AUTONOMOUS CONTROLLED ENVIRONMENT GROWTH CHAMBER

BREE 495 ENGINEERING DESIGN 3

Pierce Dias Carlson [redacted]
Rachael Warner [redacted]
Ellen Arrowsmith [redacted]

Department of Bioresource Engineering, Macdonald Campus, McGill University
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Abstract

This report details the design of an Autonomous Controlled Environment Growth Chamber (ACEGC), to be installed in the Macdonald Farm Community Engagement Center. Controlled environment growth chambers can provide consistent, ideal growing conditions for crops, which result in high yield and low variability. Existing growth chamber systems that incorporate control of radiation, temperature, humidity, HVAC, and hydroponics can be improved upon with the introduction of an autonomous system that eliminates human labor and interaction. An ACEGC was designed to fit ideal growth conditions for red butterhead lettuce, with regard to radiation, temperature, humidity, carbon dioxide, airflow, plant culture, fertigate solutions, and sterilization. Its design covered seven main components: electrical connections, lighting, support and insulation, HVAC, lettuce growth, hydroponics, and automation. The design was analyzed for safety, cost, environmental impact, and social impact, and found to be an improvement in existing controlled environment technologies, and a viable alternative to conventional farming.

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List of Acronyms and Units

ACEGC - Autonomous Controlled Environment Growth Chamber
CEC- Community Engagement Center
C - Celsius
DAQ - Data Acquisition
DO - Dissolved Oxygen
EC- Electrical Conductivity
ft - Foot
GPH - Gallons per hour
GC - Growth Chamber
HID - High Intensity Discharge
hr - Hour
HVAC-Heating Ventilation & Air Conditioning
ICCEG - International Committee for Controlled Environment Guidelines
J - Joules
kWh - Kilowatt hours
L - liter
LCD - Liquid Crystal Display
LED - Light Emitting Diode
LECA- Light Expanded Clay Aggregates
m - Meter
mg - Milligrams
NCERA- North Control Extension & Research Activity
NDIR - Non Dispersive Infrared Sensor
ppm - Parts per Million
PAR - Photosynthetically Active Radiation
PPF - Photosynthetic Photon Flux
PVC - Polyvinyl Chloride
RH - Relative Humidity
s - Seconds
S - Siemens
UI - User Interface
UV- Ultraviolet
V - Volts
W – Watts

1. Introduction

This section will introduce technologies and systems relevant to the design process, as well as relevant problems associated with these systems. Finally it will describe the objective of this design process in the scope of our client.

1.1 Controlled Environments

Controlled environment agriculture is a closed, or semi-closed system, which is conditioned to emulate the ideal growing conditions for a given crop. When plants are grown under ideal conditions, they will produce high crop yield (Despommier, 2010). The agricultural industry is undergoing a shift from traditional large scale monoculture to smaller scale productions, especially in the urban, or harsh, environment (Despommier, 2011).

There are variety of controlled environment agriculture techniques used today. Closed plant production (CPP) borrows technique from passive housing, while applying a new aspect of technology. The growth structure is wrapped in an insulated envelope, preventing free movement of air across the barrier and providing as much insulation as possible (Kozai, 2013). Often, these systems are plant factories with artificial light (PFAL), as implied, they utilize no natural sunlight to maximize insulation value, and grow plants at extremely high density (Kozai, Fujiwara, Runkle, 2016). As the system is airtight, the environment must be continually monitored and altered by: heating or air condition units, CO_2 supply, and an environmental control unit to ensure ideal humidity and temperature for plant growth (Kozai, 2013). In contrast to using sunlight, compact fluorescent light bulbs or LEDs are employed to stimulate photosynthesis. Overall CPP allows for ideal crop conditions, providing high yields but the system requires higher energy input than traditional systems, but yield higher density crops and larger volumes. (Despommier, 2011. Bamsey, et al., 2014).

Vertical farming systems work well with closed environment agriculture, as it allows for high density plant growth, making each unit of cubic space more productive. Greenhouses and closed plant production are ideal to support these systems, as supplemental lighting is often already built into the infrastructure (Despommier, 2011). Vertical farming can be integrated into greenhouses or CPP. When natural light is being used it is important to ensure all crops are receiving adequate light and are not being shaded, if no supplemental lighting is being used.

Hydroponic systems have been widely implemented in CEA systems. They have been found to reduce the amount of water used in a system, with negligible losses, with the main cause of water loss from the system is through plant transpiration. Hydroponic system use nutrient solution to fertilize plants, reducing the steps in the in the cultivation process (Merill, 2011).

1.1.1 Case study: CEA in Antarctica

Since the late 1960's, closed environment agriculture has been practiced, on small scales, at research stations across Antarctica. Some ports in Antarctica can only receive shipments for four months each year, making perishable items inaccessible during much of each year. An average food production system will produce enough fresh food to provide a weekly salad for each resident throughout the winter months (Bamsey, 2016). In 2015, there were nine active food producing stations around the continent, but 46 have been implemented over the lifetime of Antarctic exploration. The building constructions vary, but are mainly wooden buildings, steel framed domes or retrofitted shipping containers (Bamsey, 2016).

There are a variety of technologies being utilized; some practice closed plant production, with no natural sunlight, while others use translucent building materials. Generally, hydroponic systems are used, as soil is not allowed to be imported to the continent (Bamsey, 2016). Some stations have employed vertical farming, to increase the density of their production. This has been found to be very successful, as smaller areas minimize the amount of energy required for heating. To reduce water consumption, various recycling methods have been used, one being a condensation collection technique. Incineration is widely used for waste disposal on the continent, including disposal of byproducts from the food production, and this heat is collected to contribute to heating the greenhouses (Bamsey, 2016).

1.2 Issues with Human Interaction of Controlled Environments

Conventional controlled environment growth chambers are extremely useful for growing crops, but often produce inconsistent results. Hammer et al. (1978) found that lettuce grown in controlled environments showed more variability between repetitions in the same laboratory than variability between crops in separate laboratories, even with strict control over all environmental factors. This shows that while controlled environment technology and practices have certainly improved since this study in the 1970s, and some of this variation is due to the intrinsic nature of randomness within agricultural production, there are still many methods by which crop yield consistency can be improved.

The most important of these is reducing or eliminating human interaction with both the crops and the environment of a growth chamber. Existing conventional controlled environments allow for humans to enter the chamber and interact with the plants and environment, which may jeopardize the crop consistency or viability, whether through varying attentiveness to individual crops, contamination, or other human error (Conviron, n.d.).

Human touch and visitation can affect plants in a range of ways. Cahill et al. (2002) found that plants which were visited by humans and plants which were touched by humans experienced an effect on growth height and rate, in both positive and negative ways. While there is some evidence to suggest that regular human interaction may help some plant species growth, there is no question that it increases the variability of the yield.

Additionally, human visitation and interaction may have potentially catastrophic results in the form of bacterial or fungal contamination. Because controlled environment growth chambers share resources between crops (primarily air and water flow), and resources are less diluted, the introduction of a contaminated material could be catastrophic for the entire yield (Tibbitts, 1997). In controlled environments which are exposed to human interaction, the risk of this contamination is increased, by the nature of the introduction to ‘outside’ materials.

Lastly, there are other, miscellaneous errors which are increased as humans are introduced to controlled environments. These could include damage to a plant, or a misallocation of resources. Due to the nature of autonomy, there will be more inconsistencies occurring in systems controlled by humans than systems controlled by well-programmed, functional processes.

It is unquestionably desirable to limit potential sources of variability introduced through human interaction, which can be achieved through the autonomy of a controlled environment growth chamber.

Fig. 1.1 The Macdonald Campus Farm Community Engagement Center ("Macdonald Farm Community Engagement Centre / Centre d'engagement communautaire de la ferme Macdonald", 2017)

1.3 Our Client, and their Mission to Educate

Controlled environment technology and further advancements into automation and control of agricultural production offer a promising future for the agricultural sector. The Macdonald Campus Farm Community Engagement Centre is a new museum dedicated to educating the McGill and greater Montreal community, about food production, as shown in figure 1.1. They intend to focus on past and future agriculture technology, and how we, as a society, can move towards a more sustainable food system. Workshops will be held for the students in local elementary and high schools, to encourage them to begin thinking about global food issues, and hopefully encourage them to pursue a future in environmental and agricultural fields. This center will provide invaluable knowledge to the members of the community, and use education as a powerful tool to combat global food crises *("Macdonald Farm Community Engagement Centre / Centre d'engagement communautaire de la ferme Macdonald", 2017)*.

Their request from us was to produce a display that showcased the potential of these modern technologies, and display the current trends in agricultural tech. These trends are heavily shifting towards urban agriculture, controlled environments and automation.

