# VF Engineering Inc.

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December 14, 2017

Dr. Wilbert Odem
CENE Professor
Northern Arizona University
Flagstaff, AZ 86001

Dear Dr. Odem,

The following report serves as a Final Design Report for the Vertical Agriculture Capstone Project. This report was composed by the vertical agriculture project team, VF Engineering Inc. (VF). The final design report includes acknowledgements, a project description, discussions of each task completed, and a summary of the project's costs. The summary of the project’s costs includes materials purchased and work hours spent on the project by team members. The final design report also includes references and appendices as appropriate for the completed work.

A detailed appendices is also attached that includes all testing results as well as the Gantt Chart that outlines the schedule that was followed throughout the course of the project. It is the design team’s hope that you will find this report comprehensive and informative.

The final design consists of a vertical agriculture system that utilizes the nutrient film technique for watering, LED lights for lighting, and a basic metal wire rack for the structure. The cost of implementation of the prototype is $457.

Sincerely,
The Vertical Farmers

Chalmer Bitsoi
Zeb Davis
Samuel Just
Matthew Schraan

# CENE 486

# Vertical Agriculture

# Final Report

Composed by:

The Vertical Farmers

Chalmer Bitsoi

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## 1.0 Acknowledgements

The Vertical Agriculture Design team would like to thank the following people for providing assistance in this project:

- Sea of Green Hydrogardens Store for providing technical advising as well as being a resource for many of the construction materials.
- Warners Landscape and Nursery staff for offering horticultural advice in regards to plant selection and growth media.
- Dr. Wilbert Odem for acting as a client and technical advisor to help keep the design team on track and helping refine the scope and focus of the project.

Table 1: Project Personnel

| | |
|---|---|
| Matthew Schraan – Principal in Charge | |
| Civil Engineering Major, Northern Arizona University<br><br>Over three years of experience as an intern for civil engineering consulting firms. Gaining valuable time management, document preparation, and team leadership skills. | Three years of experience leading to the knowledge of and experience with:<br>● Drafting software including AutoCAD, Civil 3D, Revit, and Terramodel<br>● Design software including WaterGems, FlowMaster, CulvertMaster, HEC-RAS, and HEC-HMS<br>● Surveying practices, such as topographic and as-built surveys, and construction staking |
| Samuel Just – Project Manager | |
| Environmental Engineering Major, Northern Arizona University<br><br>Two years experience with AutoCAD and Civil3D. 3 years management experience. Has some horticultural background. | ● Has some background as a TA in AutoCAD, Revit, Civil 3D as well as some geotechnical engineering.<br>● Has management experience outside of the field of engineering that has helped develop organization and communication skills.<br>● Has some experience working on ecological restoration projects. |
| Zebulon Davis – Project Engineer | |
| Environmental Engineering Major, Northern Arizona University<br><br>Three years of engineering at NAU. Management experience in several fields. | ● AutoCAD, Civil 3D, Culvert Master, and HEC-RES modeling software<br>● Survey training and practice including using a total station<br>● Previous participation on environmental engineering design projects<br>● Some horticultural experience |
| Chalmer Bitsoi – Engineering Tech | |
| Civil Engineering Major, Northern Arizona University<br><br>Over 15 years of experience in Oil and Gas exploration, production and transportation. | ● Served as a project engineer on hazardous liquid transportation projects from feasibility studies and environmental documentation to preliminary and final design<br>● Organization, communication, and detailed-oriented skills that help successfully deliver numerous multi-discipline projects on schedule and within budget.<br>● Served as project manager, assistant project manager and/or lead engineer on the following relevant projects:<br>o Chaco Trucking Service, Farmington, NM<br>o AST remediation, Montezuma Creek UT<br>o HDD for 1000 feet of pipe reroute.<br>o Facility electrical upgrade with MCC |

## 2.0 Project Description

This project is prepared and presented by a team of qualified engineering students to develop a small scale prototype for a hydroponically grown vegetable garden that replicates systems commonly used on a commercial scale. This prototype must be designed to meet requirements for nutrient concentrations, temperature, pH levels, and dissolved oxygen (DO) levels, as will be defined later in this report. In this section, a description of the preparation of design, construction, and factors associated with the optimization of indoor vertical agriculture is discussed. It is the design team's hope that this information may be useful for a public that wishes to reduce their carbon footprint in the Northern Arizona climate, are concerned about where their food comes from, or are concerned in minimizing the health risk from store bought food [1].

### 2.1 Design Team

The vertical agriculture team consists of four well-qualified students that will complete an effective design for the vertical agricultural project. This design team has administered the project, prepared component designs, and outlined an operating procedure with attention to parameters required for optimum plant growth. Through research, this team has developed a strong understanding in nutrient solution selection for leafy green vegetables and prepared conceptual reports on the Nutrient Film Technique that will be the driving principle behind this design. Table 1 displays the team members and their qualifications.

