 AC Drive is an electrical motor controller which provides unit automation on a number of different levels and is shown in Figure 11. The AC Drive provides controls to motor speed, current and frequency.
Using the GS1 AC Drive allows the operator the input the parameters for a given motor and the module will not allow the motor to exceed those values. This level of control is crucial for the Pilot system because it allows the operator to set the motor speed without concern of overloading the motor and causing thermal damage. It also eliminates the need for a motor with a built-in thermal protection unit.

5.2.4 Fan Assembly

Assembling the fan and motor required the following additional components: a 1” diameter, 36” long stainless steel rod (fan Shaft); a 3.75 inch outside diameter (OD) pulley; a 7.75 inch OD pulley; three quick disconnect pulley bushings; two 1 inch self-aligning pillow block bearings; two 1 inch shaft collars; a 60 inch rubber V-belt; two ¼” thick steel plates; and the 1” box tubing fan structure. With the exception of the V-belt each of these components are visible in Figure 9.

The fan structure was welded to fit above the fan box of the reactor and bolt into the front and back of the frame as shown in Figure 12. The two ¼” plates were cut and

Figure 11. GS1 AC Drive for Fan Motor Speed Control.
welded into “L” shapes and bolt holes were drilled on one piece for the motor and on the other for the pillow block bearings.

![Image](image.png)

**Figure 12.** Fan Assembly Installed on Pilot Reactor

To secure this assembly to the Pilot Reactor frame the plates were bolted onto the fan structure and the entire structure was bolted to the top of the reactor. The 3.75” pulley was connected to the motor using a quick disconnect bushing. Similarly, the fan blade was connected to the bottom of the 1” fan shaft. The quick disconnect bushings eliminate the need for a key and keyway in low power situations by using a tapered geometry and bolts to compress the bushing around a shaft.

Next the motor was bolted to the motor plate on top of the fan structure. The motor plate was fabricated with milled slots through which the bolts to the fan structure are secured as shown in Figure 13. This allows for tightening of the fan belts should any slack develop due to use. The pillow block bearings were then bolted to the bearing plate as well.
To final steps of the installation required lifting the fan blade and shaft so that the shaft was inserted through the pillow block bearings. Once the fan was at the correct height, clamp collars were tightened around the shaft above each bearing. The 7.75” pulley was then attached to the shaft with a quick disconnect bushing and a level was used to ensure the proper height of the pulley. The V-belt was then attached and tightened via the milled slots.

5.2.5 Fan Shroud

The last component required for the gas circulation subsystem is the fan shroud. Figures 14 and 15 below show the installed fan from inside the reactor, and the installed fan with the fan shroud. The fan shroud was welded out of 20 gage type 304 stainless sheet metal and serves to direct gas flow through the fan and down through the side compartments. The shroud was welded to within ¼” of the fan blade tips.
5.3 Full Scale Reactor Mock-up

In order to draw an accurate comparison between the readings taken during the gas circulation subsystem test and the air velocities inside the reactor during actual operation it was necessary to create mock-ups of all components which would be inside the reactor during full scale operation. These components included the headers and membranes, light panels, and the water level inside the bioreactor. Although not all of these components have completed designs, it was still necessary to simulate the estimated size, shape and rigidity of the materials for the headers, membranes and light panels.

5.3.1 Header and Membrane Frame Mock-ups

Although the header design from the CRF-II was used in the Pilot Reactor, it was unfeasible to fabricate 14 stainless steel headers for use in the gas circulation system testing as each header requires approximately 40 man-hours of fabrication. Therefore, 2 inch OD PVC tubing was used to simulate the headers.
The membrane frames were constructed from ½ inch type 304 stainless steel box tubing. Since fabricating 14 membrane frames required minimal man-hours and the same frames used to mock-up the Pilot Reactor could be used for the full scale operation of the bioreactor, actual frames were used. The PVC mock headers were attached to the membrane frames with plumbing wall caps. A low-cost, semi-rigid fabric was sewn into two foot by four foot rectangles and stretched across the frame with cable ties. Figure 16 below shows a finished header and membrane mock-up.

![Figure 16. Header and Membrane Frame Mock-up](image)

**5.3.2 Light Panel Mock-ups**

The primary objective when mocking up the light panels was to simulate the size and shape of light panels used in previous bioreactors. Three-quarter inch thick
Blueboard insulation was chosen as the material for the mock light panels. The Blueboard insulation is lightweight, maintains a rigid shape in an air stream and can be easily hung in place inside the Pilot Reactor. The dimensions of the mock light panels (24” x 28”) were taken from light panels used in a previously operated pilot sized bioreactor.