2. Analysis of Parameters and Specifications

2.1 Growth Conditions of Lettuce

Because the Autonomous Controlled Environment Growth Chamber will be growing lettuce, design specifications will be based on ideal growing conditions as specified by the Cornell Hydroponic Lettuce Handbook (Brechner & Both, n.d.) These specifics are ideal growing conditions for butterhead lettuce, shown below in table (*Lactuca sativa L.*) 2.1:

Air Temperature	Day: 24°C Night: 19°C
Water Temperature	Maximum 25°C, cool at 26°C, heat at 24°C
Relative Humidity	Minimum: 50%, Maximum: 70%
Carbon Dioxide	1500 ppm if light available, ~390 ppm if not
Dissolved Oxygen	7 mg/L or ppm, crop failure if less than 3 ppm
pH	5.6 – 6.0
Electrical Conductivity	1150-1250 µS/cm above source water

Table 2.1 Ideal growth conditions of butterhead lettuce

From Brechner & Both (n.d.), the timeline from germination to harvest should proceed as follows:

Germination: Day 0 – Day 11

Growing period: Day 11 – Day 35

Harvest: Day 35

2.1.1 Ideal Germination Conditions

I. Day 0: Sowing; Seeds should be placed in moistened substrate, and placed in germination area, with low lighting to prevent seeds from drying, high relative humidity (RH) and 20°C environment.

II. Day 1: Nutrient solution added to substrate, and electrical conductivity maintained at 1200 µS/cm above source water electrical conductivity. pH should be adjusted to 5.8. Temperature raised to 25°C, and lighting increased, keeping soil saturated through to day 6.

III. Day 2: Decrease humidity slightly to 50-70%

IV. Day 6: Watering frequency increases

V. Day 11: Germination complete, growing period begins

(Brechner & Both, n.d.)

2.1.2 Roxy Organic Lettuce

The Autonomous Controlled Environment Growth Chamber will grow crops from organic Roxy lettuce seeds (*Lactuca sativa L.)*, otherwise known as red butterhead lettuce. Red butterhead lettuce is particularly resistant to tip burn –a breakdown of leaf edges– and to downy mildew –a disease causing leaf yellowing or greying (Australian Department of Economic Development, 2017; Scheufele, 2017; West Coast Seeds, n.d.).

2.2 Radiation

Radiation is the primary energy source for photosynthetic processes in plants. Radiation intensity, wavelength, and duration of exposure are all factors which affect plant growth and health, primarily through facilitating photosynthesis. The range of wavelengths best suited to support photosynthetic processes in plants is called photosynthetically-active radiation (PAR), which ranges between 400 and 700 nm, as shown in Figure 2.1 (Pierson et al., 2008).

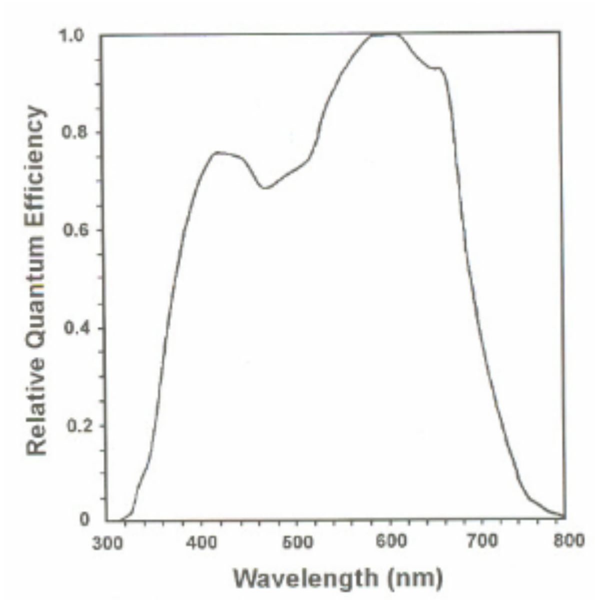

Figure 2.1 Normalized relative photosynthetic response action for photons as a function of wavelength. Reprinted from Radiation *(p. 4) by Sager, J.C., & McFarlane, J. C. Ames, Iowa: NCR-101 Regional Committee on Controlled Environment Technology and Use.*

Plants' photosynthetic radiation requirements within the PAR range depend largely on their carbon photosynthetic systems, such as C_3, C_4, and CAM. Because lettuce is a C_3 plant, the radiation sufficient to saturate its carbon photosynthetic systems is about 400 µmol/m^2·s, for 16 hours exposure per day (Sage and Zhu, 2011, Sager & McFarlane, 1997). High-irradiance plants require higher intensity radiation exposure; C_4 carbon capture photosynthetic systems require at least 500 µmol/m^2·s, for 8 hours exposure per day. However, lower-irradiance plants –such as lettuce– exposed to the same conditions will cause water loss and potentially necrosis (Sager & McFarlane, 1997). Too low irradiance within a growth chamber containing lettuce will lead to smaller biomass production, and reduced concentration of chlorophyll (Fu et al., 2012).

Growth chambers can include a wide-variety of light sources, though the most commonly-used in modern, conventional chambers are light-emitting diodes (LEDs). This is because the spectral output of LEDs can be limited to a narrow range of wavelengths which are useful to photosynthesis, as well as significant energy efficiency and temperature benefits (Martineau et al., 2012). Without the inclusion of a large spectrum of other wavelengths, growth chambers can maximize photosynthetic reactions, while reducing the energy consumption and heat emission when compared to powering broad-spectrum lights (Massa et al., 2008). Hoenecke et al., (1992) found that specifically, blue LEDs in combination with red LEDs could suppress lettuce hypocotyl (stem) growth while maximizing lettuce photosynthetic activity, thus producing lettuce which was full in shape and had high biomass content, without “leggy-ness.”

For this reason, the Autonomous Controlled Environment Growth Chamber should contain LED lights on the red/blue spectrum, capable of delivering the equivalent of 400 $\mu mol/m^2 \cdot s$, for 16 hours exposure per day.

2.2.1 Measuring and Reporting

ICCEG guidelines state that radiation should be measured at uniform height, at the level of the plant container, at the start of the experiment, and every four weeks. Mean PAR ($\mu mol/m^2 \cdot s$) and standard deviation should be reported, along with LED specifications (ICCEG, 2008).

2.2.2 Controlling

Controlling LED cycles is done through switching on and off the power supply according to day/night cycles, which can be controlled via a timer or microcomputer system attached to the controlled environment. To change LED intensity, electric current flow can be manipulated, causing the lights to dim or brighten relative to the current available.

2.3 Temperature

The growth chamber requires that all heat produced internally is dissipated, and all heat lost is replenished. A steady-state growth chamber will have a temperature which is maintained to ensure quality, consistent growth throughout. To achieve this, it is necessary to understand all factors of heat transfer within the environment, and balance the relationships such that steady-state conditions are satisfied. From Hicklenton & Heins (1997), the heat balance equation in a growth chamber at equilibrium is as follows:

$$E_s = E_l + E_R + E_C + E_L + E_M$$

Where: E_s = Energy stored within the plant. Under steady-state conditions, $E_s = 0$.

E_l = Total radiation absorbed

E_R = Re-radiated long-wave radiation

E_C = Conduction and convection

E_L = Latent heat transfer (evaporation or condensation of water at leaf surface)

E_M = Balance of heat produced (+) and heat consumed (-) in metabolic reactions

I. *Heat Balance* - E_M is generally considered insignificant, considering the energy used in photosynthesis generally contributes to less than 3% of the total energy budget (Hicklenton & Heins, 1997).

II. *Radiation Heat Transfer* - In growth chambers which use HID (high intensity discharge), incandescent, or fluorescent lights, an additional layer of glass or plastic is needed between the light source and the plant, to reduce the thermal load given to the plants via additional radiation (E_I and E_R). Because the Autonomous Controlled Environment Growth Chamber uses LEDs as a radiation source, this additional layer is unnecessary; The heat generated by the small amount of excess radiation emitted can easily be mitigated by a forced convection system, as discussed further in this section (Hicklenton & Heins, 1997).

III. *Conduction and Convection* - In addition to radiation, energy moves back and forth from the plant and its environment through both conductive and convective heat transfer. Heat is dissipated from leaf surfaces back to the environment, and, in the case of an environment which is warmer, concentrated from the environment onto the leaf surface. Although there is no uniform heat transfer coefficient between lettuce leaf surface and the surrounding environment, existing research shows that the thermal emissivity of leaves via their surface area is limited. This is primarily due to the fact that air has a low thermal conductivity (Rasche, 1960, Hicklenton & Heins, 1997). This means that lettuce in stagnant air will have extremely limited conductive heat transfer.

IV. *Forced Convection* - This heat transfer, specifically dissipation of heat from the lettuce, can be improved upon by forced convection. While convection happens naturally within controlled environments due to density gradients, forced convection is an efficient way to promote increased heat transfer interactions between the leaf and its environment (Hicklenton & Heins, 1997). A method to introduce forced convection is through low-velocity fans to facilitate air movement within the chamber. By doing this, E_c can be adapted to cancel out E_I , and E_R, and regulate the effects of E_L, as discussed further in this section.