### 2.2 Stakeholders

The primary stakeholders include the customer, client, grocery stores, large agriculture companies, independent farmers, and the environment. The primary stakeholder of concern is the client, who initially commissioned this design. The vertical agriculture design follows specifications set by this client and the client will be the initial recipient of the design and prototype.

Industry will be affected by this project because the vertical agriculture product will possibly take customers away from grocery stores. Independent owners of a hydroponic system will be able to grow their own vegetables and will not need to go to the store to purchase vegetables. With less demand for store bought vegetables, the prices will go down and some farmers or companies will be negatively affected. Larger scale designs will affect the large agriculture companies, potentially displacing many of its workers.

## 2.3 Background

The impacts of commercial scale vertical agriculture may be defined in terms of the impact that technology has on society. Agriculture has taken many advances over the past two centuries, evolving from rural, small scale farming practices to a large scale, technology driven industry. This shift, occurring from the late 1800's into the 1900's had huge social and economic impacts [2]. With advancements in technology, farm productivity skyrocketed while the need for labor greatly decreased. This reshaped the farming industry as well as rural society.

The economic and social sustainability of these advancements in farming were brought under question when it became clear that agricultural productivity could surpass the demand of the developed world. During the early 20$^{th}$ century the environmental impacts of modern methods of farming also became clear when mono-cropping resulted in the degradation of soil conditions, excessive erosion, and habitat disruption [3].

Vertical Agriculture as an up-and-coming industry may be thought of as the result of an approach towards sustainability. On a commercial scale, vertical agriculture creates significantly less impact on the environment compared to modern methods of farming and meets requirements for efficiency and productivity to be considered an economically viable option. For example, current agricultural practices use up to 70% of the United States water requirements whereas vertical farming methods could reduce these requirements to around 35-40% [4].

On a social level, a shift towards vertical agriculture would likely receive a high level of mistrust from farming communities. Much like the modernization of the agriculture industry in the early 20$^{th}$ century, this change would further solidify agriculture as a technology driven industry when it had once been much more human. A shift towards this form of large-scale commercial farming would further displace jobs from blue-collar, rural farmers and create jobs within a more technical sector.

## 2.4 Scope of Services

Vertical Farmers built a prototype and tested the design in the Northern Arizona University College of Engineering Environmental lab for its ease of access, ability to grow plants, and storage.
A detailed schedule of the tasks that the team has carried out can be found in Appendix A. The primary tasks required include:

1. Research
2. Design and Component Selection
3. Construction
4. Testing

5. Final Reporting of Results

Limitations and exclusions made for the completion of the project include:

1. Due to time constraints, design and construct one prototype.
2. The power demand needs to be kept to a 110-volt supply.
3. The cost needs to be low in order to improve on contemporary designs.
4. The design will only test the effectiveness of leafy green vegetables, to ensure that parameters for growth may be held constant throughout the system.
5. Time constraints allow for one month of testing. Improvements to the design may be made as recommendations only.

## 3.0 Technical Work Completed

This section will include a discussion of the technical work that was completed for each of the four primary tasks outlined in the scope: research, design, construction, and testing. The research section includes a description of design alternatives considered for each component of the hydroponic system. The design section describes how each of these components were incorporated into a final design. The construction process includes a summary of the creation of the final prototype. The testing section outlines the parameters and procedures used for evaluation of this prototype and include the results that were obtained during this phase of the project.

## 3.1 Task 1: Research and Component Selection

This task included background research on existing methods of indoor/vertical farming. Due to the complexity of the project, the research process was thorough and comprehensive. The design utilizes existing information taken from contemporary studies on hydroponics to the greatest extent possible. Through understanding existing technologies, VF identified potential components that could be used for each aspect of the design. The technical considerations for selecting the lighting and watering component depend on maintaining minimal power consumption, operating cost, and performance for the intended capacity of the design.

### 3.1.1 Component Selection: Lighting

VF verified that crop yield in an indoor hydroponic system is dependent on a controlled environment that simulates natural lighting by using artificial lighting. The three alternatives considered for the watering design included:

1. Incandescent
2. Fluorescent
3. Light Emitting Diode (LED)

Based on research, VF chose LED, for the lighting component of the system. LED is a type of artificial lighting that is setting the stage for improving plant growth. LED is capable of providing 660 nanometer (nm) of Red and 445 nm of Blue wavelength for photosynthesis [5]. Photosynthesis is a process by which plants absorb light energy from the sun and transform it into food in the form of chemical energy. The light energy is visible to plants as red and blue. The red and blue wavelength are absorbed from sunlight and transformed into carbon dioxide and water to form organic compounds called proteins.