5.3.3 Installation of Mock-up Components

Once the fabrication of the mock-up components was complete they were installed inside the Pilot Reactor. In order for the air velocity test to simulate full scale operation of the reactor the mock-up components had to be properly positioned inside the reaction chamber.

During fabrication of the Pilot Reactor frame, header mounts were welded together and then bolted to the upper horizontal members of the front and back sections of the frame. The membrane frames have hooks as seen in Figure 17 that are welded to either end and fit into the header mounts to support the weight of the frame and fully loaded header and membrane. Because the frames for the mock-up membranes are the frames which will be used in full scale operation, the headers and frames are installed in this same manner.
The Blueboard mock-ups of the light panels were supported using metal wire. Small holes were punctured in the Blueboard and wire was threaded through the holes and attached to the header mounts on either side. Finally a small metal rod spanned the bottom of the panels and membrane frames in each row. Cable ties connected all components to this rod, linking them together and thus eliminating any swaying of the components.

In total there were two rows of mock membranes and light panels. Each row contained seven membrane frames spaced apart 8 inches on center. The mock light panels were spaced evenly between the membrane frames resulting in six light panels per row. Figure 18 shows the setup of each row in the reactor.
5.4 Method for Taking Air Velocity Readings

In order to obtain meaningful data for the gas circulation system three things had to be established; the instrumentation for taking the readings, a test plan for taking repeatable readings at evenly distributed points throughout the reactor, and a procedure for operating the fan.

5.4.1. Instrumentation for Air Velocity Readings

The instrument chosen for taking the air velocity readings was an AirData Multimeter, Model ADM-850L, as seen in Figure 19. The AirData Multimeter takes air velocity readings with a pitot tubes as shown in Figure 20. By measuring the difference
between total and static pressure, the multimeter can compute gas velocities (in m/s) by Equation 5, below (FlowKinetics).

\[ V_{\text{gas}} = \sqrt{\frac{2 \, P_{\text{dyn}}}{\rho}} \, C \]  

(5)

Where \( P_{\text{dyn}} \) is the difference between total and static pressures in Pascals, \( \rho \) is the gas density kg/m\(^3\), and \( C \) is an experimentally determined correction coefficient specific to the pitot tube.

When used for measuring small air velocities (<1.5 m/s) the AirData multimeter takes 16 pressure readings and displays the average computed air velocity to within \( \pm 3\% \) of the actual value. The meter is also initially calibrated for local barometric pressure; however this calibration could not be verified for accuracy at the location of the bioreactor.

5.4.2 Test Plan for Taking Air Velocity Readings

In order to collect the air velocity data necessary for establishing an airflow profile, the location of data points needed to be specified. Each membrane is 24 inches
across and it was decided to take readings at 6 inches in from each end of the membrane. The AirData Multimeter would be inserted into the reactor’s main chamber, at a point centered in the space between each membrane and light panel. This resulted in 14 separate horizontal positions required in order to characterize the velocity profile throughout the unit.

Taking measurements while keeping the unit sealed required installing a temporary particle board door with holes drilled at the pre-determined locations to insert the pitot tube as shown in Figure 21. All of the remaining doors were fabricated from clear acrylic. When the pitot tube was inserted through the temporary wood door on one side, an assistant would observe its position by looking through the acrylic door on the opposite side. The assistant would verify that the pitot tube was centered and leveled in the correct space. Indicator marks were placed on the pitot tube so the operator would know the tube’s depth inside the reactor, allowing the operator to take the reading at 6 inches from either end of the membrane.

Figure 21. Particle Board Door for Air Velocity Readings.
Three air velocity readings were taken at each location and an average was computed. This process was repeated at three different heights of the membrane; 6 inches below the top, the midpoint, and 6 inches above the bottom. It was hypothesized that taking readings at three heights would identify any effects of the fan and fan shroud on airflow. Once all of these readings were taken on one side (14 horizontal spaces, 2 depths, and 3 heights) the doors were switched and the process was repeated for the opposite side of the reactor. Figures 22 and 23 illustrate the locations of the readings.

![Figure 22](image1.png) ![Figure 23](image2.png)

**Figure 22.** Horizontal View of Channels for Data Points  
**Figure 23.** Location of Data Points in Terms of Height and Depth

### 5.4.3 Procedure for Operating Fan

Once the gas circulation subsystem was installed, the procedure for operating the fan required turning on the GS1 AC Drive and adjusting the current. Ideally the fan would be operated by adjusting the speed of the motor. However, bench-top tests of the
system demonstrated that the AC Drive will give a motor overload error at currents below the nameplate maximum of 4 Amps. The AC Drive allows for current control in increments of 0.1 Amps. Controlling the fan by motor speed was tedious and often led to overloading the motor because current was not being monitored at simultaneously.