V. *Latent Heat Transfer* - Latent heat transfer, E_L, occurs as water evaporates from the surface of a plant, due to evapotranspiration. As water is evaporated, the plant's surface cools, allowing for some self-regulation of temperature. The heat transferred between the leaf and its environment during this interaction is dependent primarily on the vapor pressure of the surrounding air, directly related to the difference in leaf/air temperature: the greater the variance in temperature, the more latent heat transfer (Hicklenton & Heins, 1997). Thus, to reduce the effects of E_L on the steady-state of the environment, measures must be taken to improve transfer between air and leaves, and reduce transfer which creates large temperature gradients. The largest of these measures is by using light sources which limit excess radiation to leaf surfaces, as discussed previously. By using LEDs, the Autonomous Controlled Environment Growth Chamber will limit the amount of radiation heat transfer available to leaves, ensuring convection and conduction are the primary methods through which heat is added and dissipated.

2.3.1 Measuring and Reporting

According to the ICCEC, temperature should be recorded from at least one location at canopy height, and liquid medium temperature should be recorded, as well. (ICCEC, 2008). To measure the temperature and temperature gradients, thermocouples will be used. These are contact sensors, which are the most commonly used temperature sensor in greenhouses and growth chambers. Thermocouples work using the thermoelectric effect, which is the phenomenon where temperature gradients in metals create an electric flow (Woodford, 2018). Comparing the current in two different metals connected to a "cold end," which is a fixed temperature, and the "hot end," which is exposed to the environment in question, the temperature can be determined (Wilson, 2005).

2.3.2 Controlling

Controlling temperature is done through HVAC systems, which process air through the use of heat exchangers and heaters, which are controlled through computer systems interfacing with temperature sensors.

2.4 Humidity

Humidity in the air is measured with vapor pressure deficit or relative humidity. In regards to growth chambers, a focus will be placed on RH, as it is the value which can be conveniently measured. Relative humidity is a ratio of the actual air vapor pressure compared to the saturation vapour pressure (Hyperphysics, n.d.). RH plays an important role in plant growth, especially in controlled environments, as it influences plants rate of transpiration, as discussed in the previous section. Plants move water and nutrients through their system using transpiration, which happens through holes, the stomata, in the leaves. When the water in the leaves vaporize it creates a pressure deficit, which draws moisture and nutrient from the soil higher up into the plant system (Allen, Pereira, Raes, Smith, 2004). If the humidity in the GC is too high, nutrients will not be delivered to the plant, inhibiting its growth. Transpiration increases the humidity in the growth chamber, so there will be greater fluctuations during light - high growth - periods, compared to dark time. The ideal RH in the GC is about 50%,and should never exceed 70% (Brechner, Both, n.d.). At humidity levels about 50%, there is higher risk of microorganism growth, including mold and bacteria ("Relative Humidity and Your Home - Therma-Stor, LLC", 2018).

2.4.1 Measuring and Reporting

The standards put forward by the ICCEC on measuring atmospheric moisture suggests measuring the relative humidity daily, especially one hour after transitions between light and dark periods. Readings will be taken from canopy height, within the sensor box. This is placed away from any fresh air inlets to get as true of a reading as possible. Capacitive RH sensors work by measuring the dielectric constant of the air, which is strongly correlated with RH (Wilson, 2005).

2.4.2 Controlling

RH is especially hard to control in small spaces, as it is closely linked to the temperature and can form sinusoidal patterns in their variation (Mark Romer, personal communication, January 31, 2018). Considering the ratio of the total volume of plant growth to the total volume of the controlled environment in growth chambers, there is less concern about increasing humidity, and more focus on decreasing it. To do this the cooling coils in the mixing chamber will condense humidity, which will be collected and drained the stock solution.

2.5 Carbon Dioxide

Generally, plants respond to elevated levels of carbon dioxide by increasing their levels of photosynthesis, and thus increasing biomass production. If the level of carbon dioxide is restricted, plant growth will slow or stop, without many other indicators to warn producers. Generally, carbon dioxide has been neglected for measuring and control in controlled environments has been largely neglected, but due to the small volume of GC it is important to monitor this (Peet, Krizek, 1997). In traditional growth chambers, human interaction with the chamber cause the largest fluctuations, very quickly. This will not cause a problem in the ACE GC system, due to low human intervention.

2.5.1 Measuring and reporting

The ICCEG standards for measuring CO2 in GC state placing sensors at the top of plant canopy. As these guidelines were not set out for vertical systems, so readings will be taken along the face of the canopy. These reading should be taken hourly, and the average of all sensors should be reported. (ICCEG, 2008). Although costs have dropped significantly with advancing technology, carbon dioxide sensors are still very expensive. Most commonly used in growth chambers, non dispersive infrared (NDIR) sensors measure gas constituents using IR rays in a tube ("How Does an NDIR CO2 Sensor Work?", 2012).

2.5.2 Controlling

Most CO2 will be supplied from the fresh air. In chambers with higher CO2 requirements, affecting the plant production rate, then a CO2 emitter can be placed in the top air mixing chamber.

2.6 Airflow

Air movement in a growth chamber influences leaf temperature, gas exchange as well as transpiration and evaporation rates. This affects leaf size, stem growth and yield; growth chambers with low air movement have been found to produce plants with less volume, than those grown outside (Downs, Krizek, 1997). Air movement is essential in maintaining a uniformity in the conditions of the chamber. There are multiple factors to consider, including the velocity, turbulence and direction of movement.

Cooled air should not be directly blown onto plants, as it is dry and cold. To prevent this, there is a mixing chamber above the growth area. Here, air drawn from the outside will mix with air cooled by the condenser and the air being pushed in from the growth environment. This will all then be recirculated into the growth chamber.

2.6.1 Measuring and Reporting

The ICCEG standards, suggest taking air velocity at at least one location at canopy level, in m/s. There are a variety of anemometers available, but it is important to consider that the velocity will not be high, so it needs to maintain sensitivity (Downs, Krizek, 1997).

2.6.2 Controlling

Airflow in growth chambers can be directed up, down or horizontally. Generally, this is done with perforated walls or floors, with air being pushed out to a mixing area behind and is pushed back into the growth area through small holes, to encourage uniform distribution of flow.

2.7 Plant Culture

Light expanded clay aggregates (LECA), also known as Hydroton, is a product made solely of processed clay. The clay is processed in a rotary kiln then expanded using forms. Although this process is energy intensive, a large portion of the production can be done using electrical energy, from renewable sources (LECA, 2011). The production technique should be considered in the acquisition of the product. Due to the bulky nature of the product, it is not good for germination. Although, it could be paired with another production to allow seeds to germinate until the seedlings have become established. Rockwool is a solid growth medium that will not degrade heavily. Although, this product is known to cause lung and skin irritation. The production of rockwool is very energy intensive, although it can be recycled (Olympios, 1993). As Menzies et al., (2005) discovered, rockwool has a lower incidence of fungal colonies than soil substrate, and was found to sanitize quite well. Rockwool is melted rock, which is re-spun into a thread like structure. This is a very energy intensive process, but the recyclability of the product offsets its overall lifecycle impact.

2.8 Fertigate Solution

Fertigation is the process through which fertilizer and irrigation are delivered to plants simultaneously, through hydroponic irrigation systems. Depending on the system, one or two stock solutions tanks can be used. With some formulations of nutrients, precipitates can form, and render nutrients unavailable to plants. All nutrients required for growth will be delivered from the fertigate, so it is essential to ensure all macro and micro nutrients are being provided. Nutrient mixes are available, which are ideal for use in smaller scale systems. For germination, seeds will experience nutrient shock if exposed to fertigate, so initially only water should be used.

2.8.1 Measuring and Reporting

EC meters determine the total dissolved salts by measuring the conductivity of the water, although it does not take into account the exact salts present (Resh, 2003). Some salts conduct electricity more than others, and certain ratios of salt concentrations can help determine the exact salt constituent in the system. The pH of the solution will also be measured, and should fall slightly acidic (6-6.5).

2.8.2 Controlling

In recycling systems, it is easier to design a system with one stock solution, or use a series of injectors. Injectors work by measuring EC and pH of the solution, to determine nutrients present. Whatever the stock if deficient in will be injected into the stock solution. Although, these systems are incredibly costly.

2.9 Sterilization

Removal of organic compounds within the system is important for the reduction of microbial growth and pathogen formation within the system. Within the air, it can be removed from incoming air through the use of a charcoal filter, placed just in front of the intake fan. Any volatile organic compounds present in the system can be neutralized through ozone systems. Microorganisms can lead to total infection of hydroponics systems through infection of root zones. Typical organisms found in infected hydroponics systems include *Fusarium, Verticillium, Pythium,* and *Phytophthora,* which destroy root mass. Elimination of these organisms before infections begins is imperative, as no fungicides exist that can be used within hydroponics systems. Preventative measures are vital in the success of growth of lettuce within a hydroponics system. Other contaminants can affect lettuce growth or affect the overall safety of lettuce, and control of these contaminants through sterilization or cleaning methods is important for proper functioning of a growth chamber.

I. *Ozone* - Ozone generators produce ozone, a strong oxidant which oxidizes other chemicals. These can be implemented as a means for suppressing mould growth and eliminating airborne contaminants through oxidation of spores and particles. There is a risk associated with ozone generators as breathing of ozone gas can cause health compilations. Additionally, some plants are shown to reduce their photosynthetic rate when exposed to elevated levels of ozone.