Blue light is absorbed by the chlorophyll, more particularly the cryptochromes. Chlorophyll harvest these light photons and store them in reaction centers deep within the chloroplast [5]. These reaction centers take the light energy to use in the photosynthetic process. Cryptochromes are photoreceptors that regulate entrainment by light of the circadian clock in plants [5]. This phenomenon allows plants to grow and maintain resting patterns for a complete growing cycle that includes reproduction. Cryptochrome's response to blue light in the 400-500 nm range involves chloroplast movement, stomatal control and stem elongation of plants [5].

Natural light exposes majority of the red light to plants. The chlorophyll is efficient at absorbing all this red light in the 640-720 nm range. In the early stages of the plant, red light is important for seed and root growth [5]. As the plant matures, absorption stimulates stem growth, flowering, and chlorophyll production. The combination of the blue and red light produces mature leaf shape, more biomass, and experience higher rates of photosynthesis [5].

LED technology provides the blue and red wavelength and light intensity for plant growth without adding radiant heat [6]. Unlike incandescent and fluorescent technology, LED arrays stimulate growth by providing three times more light output for the same watt of input power on an equivalent area basis [6]. This maybe attributed to setting the LEDs in arrays to increase the amount of spectral lighting to the plants. The spectral lighting maybe programmed for controlling the amount of blue and red the plants receive without increasing the electrical load. The technological advancement of LED is bringing sustainability to the users while minimizing purchase cost and operating expense.

### 3.1.2 Component Selection: Watering

The importance of watering ensures that plants survive and can also receive the necessary nutrients. The three alternatives considered for the watering design included:

1. Aeroponics
2. Drip Method
3. Nutrient Film Technique

VF chose to utilize the Nutrient Film Technique, or NFT, because studies have proven its effectiveness in growing leafy green vegetables. NFT systems are the most common method of hydroponics used on a commercial scale. For this reason, the team sought to replicate large scale vertical agriculture with a small scale prototype to produce results that may be more relevant in real world application.

Plants require 14 essential elements in the root, stem and leaf zone [7]. The most important nutrients are nitrogen, phosphorus and potassium. Secondary nutrients are defined as sulfur, calcium and magnesium. Other elements that influence plant growth are the dissolved salts iron, manganese, zinc, boron, copper, molybdenum, chloride and nickel. These dissolved salts influence the electrical conductivity of the nutrient solution. Electrical conductivity (EC) influences the ability of a plant's root system to transport water to the rest of the plant [7]. While concentration of these trace minerals may be small in comparison to the other nutrients in a solution, they are still incredibly important.

NFT systems are comprised of a reservoir with a nutrient solution pumped through a pipe network to deliver the water and nutrients to a plant growth tray. A submersible pump conveys water to the top plant growth tray situated 5 feet above the bottom reservoir. The water is recycled through the reservoir and refreshed weekly to prevent the growth of algae or other fungi. The continuous flow provides the needed nutrient solution to the roots. Vertical agriculture allows the use of gravity to assist from top to bottom while providing negligible energy to pump water.

In the absence of soil, these nutrients must be added by a nutrient solution. Recommendations from technical advisor, Jenna Mace, led the team to select a solution comprised of 7.0% Total Nitrogen, 4.0% Phosphate, and 10.0% Soluble Potash with trace levels of dissolved salts met the electric conductivity needs of the plants [8]. A complete breakdown of the components of this solution is given in *Table 2.*

Table 2: Nutrient Solution Components

| Component | Percent Present (%) |
|---|---|
| Total Nitrogen (N) | 7.0 |
| Available Phosphate ($P_2O_5$) | 4.0 |
| Soluble Potash ($K_2O$) | 10.0 |
| Calcium (Ca) | 4.0 |
| Magnesium (Mg) | 1.5 |
| Sulfur (S) | 2.0 |
| Boron (B) | 0.01 |
| Chlorine (Cl) | 0.01 |
| Cobalt (Co) | 0.002 |
| Copper (Cu) | 0.01 |
| Iron (Fe) | 0.1 |
| Manganese (Mn) | 0.03 |
| Molybdenum (Mo) | 0.003 |
| Zinc (Zn) | 0.02 |

This solution was applied during growth at varying concentrations depending on the stage of growth. A breakdown of this application is given in *Table 3.*

Table 3: Nutrient Applications [8]

| Dosage | Application |
|---|---|
| ½ tsp/Gal | Seedling |
| 1 tsp/Gal | Early Growth |
| 2 tsp/Gal | Later Growth |

### 3.1.3 Component Selection: Structure

The structural component of a vertical agriculture system is very important. The structural component not only holds the system together but the position of light sources relative to the photosynthetic surfaces of plants has a large effect on crop productivity [5]. VF chose a metal structure that measures 36 inches wide, 16 inches long and 72 inches high. The structure has 5 adjustable shelves with a 500-pound shelf capacity. The structure is available to the general public and its assembly instructions provides ease of use in reproducing the vertical agriculture system created by the VF.