Bench-top testing led to determining a maximum safe operating current of 3.0 Amps.

To operate the fan, all loose materials were removed from the reactor, the doors were secured and the AC Drive was powered on. The operator adjusted the current to 3.0 Amps and the system was operated for 3 minutes prior to taking any readings. In addition to providing sufficient time for airflows to reach steady state, it also allowed the operator to monitor the motor current and make sure it did not exceed 3.0 Amps.
6. Results and Discussion

6.1 Containment Subsystem

6.1.1 FEA of Corner Seal Surface

The results of the FEA simulations verified the estimated bolt spacing of four inches. Figure 24 shows the results window from ALGOR for a bolt spacing of four inches. In order to demonstrate stress distribution with respect to bolt spacing, the loads and constraints on the model were altered. Initially the tensile force of the bolts was applied to the model. However, because the seal surface is two pieces of flat metal with a very small layer of gasket material there is no room for the nodes of the model mesh to displace. In this case FEA showed high stress concentrations around the circumference of the bolt holes and nearly no stress distribution between the bolts.

Figure 24. ALGOR Results Window of Stress Distribution for Four Inch Bolt Spacing
In order to determine whether or not stress was being distributed throughout the seal surface, the surfaces of the bolts which contact the angle iron were fixed. Instead of applying force to the bolts, an equal and opposite force was applied to the angle iron, creating a pulling effect. This showed a much clearer stress distribution throughout the seal surface.

Figure 25 shows a closer view of the principal stresses on the seal surface. The compressive force was evaluated for three nodes at each of the three midpoints on the seal surface analysis assembly. The average of these nine readings was a compressive force of 79.7 pounds.

Figure 25. Close-up View of Compressive Forces on Corner Seal
The compressive force at the midpoint of the bolt holes for the four inch spacing was greatly improved from the eight inch case. The eight inch bolt spacing model showed an average negative compressive force of less than 0.5 pounds at the midpoint nodes of the bolt holes. This negative force could be due to a bowing effect of the members caused by the space between the forces applied by the bolts. A negative force at the midpoints between the bolts will not compress the gasket at these points. A compressive force is critical in order for the gasket maker to maintain a seal.

Simulations were also performed for bolt spacings other than four and eight inches. However, it was decided to maintain even bolt spacing in order to provide less opportunity for error during fabrication in the shop. The results of the simulations with the high strength fender washers showed minimal improvement in the compressive force of the corner seal test.

In order to validate the FEA model the stress at nodes around the bolt holes was taken from the model and compared to calculations for the anticipated stress at these locations based on the force from the bolts. These calculations verified the accuracy of the FEA model. The FEA model also showed that estimates made in Equation 2 for the displacement the gasket would experience were good. The validation of these estimates shows that Equation 2 can be used to make accurate calculations for proper bolt spacing in this situation.
6.1.2  *FEA of Sheet Metal Surface*

The results of the FEA on the seal surface with the sheet metal verified that a four inch bolt spacing maintains a compressive force for all metal-on-metal seal surfaces. Figure 26 is the results display from the simulation. Figure 27 is a close up view of the compressive forces. The compressive force outputs at all midpoint nodes were determined in the same manner as the corner seal surface, and the average force was 108.4 pounds.

**Figure 26. ALGOR Results of Sheet Metal Seal**
6.1.3 Pressure Test of Bench-top Model

The initial pressure test of the containment system model showed immediate leakage as the pressure of 15 inches of water was lost within seconds. A snoop test was conducted and the major cause of the leaking was determined to be the bolt holes for the sheet metal on the top and bottom of the model unit. After removing the top and bottom of the model, it could be seen that the gasket material was not sealing the openings around the bolts sufficiently. The original design assumed the gasket material would flow into the bolt holes and around the bolts due to the sandwich effect caused by the surfaces.
mating. However, the less rigid 20 gage sheet metal did not force the gasket to flow evenly between the two pieces of metal. The gasket material also failed to reach the edges of the sheet metal flanges at the point where the flange meets the corner posts.

The gasket material was reapplied liberally to the sheet metal seal surfaces. Close attention was paid to making sure a sufficient quantity of the gasket material was applied near the edges of the sheet metal. Gasket material was also applied to the bolts and both the top and bottom pieces were resealed to the model. A second pressure test of the model still revealed leaks. Though the pressure loss was not as severe as the first test, the model lost all pressure within one minute. A second snoop test revealed leaks along nearly all of the TIG welds which connected the sheet metal walls to the angle iron frame pieces.