II. *System Components* - All materials used within the chamber should be made of plastic if possible. Metal fittings in pipework can contribute significantly to toxic amounts of zinc and copper within the nutrient solution. Stainless steel should be the metal of choice in these systems, Plastics such as flexible PVC can be phytotoxic, as such, rigid PVC or ABS is preferred for usage. Vapours of dibutyl phthalate (a phytotoxic plasticizer) were found in glazing strips, plastic liners, and plastic pots, so ensuring the nature of all materials used is important to prevent inhibition of plant growth. Epoxy in paints and sealants can release toxins after they have dried, and should be avoided. Hydrocarbon-based sealants can produce vapours with phytotoxic effects as well.

III. *Algae* - Any surface within a growth chamber can be susceptible to algal growth. Glass, plastic, and metal surfaces all harbor the potential for algal growth, with high humidity levels and condensation offering potential for algal colonies to form. Algal growth can lead to further problems within the growth chamber, such as interference with transmission of light, pathogen growth, and disruption of nutrient delivery to plant roots. Reduction of algal growth can be achieved in several ways. Black plastics can limit transmission and reflection of light to surfaces where algae could possible grow. Reduction of temperature differences on surfaces to prevent condensation will help to prevent algae growth on moist surfaces. Nutrient Stock Solutions should be kept in opaque containers, and all irrigation lines should be opaque dark plastic to prevent growth within the nutrient rich fertigate. Anti-algal solutions can also be added to the feedstock.

IV. *Water filters* - Charcoal water filters have a high affinity for high-molecular weight, hydrophobic compounds. Other filter methods include sub-micron filtration, with 0.2 to 0.4 micrometer pore size, but these filters must be replaced frequently to maintain system efficiency.

V. *Ultraviolet Light Sterilization* - UV light treatments can be used to treat water, neutralizing pathogens through the physical disruption of cells by the ultraviolet wavelengths. UV light with a minimum output of 25 mW cm^2 sec^{-1} reduces counts of bacteria within the fertigate to less than 5% compared to non-treated solutions. Even 4 hours of exposure within a irrigation tank can remove 90% of solution bacterial populations. UV sterilization has been shown to reduce root rot of spinach caused by the *Pythium aphanidermatum* bacteria. UV light can cause iron chlorosis as it deconstructs iron chelate, but this can remediated by using nutrient solutions with slightly elevated iron levels. (Tibbits, 1997)

3. Prototyping and Design Process

3.1 Design Process Overview

3.1.1 Design 2 Course

A. *Securing Funding* - The Design 2 Course began with the idea to create an automatic compost tea maker for hydroponics systems as funding for the ACE Growth Chamber had not yet been approved. Funding requests for the ACE Growth Chamber began in June of 2017 but had not been approved as of September 2017. In October 2017, funding was approved, and the Design 2 course switched to the ACE Growth Chamber in the interest of putting efforts into only one project for the 2017-2018 year. An early sketch of the idea can be seen in figure 3.1.

Fig. 3.1 First Sketch of System

B. *Identification and analysis of subcomponents* - The Design 2 course focused around identification of the subcomponents as seen in figure 3.2. This involved conducting extensive literature review of existing controlled environment systems, and analyzing those which would be most feasible and efficient within the proposed system.

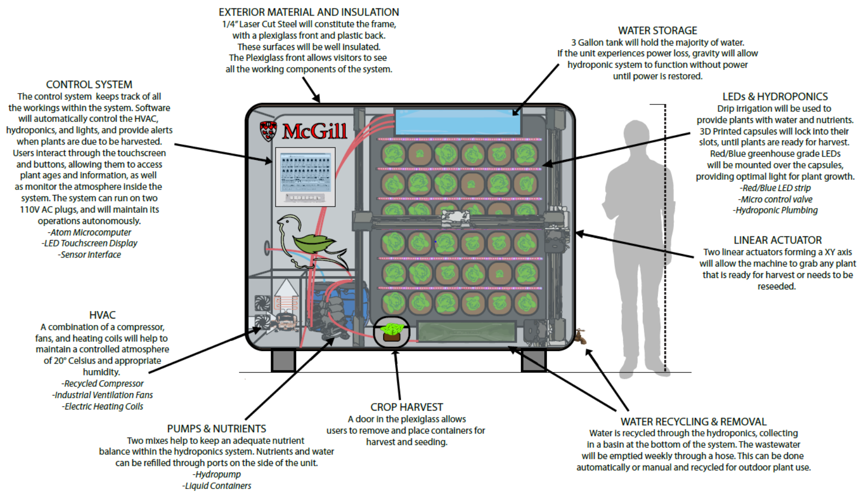

Fig. 3.2 Sketch showing necessary components

C. *Early Sketches* - Early sketches and brainstorms for the layout of the display system were considered. One idea was to have all plants on a rotating vertical conveyor, but this was scrapped in favour of a vending-machine style harvester. Early AutoCAD renderings (figure 3.3) were created to show how the chamber might look, and help with the securing of funding.

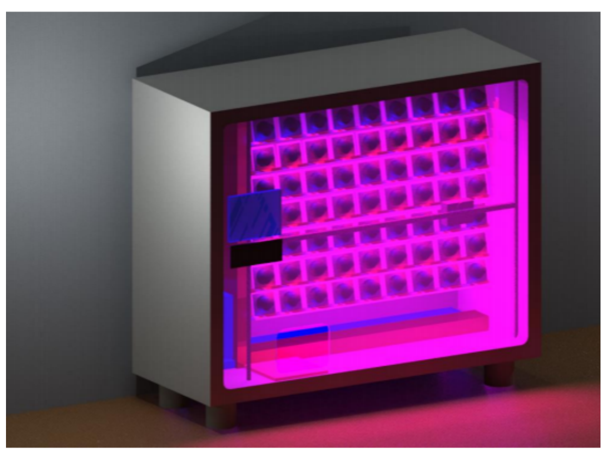

Fig. 3.3 AutoCAD rendering of potential design

3.1.2 Design 3 Course

D. *Design Constraints* - As funding had been approved, the first step to progression with the project was the identification of design constraints and analysis of parameters required for plant growth. The use of NCERA-101 growth chamber handbook played a large role in the designation of the layout and capacity of subsystems, with the team meeting with growth chamber specialist Mark Romer for assistance in beginning the layout process and input on possible challenges.

E. *Solidworks rendering* - The first step was the purchase of a used double-door commercial refrigerator as a frame. The refrigerator had existing insulation, and a working heat exchanger/compressor system. From here, the dimensions were uploaded to solidworks and the integration of the other subcomponents was possible, as seen in figure 3.4.

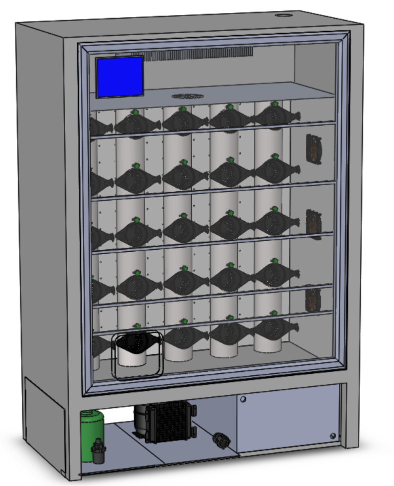

Fig. 3.4 Solidworks Assembly of Final Design

F. *Germination Testing* - Growth of lettuce within hydroponics system requires careful consideration of nutrient levels, light, and environmental control. The initial germination of lettuce seeds is typically done outside of the hydroponics environment, so the design team had to come up with a way to integrate germination of the seeds into the growth chamber. This was done by testing the feasibility of beginning pelleted lettuce seeds in a small rockwool cube, irrigated by a 100% water solution.

G. *Beginning of construction* - As the main frame had been purchased, the design team went about scrapping any unnecessary existing components within the frame as seen in figure 3.5. Purchasing of hydroponics materials such as netcups, seeds, the growth medium, and pumps began, with certain limitations due to the project funding process. LED bars were cut to size, and sheet metal was cut, punched, and bended for the perforated back panel that allows for uniform air flow. Subcomponents were put together outside of the frame to ensure they worked individually. Due to the high cost of this project, time was taken to ensure all design choices were made with consideration for aesthetic properties. Finishing paint coats will be applied once all components have been sized and are ready for final installation.

Fig. 3.5 Growth Chamber in the shop

3.1.3 Summer 2018

H. *Finalization of construction* - Over the course of the 2018 summer, the construction of the growth chamber will be completed as the Design team will be working full time hours on finishing it.

I. *Implementation of coding* - Once construction is complete, the team is challenged with writing and finishing the code that will run on the microcomputer. The team has prior experience with LabVIEW software and sensor interfaces that will ensure the growth chamber is ready for installation in the CEC by September 2018.

4. System Overview

This section will cover the overview of the system, including thorough explanation of processes, materials, and layout of the systems. A solidworks render of the system is seen below in figure 4.1.