## 3.2 Task 2: Design

A general schematic of the system, drafted in AutoCAD, may be viewed in *Figure 1*. The schematic depicted shows the direction of flow within the system as well as the general layout of three growth levels. The dimensions depicted are in inches.

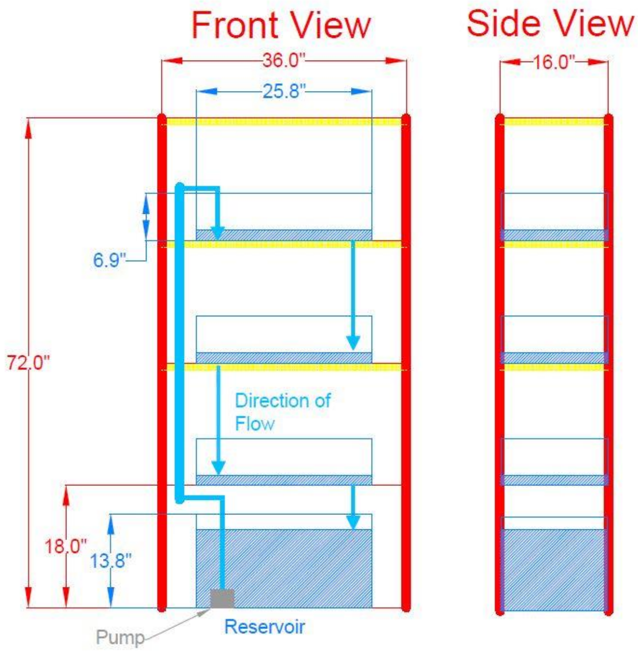


Figure 1: General Schematic

In this design the reservoir holds a maximum of 15 gallons, which is also the total capacity of the entire system. The reservoir uses an ECO 396 pump designed for a maximum flow rate of 396 gal/hr. The ECO396 pump is capable of delivering 6.5 feet of head, approximately 1.5 feet more than our reservoir to the top tier of the system. The nutrient solution that is stored in the reservoir is pumped to the top tier of the system where gravity will transport it down the network to return to the reservoir. The system uses a ½-inch tubing to transport the nutrient solution. Each plant growth tray on each level are comprised of fittings that allows for even distribution of the solution.

The lighting arrays are created by weaving the strip LED lighting through the metal wires of each shelve equally spaced in four rows above each growth platform. The strip lighting provides an adhesive backing side that may easily be attached to the wire rack structure for secure the lighting. For safety reasons, it is important that strip lighting be water resistant as the lights are woven above and beneath the plant growth tray making water to come in contact with the lighting strip. To incorporate the circadian clock, a timer is installed to allow the plant to rest for 6 hours and the control of red to blue lights programed for improved photosynthesis rates.

The plant growth tray on each level are held in raised platforms. These platforms contain slotted plant holders filled with clay pebbles to hold the plants in place and assist in watering the plants with the required amount of water. The clay pebbles are like sponges, they hold the right amount water and drain any excess water to avoid plant drowning. As in the soil environment, plant roots grow downwards toward the flowing nutrient solution.

## 3.3 Task 3: Construction

Prior to beginning construction, each component was purchased and collected in the lab where testing was to take place. All structural components of the design were purchased from Home Depot. These included three plastic bins to be used to convey nutrient flow on each level, a 20 gallon bin to be used as the nutrient solution reservoir, and wire rack previously described in this report.

### 3.3.1 Construction: Initial Structure

The initial construction was completed by combining the components for the structure and NFT watering system. The ECO396 pump that was selected was added to the bottom reservoir and a ½” tubing was used to convey the solution to the top level of the system. Gravity then transported the nutrient flow throughout the lower levels of the system and then ultimately back to the reservoir where it would be recirculated. This initial construction may be seen in Figure 2.

Figure 2: Initial Construction

A wooden frame was then constructed for each level from materials acquired from Home Depot. Wiring was added across this frame to hold plant fixtures at even spacing. These fixtures were suspended so that they could be raised and lowered as needed so that the roots of the plants would have adequate contact with the nutrient film. Clay pebbles were selected as the growth media based on a recommendation from the team's technical advisor. Compared to other growth media, clay pebbles have a high surface area and porosity that allows for the uptake and retention of the nutrient solution. This component of the design may be seen in Figure 3.