The issue of pressure leaks along the welds of the bench-top model could be anticipated with the Pilot Reactor’s containment system. The side walls of the model were fabricated by an inexperienced welder. Due to the large amount of welds required on the Pilot Reactor (126 linear feet of TIG welds), the welding was completed by a number different lab assistants, all with little to no TIG welding experience. Observation of the Pilot Reactor fabrication uncovered the difficulties of welding 20 gauge sheet metal to 1/8 and 1/4 inch angle iron when all materials are stainless. When excess current was applied the weld would essentially burn through the sheet metal. Filler rod was required for much of the process which can lead to issues with inexperienced TIG welders. The leaking or porosity of TIG welds can result from improper shielding gas flow and excessive heat (current) (Fabricating and Metalworking, 2008). Proper control of both requires much experience and practice with TIG welding.
In order to address the leak issue the lid was again removed and a silicone sealant was applied along all of the TIG welds. The lid was reassembled and a third leak test was performed. The model held a pressure above 10 inches of water for approximately 10 minutes. A third snoop test showed leaks were still present along many of the welds.

It should be noted that once the lid was removed from the model after the first snoop test, snoop was present inside the reactor. This fluid was removed and the inside of the model was dried. After the second snoop test the lid was removed and the model was checked for moisture. No moisture was found, yet during the snoop test bubbles were again present, indicating that the seal surface was watertight, but not gastight.

The elapsed time pressure test showed the performance of the containment subsystem design after all modifications described previously were implemented. The averages of the results of the five tests are displayed in Table 1.

**Table 1.** Model Pressure versus. Time

<table>
<thead>
<tr>
<th>Elapsed Time (min)</th>
<th>Model Pressure (in. H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.00</td>
</tr>
<tr>
<td>5</td>
<td>12.50</td>
</tr>
<tr>
<td>10</td>
<td>9.90</td>
</tr>
<tr>
<td>15</td>
<td>7.55</td>
</tr>
<tr>
<td>20</td>
<td>6.15</td>
</tr>
<tr>
<td>25</td>
<td>4.50</td>
</tr>
<tr>
<td>30</td>
<td>3.55</td>
</tr>
<tr>
<td>35</td>
<td>2.75</td>
</tr>
<tr>
<td>40</td>
<td>2.05</td>
</tr>
<tr>
<td>45</td>
<td>1.45</td>
</tr>
<tr>
<td>50</td>
<td>1.05</td>
</tr>
<tr>
<td>55</td>
<td>0.85</td>
</tr>
<tr>
<td>60</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Comparing the pressure decrease due to the leaking welds to the pressure increase of the Pilot Reactor due to combustion gas required a few steps. First, the average leak rate and the maximum leak rate were determined. Next, the linear feet of TIG welds were calculated for both the model and the Pilot Reactor. This value was used to determine the anticipated mass of gas lost from the full scale Pilot Reactor during operation. Last, the difference between these values was calculated to establish whether or not the Pilot would be generating more gas than was leaking from the reactor through the welds. Further, if the loss rate was less than the generation rate, the time to reach a critical pressure was determined.

Figure 28 displays the pressure decreases for the bench-top model, which were The average and greatest pressure decreases were determined to be 0.23 and 0.50 in. H₂O/ min., respectively. These values correlate to decreases of 0.0038 and 0.0083 in. H₂O / sec. The linear feet of TIG welds on the model and Pilot Reactor are 16 and 126.33, respectively. Accounting for the length of welds gives an average and greatest leak rate for the Pilot Reactor of 0.030 and 0.066 in. H₂O / sec., respectively.
Figure 28. Pressure Decrease of Bench-top Model

Figure 29 below shows the net pressure increase of the Pilot Reactor, with respect to the average pressure loss, the worst case pressure loss, as well as an anticipated pressure loss. The anticipated pressure loss takes into account the leak rate that corresponds to different pressures.
Figure 29 shows that after an hour of burner operation the anticipated pressure of Pilot Reactor will be 145 in. H₂O, which is equal to 5 psi. Based on thermal demands it is highly unlikely though that the burner would be running continuously for a full hour. A more accurate estimate for burner operation would be in the range of ten minutes, which would build up an anticipated pressure of only 27.5 inches of water, or 0.85 psi. This pressure would not warrant the need for a pressure release valve. Further, gas loss while the burner was off would reduce the pressure significantly between cycles.