Fig. 4.1 Solidworks Rendering of ACE Growth Chamber

Solidworks Rendering of the system with the basic components integrated. Due to the complexity of certain components such as irrigation lines, wires, and pumps, these have been omitted from the rendering. Additionally, several components such as the automatic harvesting arm, sliding harvest door, and various filters, ozone generators, and heaters are not included, as their exact specifications depend on the installation of the hydroponics system for clearance reasons. General locations of components are seen below in figure 4.2.

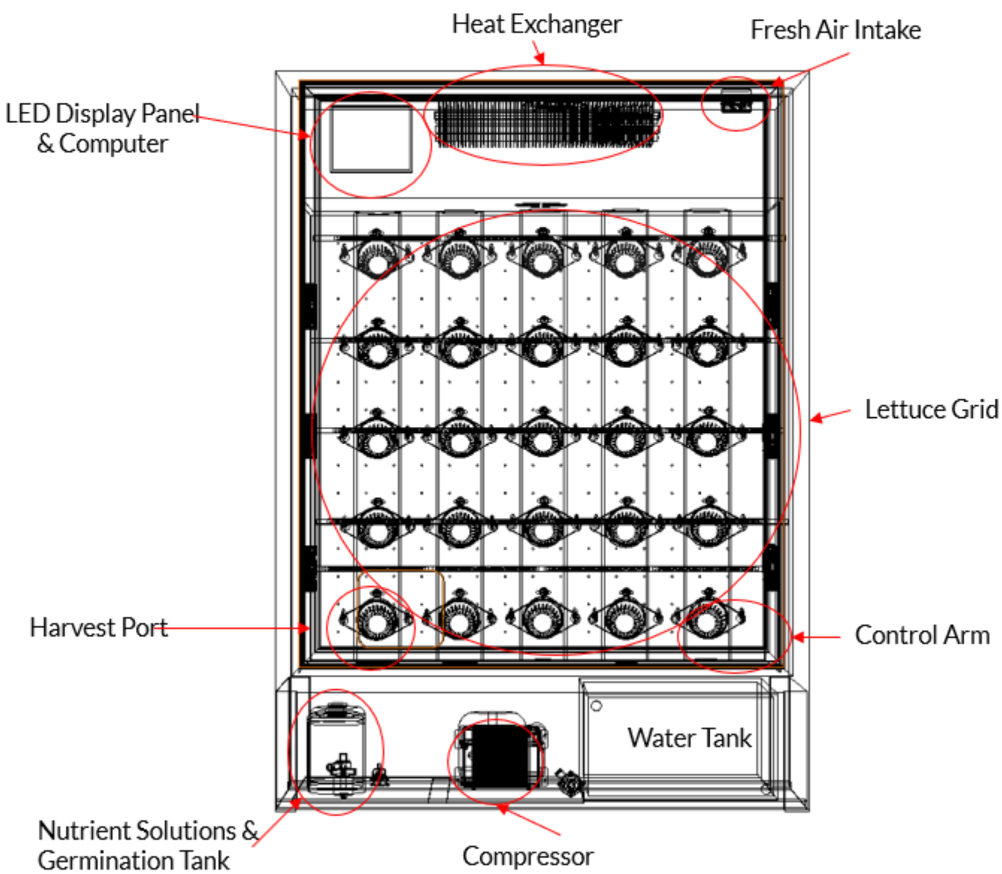

Fig 4.2 Layout of system components

4.1 Electrical Connections

As this is a student project, many limitations are placed on the electrical components due to limited experience with electrical engineering. For this reason, integration of a 220V circuit was not included in the design. Instead, two 110V lines will be plugged into different circuits within the CEC. This reduces the risk of blowing fuses within the CEC from excess power draw on any one circuit. Figure 4.3 shows the electrical connections, detailing how the microcomputer sends signals through a programmable logic controller, to the two power interfaces.

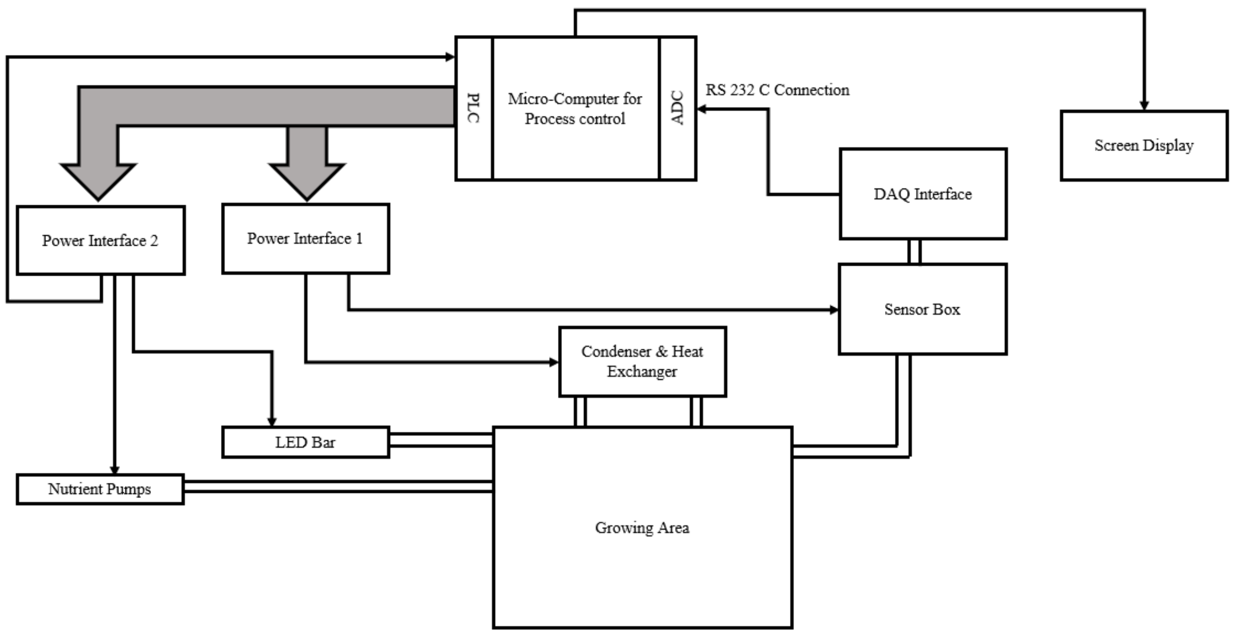

Fig. 4.3 Diagram showing General Electrical Connections

Power Interface 1 will be connected to nutrient pumps, LED bars, and the microcomputer. These systems have low startup power requirements, and are on almost continuously. The second power interface powers the HVAC system, as well as the sensor box. Since the compressor has a high startup draw, all the other components on this circuit were chosen based on their low power requirements. Sensors require very little energy to function, and as such they were included on this system. Additional components such as ozone generators and the screen will be included on Power Interface 1. Connection of the electrical components so that they interface with both the 110V circuit and can be controlled by the microcomputer will be done over the summer of 2018. Figure 4.4 shows the rail used for powering the LED bars.

Fig. 4.4 LED Power Supply Rail

4.2 Lighting

Lighting of the system is done using five 4 ft long LED bars. LEDs were chosen based on their significantly reduced heat generation and low energy use. Whereas typical growth systems use lighting systems based on the principle of creation of an arc in a gas, which generates heat, LEDs produce light through a P-N Junction, as seen in figure 4.5.

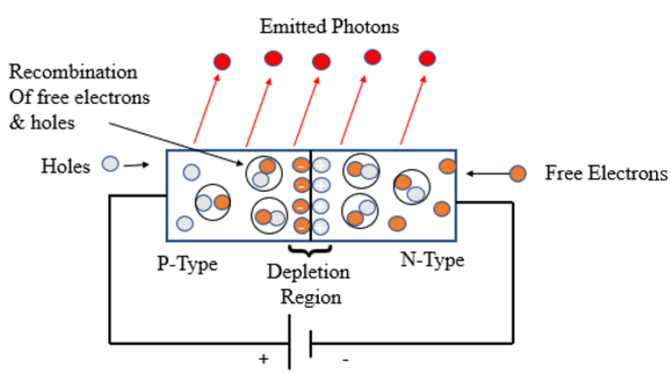

Fig. 4.5 The P-N Junction of an LED

The LED bars are operated as per the following specifications.

I. *Red/Yellow/Blue system*

   A. *LIDLUM PC1202* - The LEDs used in this system are custom made by Lidlum, a light system manufacturer specializing in stadium lighting. They are similar in agronomical effect to 1000W High Pressure Sodium, while using less power and generating less heat. Rather than just having a 5:2 ratio of Red/Blue LEDs, the LED strips use a combination of red, blue, and yellow diodes to achieve a broad spectrum of photosynthetically active radiation. This is done through a 10:5:1 Ratio of red:yellow:blue LEDs, achieving coverage of the most important PAR spectrums. This include infrared and UV radiation. The LED bars used are seen in figure 4.6. LEDs are arranged with 28 Diodes per foot. Calculation of total LEDs in the chamber follows:

1. 28 LEDs/ft x 4 ft x 5 bars = 560 diodes for the 16m^2 growing area.