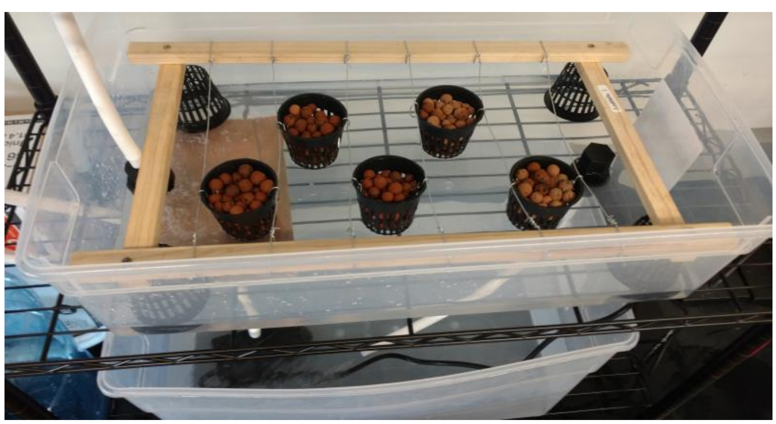

Figure 3: Wood framing and wire suspension

### 3.3.2 Construction: Transplant Procedure

Nine green leaf lettuce crops and six arugula crops were transplanted into the system on November 2, 2017. These crops were two weeks old and grown in soil up until this stage. When removed, all soil was carefully washed from the root system of each plant as may be seen in Figure 4.

Figure 4: Lettuce transplants

The plants were then placed into holders with clay pebbles carefully placed around the root system of each plant. These containers were then attached to a wire and wooden frame to be placed within the three bins located on each level of the system. This process is depicted in *Figure 5.*

Figure 5: Transplanting crops into growth containers

### 3.3.3 Mixing the Nutrient Solution

After successfully transplanting each plant into the system, 15 gallons (56.8L) of water was added into the nutrient reservoir. A nutrient solution was added following a ratio of 1.25mL Solution / 1 L Water [8], totaling in 71 mL of solution for the total 15 gallon system. This solution was mixed into the system through continuous cycling through the three levels using the reservoir pump.

After mixing the nutrient solution, screening was added to each level to prevent plant leaves from coming into contact with the nutrient solution. An image depicting the completed system at the start of experimentation may be seen in Figure 6.

Figure 6: Final System

## 3.4 Task 4: Testing

During the growth cycle there were several factors that needed to be consistently monitored to ensure healthy growth of each plant. These included:

- Light Application
- Nutrient and Watering Levels
- pH
- DO Levels and Temperature

Each of these factors and monitoring schedule are described in detail within this section. In addition to these parameters necessary for plant growth, water uptake and plant size were also measured twice a week to assess the success of the design.

A complete schedule that was followed throughout the month of testing may be seen in Appendix B.

### 3.4.1 Light Application

In natural conditions, all plants require periods of darkness to rest and metabolize. Lettuce and arugula are considered long day plants and grow most effectively when summer solstice conditions are imitated, allowing for 18 hours of daylight and 6 hours of darkness [5]. For this reason, the design team's lights were set to a timer to allow darkness from the hours of 10:00 PM to 4:00 AM.

### 3.4.2 Nutrient and Watering Levels

In Nutrient Film Technique (NFT) hydroponic designs, the rate and depth of flow of the nutrient solution is critical to the success or failure of the design. As the name indicates, the flow of solution needs to only be a thin film along the bottom of the channel, less than a centimeter in depth. If the depth of flow exceeds this it may overload the root structure of the crops and drown them [9].

The length of channels used in NFT designs can vary greatly from 20 meters to less than 3 meters. The design implemented by the Vertical Agriculture team is unique in that the flow is connected in a network of 3 levels for one source of flow. The combined length of these three levels falls below 3 meters in total channel length. According to a study by Dr. Lynette Morgan, a flow rate of 0.2 liters/min was determined to be optimum for NFT systems of 3 meters in length or less [10].

Theoretically, nutrient levels and dissolved salts within the solutions are absorbed over time by the crops. Rather than monitoring these levels and supplementing in constituents as they are reduce, the design team opted to completely refresh and remix the solution each week. This will ensure adequate concentrations as well as help prevent the spread of bacteria or other organics within the solution [9].

### 3.4.3 pH

The pH for the nutrient solution for lettuce and arugula must be maintained between 6.0 – 7.0 at all times [9]. PH levels can have a drastic impact on a plant's ability to develop root mass and impact germination. PH levels at extreme levels, below 5 and greater than 7.5 can have a corrosive effect on a plant's root system. Different plants ability to uptake nutrients can be greatly impacted by the pH of a nutrient solution. Nutrients such as nitrogen and phosphorus may become unavailable to leafy greens if pH reaches levels above 7 or below 6 [9]. For this reason, pH was monitored and recorded twice a week. If pH reaches a level above 7.0, an acid was added and if pH drops below 6.0, a base was added.