The maximum leak rates determined from the pressure test only accounted for pressures less than or equal to 15 in. H₂O. This maximum pressure was determined by the range of the Magnehelic® pressure gage used to take the readings. Since the prediction
for pressure increase due to combustion is greater than 15 in. H$_2$O within six minutes, it is possible that higher leak rates could exist at higher pressures.

It should be noted that although the pressures building up inside the pilot bioreactor are relatively low and do not pose any safety risks, a pressure release valve would provide an advantage to the system. For safety reasons the final location of the Pilot Bioreactor will require an exhaust gas evacuation system. This system will need to be capable of removing all gases from the system in case of catastrophic failure. The advantage of a pressure release valve is that during normal operation the valve would give a controlled exit for gases. Further, a valve which opens at very low pressures would allow gases to escape, thus reducing the strain on the containment subsystems seal surface. This feature would add to the overall safety of the system.

6.2 Gas Circulation Subsystem

6.2.1 Initial Results – No Flow Modifications

The initial results from testing the gas circulation subsystem showed uneven velocity profiles with large variations in velocities from the center membranes to those located near the side walls. The motor was running at 3 Amps with a speed of 572 rpm. Taking into account the pulley ratio (N) of 0.485, the speed of the fan was approximately 277 rpm. The results were displayed graphically using MATLAB in order to visualize the velocity profile. Figure 30 is a CAD image of the top of the reactor with the fan system removed. The area outlined in red corresponds to the velocity profile developed from the airflow readings. Figures 31, 32 and 33 show the velocity profiles at the heights of 6 in.
below the top of the membrane, the middle of the membrane, and 6 inches above the bottom of the membrane, respectively.

![Figure 30. CAD Image Displaying Velocity Profile Area in Red](image1.png)

**Figure 30.** CAD Image Displaying Velocity Profile Area in Red

![Figure 31. MATLAB Plot of Velocities at 6in. Below Top of Membrane](image2.png)

**Figure 31.** MATLAB Plot of Velocities at 6in. Below Top of Membrane
Figure 32. MATLAB Plot of Velocities at Midpoint of Membrane

Figure 33. MATLAB Plot of Velocities at 6in. above Bottom of Membrane
Visual inspection of the MATLAB plots indicates that the largest airflow
differences occur at the height of 6 inches above the bottom of the membranes. Data
analysis of the 28 average velocities at each horizontal elevation was performed. Table 1
below presents the number of velocities which fall within the target value of \(1 \pm 0.2\) m/s
for each height.

<table>
<thead>
<tr>
<th>Height</th>
<th># of Readings within Target</th>
<th>% of Readings within Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 in. Below Top</td>
<td>18</td>
<td>64.3</td>
</tr>
<tr>
<td>Midpoint</td>
<td>9</td>
<td>34.6*</td>
</tr>
<tr>
<td>6 in. Above Bottom</td>
<td>5</td>
<td>17.9</td>
</tr>
</tbody>
</table>

* Note: % of Readings at Midpoint is out of 26 due to Structural Interference with 2 Data Points

Table 2 clearly demonstrates that the lowest height provides the least number of
acceptable readings, however none of the levels show a significant majority of all
velocities within the target value. These initial results identified a need to implement flow
modification. Due to the amount of time required to take readings at all 3 heights it was
decided to focus on only the lowest height for evaluating the flow modifiers.

Due to the low percentage of acceptable readings it was also decided to alter the
target air velocities to \(1 \pm 0.2\) m/s at 75% of the data points, a reduction from 100% of the
data points. The modification to the air velocity target was deemed acceptable because of
the anticipated effects of the burner. The current burner location is assumed to be in the
side compartments. As the burner operates the sheet metal which forms the walls of the
compartments is going to become very hot, much hotter than the 120°F environment of the reaction chamber. It is hypothesized that this heat will harm the organisms growing on the four membranes positioned closest to the side compartments. Therefore 29% of the membranes will be in a suboptimal environment due to burner operation.

6.2.2 Flow Modifications – Vanes

After analyzing the initial data, it was obvious that air inside the system was exiting the side compartments and flowing directly into the middle channels, almost completely bypassing the channels near the outermost membranes. It was decided to force air into the outer channels while still allowing some to take its original path to establish a more even flow distribution.

This was accomplished by using vanes to direct flow. The potential need for vanes had been previously discussed during the design stage, but it was decided to incorporate them only if the need arose. The main concerns with vanes was that they needed to be installed so that they would not interfere with any access to the membranes or light panels, they did not interfere with removing the door, and they did not provide a large surface for algae to grow on. Also, any flow modifications needed to allow water to flow down the membranes and into the growth tank without obstruction.