Fig. 4.6 The 5 LED Bars

B. *Longevity & Efficiency*

1. An advantage of these LED bars is their reliability and efficiency. Lidlum specifications report that even after 100 000 hours of operation, the LEDs will output over 70% of their nominal flux of 550 µmolm^{-2}s^{-1}. The power supply efficiency is rated at more than 92% and the electrical efficiency is stated to be 1.8µmol/watt.

4.3 Support & Insulation

Facilitation of plant growth & environmental control requires the structure to be well insulated and support the system components. A rear view of the chamber frame is shown in figure 4.7.

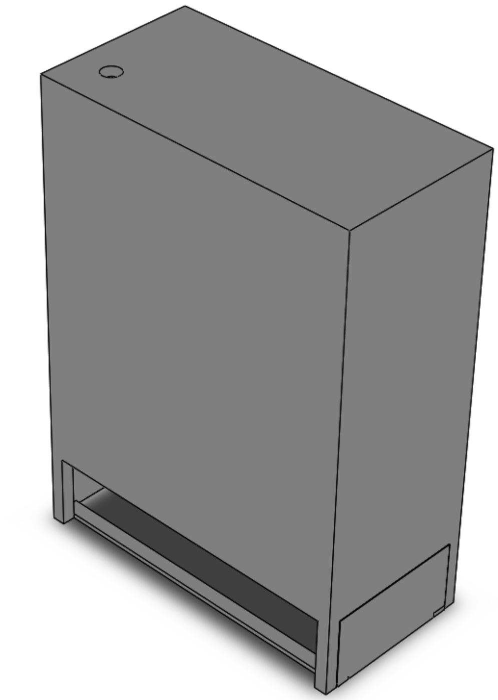

Fig. 4.7 Rear View of Chamber Frame

I. *Frame* - The main structure of the ACE Growth Chamber is a used double door commercial refrigerator. The frame is completely insulated with 1 inch of expanded polyurethane between 18 gauge painted sheet metal throughout, save for the open front face. Stainless steel and painted sheet metal screws and roofing screws are used for fastening all components to the frame assembly.

II. *Display Pane - Polycarbonate (Lexan) Plastic* - The front of the growth chamber consists of a large window for observation of the chamber components. This window must also open up to allow access to the inside of the growth chamber for maintenance. The frame for this display pane is made of mitered and welded square steel tubing, on heavy duty hinges. Two polycarbonate plastic panes on each side of this frame constitute the bulk of the window. A small sliding door on the lower left of the unit allows retrieval of lettuce after harvesting, while maintaining an airtight seal when closed. On the interior side of the polycarbonate panel, transparent Teflon tape which reduces CO_2 and water vapour absorption is applied. When the display pane is closed, a rubber gasket seal prevents any air from leaking.

III.

4.4 HVAC - Controlled Environment

I. *Air Flow* - Air flow within the chamber is crucial for facilitating proper heat transfer from temperature control units, as well as providing plants with stress to give them sturdy tissue structure. Air flow within the chamber also helps to remove heat generated by the LED bars and ensure uniform air temperature throughout the growing area.

   A. The flow into the chamber is through perforated back wall, with the air already in the chamber pulled out through the sides by way of six 120mm fans, forcing air forward through the holes in the perforated wall. This arrangement of small holes allows for uniform airflow across the whole back of the growth area. Refer to Figure 4.8 to see the flow pattern. The top chamber allows for mixing and circulation of outside air with the cooling heat exchanger and resistance heater, with the net positive pressure pushing air into the chamber through the perforated backing.

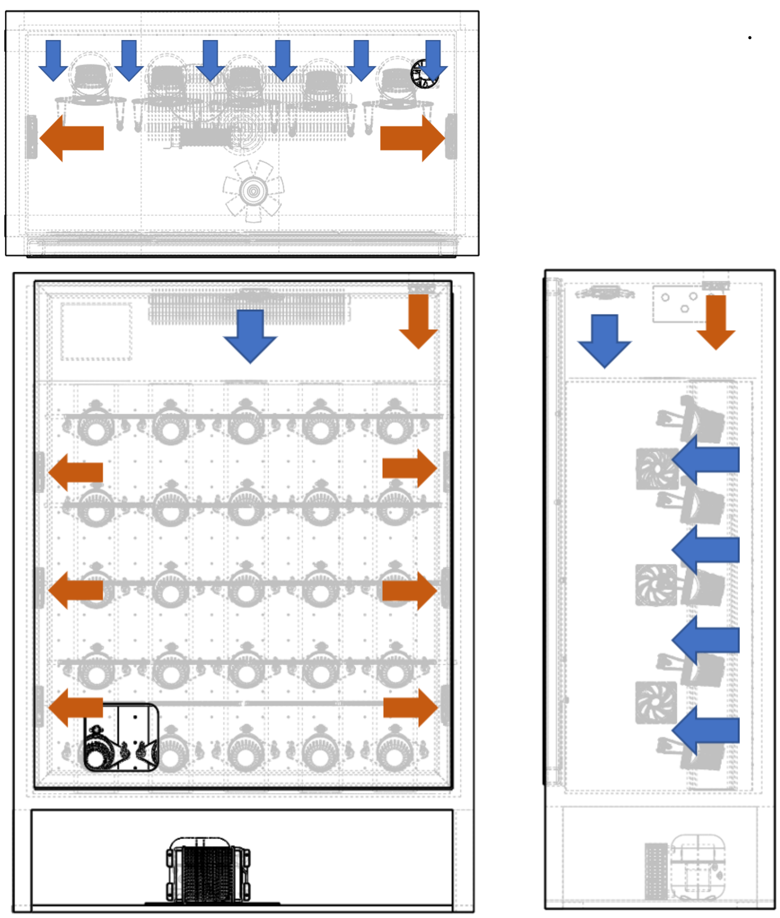

Fig. 4.8 Airflow within the chamber with Orange Arrows (Warmer Air) and Blue Arrows (Cooler Air)

B. The levels of CO_2 will not be controlled in the system, only monitored. After testing, in the event that the system needs additional CO_2, a CO_2 emitter will be added in the mixing space.

II. *Temperature Regulation - See Automation, Temperature, C. Temperature Control*

III. *Humidity regulation*

A. *Sources of Humidity* - Air moisture within the growth chamber can come from 3 sources. Through evapotranspirative processes, the lettuce will naturally emit water vapour through its stomata. Air that is brought into the chamber will have a moisture content that fluctuates with season and depends on the HVAC of the CEC. Passive evaporation of water from drippers and on the growth media will also contribute to buildup of moisture within the growth chamber.

B. *Outside Ariflow*: Outside air will be brought in from the top of the chamber, at a rate of about 15%/hour. The incoming air will be about from the controlled environment of the CEC, which should not be above 50%, and in winter months, should lie between 30-40% ("Relative Humidity and Your Home - Therma-Stor, LLC", 2018). As this is lower humidity levels than the within the chamber, it will lower the humidity level.

1. Calculation of airflow for ACE Growth Chamber :
   48”x 22”x 49” internal air space = 51744 in^3 = 0.848 m^3
   15% recycled air/hour requires external air flow of 0.127 m^3/hr

C. *Condensation on heat exchanger:* Dehumidifying will be done through condensation on the coils in the top of the chamber (Spomet, Tibbits, 1997). When the RH falls outside of the optimal range, the system will begin to blow air across the coils to dehumidity. This will also cause fluctuations in temperatures, which the systems will also address. Condensate from the heat exchanger will drip onto a top panel which is removed from the system through a plastic tubing.

4.5 Growth of Lettuce

This section will walk through the hydroponics system, relative to the growth stages of lettuce. Controlled environment growth of lettuce is optimized for production of 150 gram heads of leaf lettuce (Brechner, Broth, n.d.). The total growth period is typically 35 days under optimal conditions. Germination of the lettuce usually takes 11 days with the rest of the growth happening up until day 35 (Brechner, Both. n.d.). Because the grid system has 25 spaces for lettuce growth and lettuce will be harvested in 35 days, production will be of one head of lettuce per 1.5 day, allowing harvest of alternating 4 or 5 heads every week.

In the instance where a growth port remains empty, the water will be recycled back into the system by a lip at the bottom of the opening, preventing the fertigate to drip onto the plants below.

I. *Germination* - Germination of seeds will be done using pelleted seeds. Bare seeds would require special humidity covers to allow the seeds to properly germinate. Additionally, these pelleted seeds do not require thinning like traditional germination, as the germination rate is much higher (90%). Other germination methods including peat pellets and potting soil do not work in hydroponic environments as they break down and clog pumps, while also contaminating the nutrient solution. Pelleted seeds will then be placed into small cm^3 seed plugs, made out of the inorganic material rockwool. This is placed into the net cup (figure 4.9), filled with soaked expanded clay. Placed properly underneath the drip irrigation spout, the seeds will germinate successfully. As the plant develops, its roots will grow through the growth medium, and upon harvest, the root system will be easily removable from the LECA. Of the 5 hydroponic towers, one is dedicated to germination, running a water-only irrigation in order to prevent nutrient shock to seedlings. Once the plant has germinated, the plant will be automatically moved out of this zone into an empty grid space. If germination is not successful, the user can use the LCD interface to instruct the robotics to remove the cup and replace with another seed.