### 3.4.4 Temperature and Dissolved Oxygen

Oxygen availability is crucially important in all hydroponic designs. In NFT designs it can become even more important since plant roots are in constant contact with the solution. If water levels are too high, root contact with the air may be limited and the plant may drown. To counter this effect it is important to use oxygen pumps to constantly aerate the solution and raise dissolved oxygen (DO) levels as much as possible [10]. DO in a nutrient solution prevents anaerobic conditions where harmful microorganisms may begin to consume available nutrients and in some cases attack the root structures of the plants.

DO is especially important in hydroponic systems for its influence on a plant's ability to transport nutrients and minerals from its roots. If oxygen levels drop below ideal levels, the plant will no longer absorb nutrients and starve [10]. Dissolved oxygen levels typically vary greatly based on the temperature of the solution. As temperature increases, DO levels will be limited by the saturation limit given the present conditions. While this is the case, a plant's ability to uptake oxygen will increase exponentially with increases in temperature.

For this reason temperature must be maintained between 65-80 degrees Fahrenheit and dissolved oxygen kept above 4 ppm, a range that optimizes plant uptake of oxygen without significantly decreasing DO levels [9]. A drawback of using air pumps is that they will also add CO2 to the nutrient solution which, through reaction with elements found in the solution will raise pH levels. This effect was closely monitored throughout the experimentation process through continued pH adjustments.

### 3.4.5 Electrical Conductivity

The solution are comprised mainly of salts. As the nutrient salts are mixed with water in the reservoir, the salts are dissolved and the roots are immediately provided the required nutrition. Electrical conductivity is the measure of a material's ability to conduct an electrical charge, measured in Siemens per centimeter [10]. The charge is the movement of electrons over time across a medium such as water to measure how the current moves in solution.

As the proper pH level is obtained, it is important to fine tune the electrical conductivity of the solution. This ensures the ratios of the amount of water and nutrients are properly added. The higher the concentration of nutrient solution dissolved in water, the higher the EC. The more diluted the nutrient solution, the lower the EC. As the nutrient solution becomes saltier, the plants have difficulty absorbing water. The leaves tend to curl and a noticeable brown around the edges forms or the solution may absorb all the water from roots causing plants to wilt and die.

An EC meter is a great tool for measuring the strength of hydroponic nutrient solutions. Pure water doesn't conduct electricity, which means distilled water or deionized water has an EC of zero. The meter is comprised of two electrodes to which voltage is applied. The voltage reading is the resistance of the solution. The instrument calculates the reciprocal of this value, allowing electrical conductivity to be calculated [11].

## 4.0 Final Results and Recommendations

All of the measurements that were taken during the testing stages, EC, DO, reservoir volume, pH, and temperature may be seen in Appendices C-F. As may be seen in Appendix F, pH was adjusted to maintain the optimal range between 6 and 7 throughout the course of testing. After EC began to be measured on November 14, it was found that the overall solution concentration fell below the desirable range. For this reason, a higher concentration of solution was added to the system.

Water volume loss throughout the course of testing indicated that the plants continued to uptake water and thus the nutrient solution. A DO meter was not acquired for testing until November 9. The initial measurements of DO indicated levels above saturation, which was found to be due to improper calibration of the device. Temperature was always found within the desired range of 65-80 degrees fahrenheit and was therefore not adjusted.

The tables given below show the results of plant growth for arugula and lettuce in the system.

Table 4: Arugula Growth

| Date | Top Row (in) | Middle Row (in) | Bottom Row (in) |
|---|---|---|---|
| 11/2/17 | 5.50 | 3.20 | 2.30 |
| 11/7/17 | 3.50 | 3.50 | 3.50 |
| 11/9/17 | 4.00 | 3.75 | 3.75 |
| 11/14/17 | 4.05 | 4.10 | 4.00 |
| 11/16/17 | 4.11 | 4.23 | 4.05 |
| 11/21/17 | 4.26 | 4.40 | 4.07 |

Table 5: Lettuce growth

| Date | Top (in) | Middle (in) | Bottom (in) |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 11/2/17 | 5.5 | 3 | 4.1 |
| 11/7/17 | Dead | Dead | 3.5 |
| 11/9/17 | Dead | Dead | Dead |

As seen in the tables, the arugula proved to be successful while the lettuce died almost immediately upon transplant. Lettuce is notoriously difficult to transplant, and the design team considers this to be the primary cause of death. Water levels were also lowered after the lettuces death, since the plants showed symptoms of overwatering. In future tests it is recommended that a lower flow of solution is used for the growth of lettuce.