To address these concerns vanes consisting of wood planks were installed at the bottom of the side compartments. A CAD image of how the planks were positioned is shown in Figure 34. Figure 35, presents a geometric description of the vane size and position where H represents the height of the plank and \( \theta \) represents the angle of the plank measured from the horizontal frame member.
By modifying $\theta$ and $H$, vane configurations that optimized flow distribution were obtained. In order to experiment with as many configurations as possible, it was assumed that the velocity readings were symmetric with respect to location in the Pilot Reactor. Therefore, readings were only taken for one quadrant at the lowest height. This reduced the total number of readings to 42, down from the 168 readings required for the entire level. It should be noted that although readings were only taken for one quadrant the vanes were installed in the same configuration at the bottom of both side compartments to assure effects were uniform throughout the reactor. Figure 36 shows how the plank was positioned inside the reactor.
Data collected from air flow testing with vanes was analyzed to see if the target specifications were met. As seen in Table 2, many configurations demonstrated either no improvement in air flow distribution, or a reduction in air flow distribution. In these cases testing was halted and a new setup was configured.

**Table 3.** Air Velocity Averages with Air Flow Vanes at 6 in. Above Bottom

<table>
<thead>
<tr>
<th>H (in.)</th>
<th>θ(°)</th>
<th># of Readings within Target (out of 14 averages)</th>
<th>% of Readings within Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30</td>
<td>5</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>6</td>
<td>43</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>8</td>
<td>45</td>
<td>6</td>
<td>43</td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>8</td>
<td>75</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
<td>6</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>6</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>6</td>
<td>43</td>
</tr>
<tr>
<td>6</td>
<td>75</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>6</td>
<td>90</td>
<td>7</td>
<td>50</td>
</tr>
</tbody>
</table>
Airflow testing with the vanes showed promise in certain arrangements, up to 57% of acceptable readings. In these arrangements airflow readings were taken for the entire velocity profile in order to verify the assumption of symmetry in the reaction chamber. Although all other tests showed symmetry, the airflow vane tests did not. Although the initial seven readings, representing one quadrant of the reaction chamber, showed 57% acceptable readings the remaining three quadrants showed small amounts of airflow. The test setup was inspected for flaws, however none were found. The asymmetrical velocity profile was puzzling and led to the decision to test other modifications.

6.2.3 Flow Modifications – Screens

After trying numerous configurations of flow modifying vanes, a new approach was taken. A size 15 mesh plastic screen was installed underneath a portion of the membranes and light panels as shown in Figure 37. The motivation for using screen material was to create an obstruction for the air moving into the channels between the middle membranes and light panels. In all previous tests it was nearly impossible to decrease airflow in this region without forcing nearly all of the air into the side channels.

At first, the screen was only attached underneath the middle three membranes on each row. Cable ties were used to secure the material to the metal frames. Preliminary testing showed promise for the screen material as a flow modifier. A second test was conducted with the material stretched across the middle five membranes as seen in Figure 37. The uniformity of the airflow distribution significantly improved as compared to the previous configuration.
The installation of the screen material initially raised concerns about algae collecting and proliferating on the screen. Algae collecting on areas other than the membranes could compromise results of full-scale operation. Also, algae that gather on the screen will not circulate through the system and would not be collected during harvesting. In order to address these concerns, individual screens were constructed to serve as air flow modifiers.

The criteria for the new modifiers were as follows:

- Algae must be able to drip off the membrane and into the growth tank
- Easy to install and remove
- Durability
- Easy to maintain (i.e. can be rinsed, screen can be replaced)
These criteria led to the screen flow modifier shown in the CAD image in Figure 38 below. The frame of the modifier is ¼ inch stainless steel tubing. The screen is stretched across the frame and either stitched in place or secured with small cable ties. The bends in the frame allow the modifier to set in place between the membrane frame and hang below the light panels. This design also serves to stabilize the membrane frame from possible swaying, eliminating the need for the stabilizing rod described in section

![Figure 38. CAD Image of Screen Airflow Modifier](image)

The dimensions of the screen modifier are such that a ¾ inch gap is present on either side of each membrane frame, allowing algae to drip off the membrane without gathering on the screen. Figure 39 shows the membrane frames with the screen modifiers installed. Figure 40 is a view of the installed screen modifiers rotated to show the spaces for algae to drip through.
In order to test the screen flow modifier design, mock-ups were again constructed. Wood dowel rod was used for the frames and the same 15 mesh screen material was stretched across them. The only change to the design was that the modifiers were secured to the membrane frames with cable ties, to eliminate the need for any bending. Figure 41, shows an installed mock screen flow modifier.
The mock screen flow modifiers were installed between the middle five membrane frames on both rows, requiring 8 flow modifiers in total. The preliminary test of this configuration demonstrated the best airflow distribution of any modification tested. Readings were taken in all four quadrants at a height of 6 inches above the bottom of the membrane. The results were again input to MATLAB generating the flow profile as presented in Figure 42. Analysis of the data indicated that this configuration of screen flow modifiers met the target air velocity at only four locations, or 7% of the total.