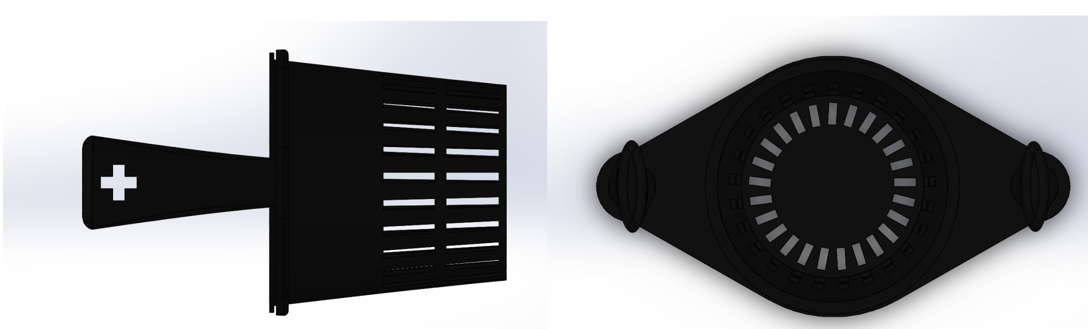

Fig. 4.9 Netcup with attachment for Automated Harvest Retrieval

II. *Seedling to Vegetative Growth*- Once germinated the seedings pot will be moved into an empty space in the grid where it will begin to be irrigated with the nutrient solution. The seedlings can stay in the germination tower a minimum of 7 days, and maximum of 11, as it will need nutrient solution from this point onward to continue growth. This variability allows for flexibility in the schedule of the operator, so the exact day does not have to be met. A large advantage with this system is that seedlings do not have to be physically transplanted, so there will not be any damage done to the young roots of the plants. Within the nutrient-fed PVC towers, the lettuce will undergo vegetative growth until it has reached a vegetable mass of adequate size, dictated by length of time.

III. *Pre-Harvest* - At this point the growth of the head of lettuce will have been in the chamber for 35 days. The LCD interface will prompt the user that the head is ready for harvest, and the user will instruct the machine to do so. This is a time based system, so the prompt will be made on the 35th day the lettuce is in the system.

IV. *Harvest* - Once the user directs the system to remove the net cup, it will be brought to the port, which is accessible by a sliding door. This process is further detailed in the automation section.

V. *Post-harvest* - After the harvest, if a seedling is ready to be moved into the fertilized growth stage it will automatically be moved. The operator must then empty the net cup and rinse the clay pebbles, to remove any remaining roots from the harvested head of lettuce. This will upkeep a high level of sanitation, as it will discourage the growth of microorganisms feeding on the debris. The operator can then input a new rockwool cube and seed, place it in the port and instruct the machine to place it in the germination tower

4.6 Hydroponic System

I. *Pumps* - Hydroponic pumps are sized based on their GPH. For the germination tower, GPH requirement is 9.5 GPH (0.6 L/s), which will be supplied by a 50 GPH pump. For the nutrient solution, the requirement is 40 GPH. A 100 GPH pump will be used to ensure sufficient head through the system. The breakdown of this system is seen in figure 4.10.

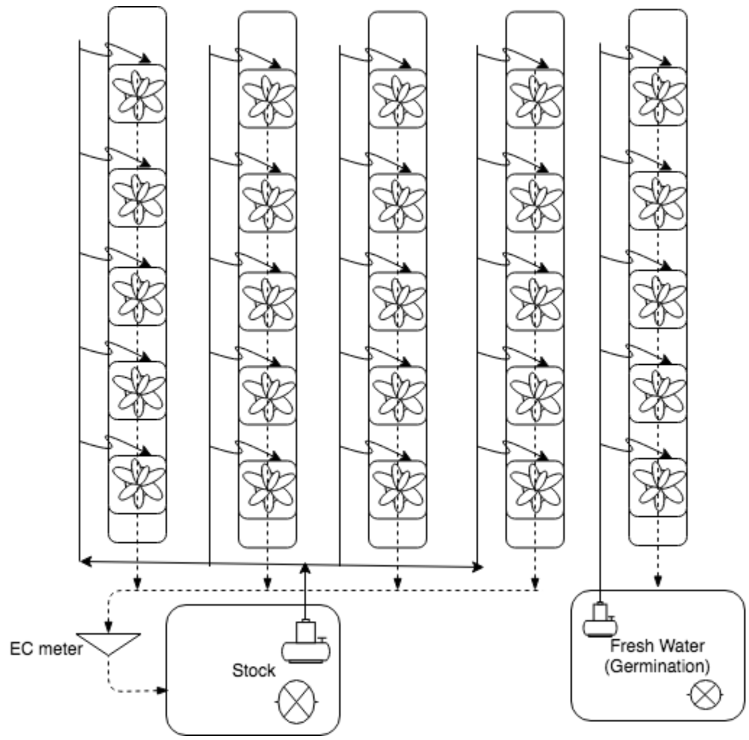

Fig. 4.10 The two loops of the hydroponics system.

II. *Tubing* - Most of the hydroponic delivery system will be be black, flexible polyethylene pipe and PVC micro-tubing, as seen in figure 4.11. This opaque material reduces light transmittance and reduces the risk of algae growth. Half inch black polyethylene pipe delivers water from the pump up the growth towers. Behind each plant an emitter is inserted into the pipe, from which the micro-tubing is connected, which delivers the solution to the plant.

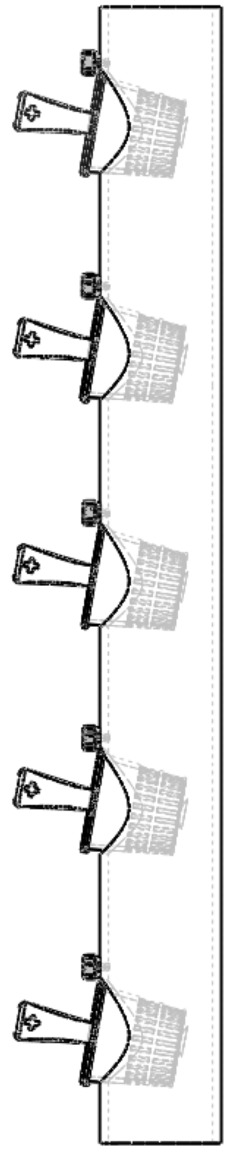

Fig. 4.11 The PVC hydroponics tower. All irrigation lines and drainage lines will run through the PVC, and small plastic catchments will keep liquids from dripping out of the PVC structure

III. *Emitter* - The emitter regulates the flow of water coming from the high pressure line from the pump, to the plants. This regulates the flow rate, which will be 2 L/hour for each plant. Anti-drainback drippers will be used, so the flow to plants resume the moment the line becomes pressurized.

IV. *Recycling* - All of the water which is not taken up by the plants will flow back down the PVC, into tubing on the bottom of the towers and be returned to the tanks.

V. *Sterilization* - Placed in each tank will be an 8 watt UV sterilizer, to kill any possibly harmful microorganisms in the system. As the fertigate is being recycled, it is important to sterilize the fertigate as disease will spread quickly through the system.

VI. *Filtration:* All of the fertigate is pumped through a 20 micron filter before it is sent into the drip irrigation lines. This removes sediment and reduces the risk of the lines plugging. Also, it reduces the risk of algae getting into fertigate lines and overtaking the system ("1 Micron - 10 Micron - 20 Micron - 40 Micron - Water Filters", 2017).

4.7 Automation

4.7.1 Main Control Unit

A. *LabVIEW Software* - LabVIEW is a system-design platform that runs on windows, linux, and mac OS x operating systems. This allows it to be installed on a small touchscreen microcomputer which is the centerpiece of the control system. LabVIEW is specially developed as a data acquisition software, with a customizable “front panel” graphic user interface that is easy to work with. No special syntax must be learnt as the coding is done by connecting different components with links and using various loops to create a functioning instrumentation and control platform. The labVIEW software also natively incorporates clock-based loops and offers a wide range of data acquisition types, expanding the available sensors (National instruments, 2017).

B. *Grid System & Time based events* - The code runs various systems at a time with nearly all operating on time based systems, as will be discussed in their respective sections. A simplified diagram of the code processes can be seen in figure 4.12.