Spinach was added to the system during the last two weeks of testing but no measurements on plant growth were taken. These plants have proven to survive and show signs of growth over the course of two weeks. This indicates that the design may support certain types of plants while other types may not be suited to these conditions. It is possible that a different growth media other than the clay pebbles used in this design may have been more effective in supporting the weak root structures of the transplanted lettuce crops.

Figure 7: Spinach in system

The design team believes that this prototype could be improved upon by future teams and could have potential uses for further experimentation. Some examples of other potential uses include phytoremediation studies, oxygen and carbon dioxide uptake monitoring as well as using assessing nutrient and contaminant uptake using spectrophotometry.

## 5.0 Summary of Project Costs

The summary of project costs will include a discussion of the materials purchased to build the prototype, maintain the system, and test the system. There will also be a discussion of the cost for the work hours spent by team members for each task. This discussion will include a comparison of the proposed cost to the actual cost.

## 5.1 Material, Maintenance, and Testing Costs

The following table shows the summary of material costs at the project's current stage of completion.

Table 6: Material Costs

| Item | Quantity | Cost | Total |
|---|---|---|---|
| LED Lights | 3 rolls | $84 | $84 |
| Wire Rack | 1 | $40 | $40 |
| Plastic Tubs | 3 | $10 | $30 |
| Reservoir Tub | 1 | $10 | $10 |
| Tubing | 15 ft | $1 | $15 |
| Wood Framing | 18 ft | $1 | $18 |
| Plant Holders | 16 | $1 | $16 |
| Pump | 1 | $30 | $40 |
| Tube Fittings | 6 | $2 | $12 |
| Metal Wire | 1 roll | $12 | $12 |
| Clay Pebbles | 1 bag | $43 | $43 |
| Nutrient Solution | 1 bottle | $26 | $26 |

Total = $457.00

## 5.2 Cost of Labor

Table 7 provides the hours spent on each task completed throughout the course of the project. The total hours spent are a summation of all time spent by each team member on each task. These hours are compared to the estimated time that was indicated in the project proposal. This table also includes rates of pay as estimated using comparable billing rates used by engineering companies [12].

Table 7: Engineering Hours

| Position | Rate of Pay [14] | Hours | | Cost | |
|---|---|---|---|---|---|
| | | Proposed | Actual | Proposed | Actual |
| Project Manager | $140/hr | 120 | 110 | $16,800 | $15,400 |
| Senior Engineer | $130/hr | 190 | 180 | $24,700 | $23,400 |
| Engineering Technician #1 | $75/hr | 240 | 300 | $17,250 | $22,500 |
| Engineering Technician #2 | $75/hr | 240 | 300 | $17,250 | $22,500 |
| | Total | 790 | 890 | $76,000 | $82,540 |

## 5.3 Summary of Costs

The total anticipated cost of labor was valued at $79,000. At completion the total cost of labor is estimated at $82,540. This increase from the predicted cost may be due to the fact that the testing phase predicted during the project proposal did not anticipate the significant amount of lab time that would be needed to complete testing twice a week. The total hours for Project Manager, and Senior Engineer however, were lower than anticipated. This is due to the fact that the design and project management component of the project required significantly less time than the construction and testing stages.

In effort to keep the overall material costs down, the design team chose to use affordable materials and construct components of the design by hand rather than purchasing them prefabricated. Many premade hydroponics systems of this scale can range in cost from $800 - $2,000 [13]. As can be indicated by the total material cost, $457.00, the efforts to be cost efficient have proven to be successful.

## 6.0 References

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## *7.0* Appendix A: Gantt Chart