Figure 42. MATLAB Plot of Velocities at 6 in. above Bottom of Membrane with Screen Airflow Modifiers

Although the screen flow modifications led to target airflow at only four locations, they did show the best distribution of airflow. All but three locations which did
not meet the target value had average air velocities below 1 m/s. Unfortunately, because
the AC Drive gave error messages for motor overload, the speed of the fan could not be
increased. If the fan speed could have been increased and more air could have been
moved throughout the reactor the target velocity possibly could have been met. A more
powerful motor could be installed in the future to increase the velocities throughout the
reactor when screen flow modifiers are in place. Due to the lower air velocities the
experimental target was modified to 0.5 ± 0.2 m/s for the setup with the 1 hp motor.

A second modification to the air velocity target specification was deemed
acceptable. This modification was based on concerns of overheating of the membranes in
the reaction chamber which are closest to the side compartments. During operation of the
burner the sheet metal walls which make up the inside walls of the side compartments
will likely become hot. This high temperature will damage the organisms and inhibit
growth. Data points which were between the side compartment wall and the outmost
membranes were eliminated. Figure 43 is an image displaying the modified area, outlined
in red, for which data points were taken. With modifications to the target air velocity and
area of data collection, 86% or 48 out of 56 of the readings, met the target air velocity of
0.5 ± 0.2 m/s.
The distribution seen in Figure 42 is important to the operation of the full scale bioreactor. The first reason is to maintain the capacity of the Pilot Reactor for algae growth. If no airflow is present at membranes then those membranes lose the capacity to grow algae. Visual inspection of Figure 33 shows that roughly one third of the membranes would receive little to no airflow if flow modifications are not present. Also, the fast moving air in the center channels could potentially dry out portions of the membranes which have less than uniform water flow coverage.

The second reason an even distribution of airflow is important is related to the burner subsystem. As the burner operates it will produce large quantities of heat in the side compartments of the bioreactor. This could heat the sheets of metal forming the compartments to a temperature which could kill the algae present on the outside membranes. By keeping air moving in the outermost channels this effect will be minimized and a more even temperature distribution will be created. Also, even airflow
will keep the membranes in the center from receiving too much hot gas which could also harm the organisms.
7. Conclusions

7.1 Containment Subsystem

The objective of designing and constructing a containment subsystem for the Pilot Reactor was accomplished. The containment subsystem met all of the design criteria with the exception of being completely gas tight. Snoop testing showed that the cause of pressure loss was porous welds. According to the leak test results the average pressure loss of he full scale system will be 0.030 in. H₂O/sec. The greatest pressure loss of the full scale system would be 0.066 in. H₂O/sec.

The net pressure of the system will increase during operation of the burner. The estimated pressure inside the reactor will be 27.5 in. H₂O or 0.85 psi after 10 minutes, and 145 in. H₂O or 5 psi after one hour. A pressure release valve is not necessary to maintain a safe pressure inside the Pilot Reactor, however it is recommended as a precautionary measure.

The results of the containment subsystem testing can only be representative of full scale operation if the facility has a natural gas compressor. Without one the pressure inside the reactor would build to levels above that of the natural gas supply, causing the burner to turn off. Also, as the pressure of the system nears 11 in. H₂O the pressure of the unit will reduce the fuel flow rate to the burner.

The results of the leak tests validate the FEA simulations for the bolt spacing of the seal surface. These results in turn validate the estimated bolt spacing of four inches found via Equation 2. Also, the Right Stuff ® gasket maker performed well by filling imperfections in the seal surfaces.
7.2 **Gas Circulation Subsystem**

The objective of reaching the target specification of $1 \pm 0.2$ m/s was not met. The initial system setup resulted in only 18% of the data points within the target value at a height of 6 inches above the bottom of the membranes. Air modification vanes improved the airflow distribution; however the target specification was still not met. The target specification was met at 57% of the locations with air modifying vanes.