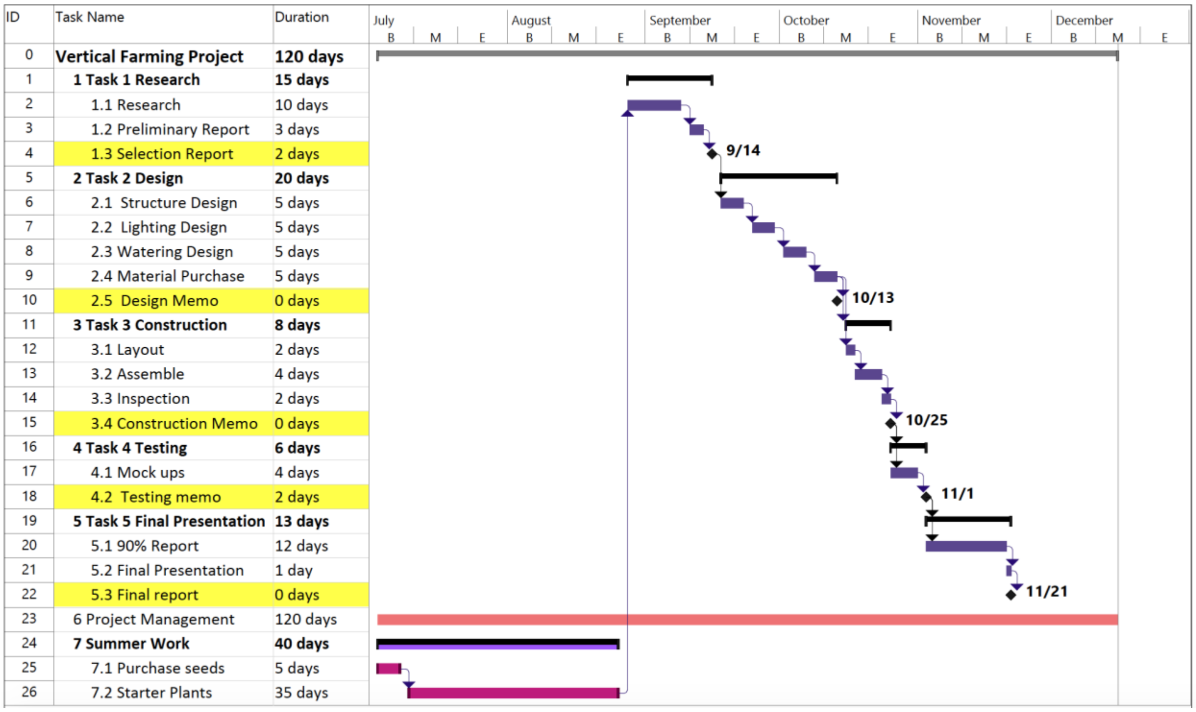


Figure 8: Gant Chart

## 8.0 *Appendix B: Testing Schedule*

| Date | Tasks Completed |
|---|---|
| 11/2/17 (Thursday) | Transplant, plant growth, pH, temperature, DO |
| 11/7/17 (Tuesday) | pH, temperature, DO |
| 11/9/17 (Thursday) | Plant size, pH, temperature, DO, water uptake refresh solution |
| 11/14/17 (Tuesday) | pH, temperature, DO, EC |
| 11/16/17 (Thursday) | Plant size, pH, temperature, DO, water uptake, refresh solution, EC |
| 11/21/17 (Tuesday) | pH, temperature, DO, EC |
| 11/23/17 (Thursday) | Plant size, pH, temperature, DO, water uptake refresh solution, EC |
| 11/28/17 (Tuesday) | pH, temperature, DO, EC |
| 11/30/17 (Thursday) | Plant size, pH, temperature, DO, water uptake refresh solution, EC |
| 12/01/17 (Saturday) | pH, temperature, DO, EC |

*9.0 Appendix C: Dissolved Oxygen versus Saturation*

| Date | 11/2/17 | 11/7/17 | 11/9/17 | 11/14/17 | 11/16/17 | 11/21/17 | 11/23/17 | 11/28/17 |
|---|---|---|---|---|---|---|---|---|
| Temp. (ºF) | 70.1 | 70.0 | 65.0 | 70.8 | 67.4 | 69.2 | 67.8 | 70.7 |
| DO (ppm) | - | - | 7.5 | 7.5 | 7.0 | 6.5 | 6.2 | 6.2 |
| Saturation Level for DO (ppm) | 6.8 | 6.8 | 7.2 | 6.7 | 7.1 | 6.9 | 7.0 | 6.7 |

## *10.0 Appendix D: EC Measurements*

| | 11/2/17 | 11/7/17 | 11/9/17 | 11/14/17 | 11/16/17 | 11/21/17 | 11/23/17 | 11/28/17 |
|---|---|---|---|---|---|---|---|---|
| EC (mS/cm) | - | - | - | 0.76 | 0.66 | 0.89 | 1.11 | 1.05 |

## *11.0 Appendix E: Volume Measurements*

| Date | Top Row (in) | Middle Row (in) | Bottom Row (in) | Reservoir (in) | Total (in) | Volume ($x10^3$ $in^3$) | Volume (gal) |
|---|---|---|---|---|---|---|---|
| 11/7/17 | 0.45 | 0.75 | 0.75 | 6.30 | 8.25 | 3.36 | 14.56 |
| 11/9/17* | 0.45 | 0.75 | 0.75 | 5.80 | 7.75 | 3.16 | 13.68 |
| 11/9/17 | 0.50 | 0.75 | 0.75 | 6.30 | 8.30 | 3.38 | 14.65 |
| 11/14/17* | 0.45 | 0.85 | 0.75 | 4.70 | 6.70 | 2.73 | 11.82 |
| 11/14/17 | 0.45 | 0.75 | 0.75 | 6.30 | 8.25 | 3.36 | 14.56 |
| 11/21/17* | 0.45 | 0.75 | 0.75 | 6.00 | 7.95 | 3.24 | 14.03 |