Due to concerns about high temperature from the burners the area within which the readings were taken was reduced, eliminating the readings between the outermost membranes and the side walls. The target velocity was reduced from $1 \pm 0.2$ m/s to $0.5 \pm 0.2$ m/s due to overloading of the motor when airflow modifying screens were installed. With these modifications the target air velocity was not met at all locations. The target velocity was reached at 86% of the data locations. The best airflow distribution was obtained when implementing screen flow modifiers.

7.3 **Pilot Project Status**

Due to the work completed during this thesis the Pilot Bioreactor now has functional containment and gas circulation subsystems. Both systems are safe and contribute to the overall efficiency of the Pilot Reactor. These subsystems are ready for integration with the remaining subsystems as well as full scale operation once the reactor has been moved to its final location.
8. Recommendations and Future Work

The results of the containment subsystem testing only considered the initial seal surface design. Full scale operation of the Pilot Reactor will include other possible leak points. These leak points will include a shaft seal located on top of the fan box, plumbing and fiber optic cable lines, and the doors. Gas leakage at any of these points will result in a decrease in pressure inside the reactor. Also, a lack of gas containment will reduce the CO₂ concentration inside the reactor, requiring the burner to run for a greater period of time and decreasing the overall efficiency of the system. Leaking at any of these points should be monitored and if possible quantified prior to full scale operation.

The gas circulation subsystem was tested with ambient air. The air velocity profile could be altered during full scale operation of the velocity. This could occur due to the high temperatures of the gases being created while the burner is running. The burner may affect airflow by creating an obstruction inside the side compartments of the bioreactor as well. Also, a temperature gradient could occur throughout the system due to the geometry of the growth tank, which will be filled with a warm nutrient solution. It is recommended that the air velocity profile be established during full scale operation.

The temperature of the gases inside the reactor will likely be a serious issue throughout the project. Hot spots developing inside the reactor at areas of low airflow could harm algae. These potential hot spots should be identified. In order to investigate the effects of gas temperatures a computational fluid dynamics (CFD) model of the Pilot Reactor should be created. A CFD model will help in designing the remaining subsystems by illustrating unforeseen problems.
The air velocities inside the reactor will likely be altered due to moisture in the gases being circulated as well. This moisture will reduce the velocity of the gases due to their weight. Although the velocity of the gases will decrease, the gas flow distribution should remain consistent with those observed during this project. A larger motor of at least 2 hp is recommended to address the decrease in velocity. A larger motor will also be necessary if the initial target velocity of 1 m/s is sought and screen airflow modifiers are implemented.

Because the airflow subsystem performance may be affected by the burner subsystem is it recommended that airflow testing his postponed until the burner is operational. Once a working burner is installed the airflow distribution should be tested with both systems running. A new motor should be installed during this time. It is also recommended that the growth tank be filled to capacity when operating the airflow and burner subsystems. Doing so should provide a moist environment due to evaporation. Testing under these conditions will allow further researchers to examine the realistic airflow distribution during full scale operation. It is also recommended that testing with the larger motor is conducted to observed if the initial target value of 1.0 ± 0.2 m/s can be achieved with the air modifying screens.

Although there are full scale considerations for the subsystems tested, both have been integrated safely into the overall system are ready for full scale operation. It is recommended that the next step towards completing the Pilot Reactor is the design and testing of the burner subsystem. The burner affects each of the subsystems and it is vital that its impact on the overall system be studied.
References


Appendix A: Corner Seal Surface Assembly

1: Take the 1/4” thick steel angle member and position member securely with seal surface facing upward.

2: Apply The Right Stuff®, gasket maker in 1/4" thick bead along the 1/4" thick stainless member’s seal surface. Position the bead 1/2” from the edge of the seal surface and create a complete path around the surface. Be sure to apply the gasket maker along the entire circumference of the bolt hole.

3: Take the 1/8” thick steel angle member and align the bolts with those of the 1/4” thick member.

4: Take a 1/4 – 20 stainless steel bolt (at least 1” long) and place a 1/2” OD washer over it. Insert the bolt through the bolt holes of both members. Place a second 1/2” OD washer on the other side of the members. Screw on a 1/4 – 20 stainless steel nut.

5: Using a 7/16” and a torque wrench with a 7/16” socket, tighten the bolt and nut to 10 ft-lbs.

6: Wipe off excess gasket maker and allow to cure for 24 hours before operation.

7: Apply a 1/4” bead of high temperature silicon sealant (Dow Corning Type 732) along all linear feet of TIG welds.

8: While wearing gloves, use your finger to smooth the sealant over the entire weld. Allow 24 hours to cure.