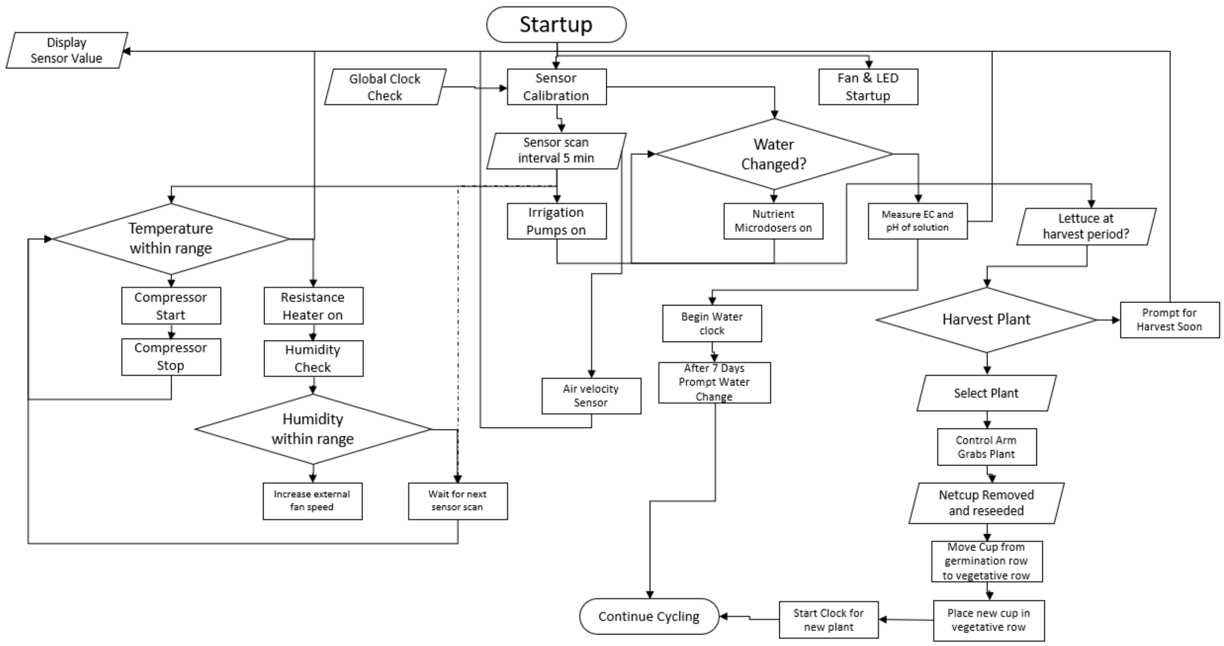

Fig. 4.12 Flow-chart showing the basic layout the code will follow

4.7.2 Temperature

C. *Sensors*

1. *Temperature Sensor* - Analog temperature sensors provide a voltage reading correlating to the temperature of the sensor. Calibrations are often required with sensors or they come with scale factors such as 10mV/degrees Celsius which must be incorporated into the software to provide accurate feedback (Marhaenanto, 2001). These sensors use a thermocouple which uses two electrical conductors that form electrical pathways at different temperatures (Qiang, 2013). The air temperature sensor located in the sensor box reports voltage to the DAQ interface. This value is recorded continuously for the purpose of environmental parameter display.

2. *Air Speed Sensor* - The air speed sensor within the ACE growth chamber works on the principle of a small fan that is turned by air movement. Turning of the fan induces an electric charge which is sent as a voltage to the DAQ interface. This measurement is calibrated in the LabVIEW software and reported to the display screen. Since air speed is not of great

importance for the growth of lettuce, it is reported purely for educational purposes. It is located near the light sensor, away from the sensor box so as not to be affected by the sensor box fan.

D. *Airflow effect on Temperature* - The amount of air brought in from outside will affect the temperature regulation of the growth chamber. Too much airflow will place a strain on the compressor that will cause it to burn out prematurely. When the chamber is operational, testing will show whether air flow needs to be reduced in order to reduce load on the condenser. However, because the chamber temperature will be similar to ambient external temperatures, the temperature difference between the growth chamber and CEC interior should not be too large in that it causes problems. Airflow within the chamber affects the chamber as well, having a convection effect over the LED bars, which will be producing light.

E. *Temperature Control* - Temperature is regulated automatically through the condenser and resistance heaters. When a temperature decrease is required, R134a coolant in the refrigerant lines is compressed in its gas state to a higher pressure in the compressor. It flows into the external heat exchanger where it meets external air temperatures and changes into a liquid. In the liquid form at high pressure, it flows into the heat exchanger at the top of the growth chamber, where it absorbs heat from inside the chamber, cooling down the air. The R134a finally evaporates into a gas, and the cycle begins again. This cooling process is used for changes of 1 degree or more. A small resistance heater in the air mixing chamber is used for fine tuning of the air temperature. The small addition of heat helps bring the temperature up to the desired value. This is all done through the LabVIEW software, with processes turning the condenser on for a time period corresponding to the desired temperature change.

4.7.3 Humidity

F. *Humidity Sensor* - Humidity sensors use capacitive measurements to determine the amount of moisture in the air. The change in voltage caused by moisture in the air between two conductors causes a capacitive change in voltage that is converted into a digital measurement. These sensors are quite small and usually operate within a margin of error of 3% (Qiang, 2013). In the ACE growth chamber, the humidity sensor is located in the sensor box, where humidity levels are reported continuously through the DAQ interface.

G. *Airflow Regulation* - If humidity levels exceed the maximum accepted value, the fan which draws outside air will increase its speed, drawing more drier air in from outside. Additionally, the temperature can be lowered, forcing moisture out of the air, and then increased again, to reduce the moisture content of the air.

4.7.4 Radiation

H. *LED Operation* - As per the growth requirements of lettuce, the LED system operates within LabView on a global clock system, turning on at 6h00 every day and turning off at 22h00 every day.

I. *Radiation/PAR sensor* - The radiation sensor is located at the top of the plant canopy to obtain the minimum and maximum radiation levels over the plant growing area. This sensor measures the flux produced by the LED system. This value is reported through the DAQ interface to the display screen, but is included only for educational purposes.

4.7.5 Fertigate

J. *Dissolved Oxygen Sensor* - This sensor is used to determine the current amount of dissolved oxygen in the nutrient solution. This is an important value to measure as hydroponics systems require a certain degree of aeration to properly deliver nutrients to the plant. These sensors are more expensive than others and require special interfaces and software (Qiang, 2013. Marhaenanto, 2001). The need for this sensor in the preliminary tests of plant growth will be evaluated. Between the pumps cycling water from the bottom to the top and the drip irrigation, water will be sufficiently aerated to reach desired dissolved oxygen levels for the plants. This value is reported only for educational purposes, as the design has no mechanism for adding additional dissolved oxygen to the nutrient solution.

K. *pH Sensor* - This sensor measures the hydrogen ion concentration within the nutrient solution. With a range from 3.0 to 10.0pH units, its value is reported through the DAQ interface where it corresponds with a LabVIEW loop. This measurement is taken daily, and a microdoser system adds pH up or pH down solution to meet the desired value of 6.4pH. Microdosers are connected through the control interface, and are calibrated to add an amount pH down or up corresponding to the desired value.

L. *EC Sensor* - The EC sensor measures the electrical conductivity of the nutrient solution, or the ion concentration corresponding to the available nutrients for plants. Since water is changed weekly however, it is not preferable to continuously add nutrients to the solution based on EC value. As such, the LabVIEW code is programmed so that when water is changed, the operator can press a button, and the code will cause a microdoser to automatically add a fixed amount of nutrient solution to the tank, This EC sensor just reports the value for educational and informative purposes, with a range of 1 to 10^{-2}mS m^{-1}.

4.7.6 Harvest

M. *Growth* - In order for the system to harvest the lettuce when it is ready, it must know how long the lettuce has been growing for. This is achieved through the LabVIEW software through the grid system. When a plant is placed is placed into the germination tower, the code logs it as a new plant, logging how many days it has been in the system. Once the plant is transferred to a nutrient tower, the code continues to update with how many days it has been in the chamber. Once a plant has reached its harvest date, it will create an alert on the Graphic User Interface, indicating a plant is ready for harvest. The user then presses the corresponding button on the interface, and the plant retrieval begins.

N. *Plant Retrieval* - This system uses the grid-layout of the hydroponics system to retrieve lettuce plants and bring them to the harvesting door. This system operates in a similar fashion to a vending machine, with the addition of a Z direction which reaches forward to grab the lettuce. 3D printed netcup attachments have special arms that stick out with cross shaped holes. These cross shaped holes will allow the harvesting grabber to interlock with the netcup and prevent the lettuce from swinging down. Once the arm has picked up a netcup with lettuce, it will pull it out of the PVC tower, rotate it upright, and bring it down to the harvest door. This is made possible through the combination of stepper motors, which can keep track of their positioning, allowing for coding of specific arm positions which correlate to each location within the grid. The harvesting grabber sits on a X-Y axis actuator system, in which stepper motors turn a timing belt, that moves the arm in the corresponding direction. Harvest is controlled through the touchscreen, as a human must instruct the chamber to perform harvesting when a lettuce is ready, to prevent accumulation of multiple lettuce plants in the harvest door if someone failed to collect them.

4.7.7 Instrument Precision and Measurement Accuracy

All sensors are placed within a box, near canopy height, excluding of course any light sensor. This box has a small fan on the bottom, blowing air across the sensors, to ensure a true reading of the environment. Sensors will run through a data acquisition interface (DAQ) before being processed by the

O. The sensors precision and accuracy can be expected to have values as presented in Table 4.1, adapted from the Growth Chamber Handbook (Krizek et al., 1997):

Parameter	**Instrument Precision**	**Measurement Accuracy of Reading**
Radiation Flux	±1%	±10%
Air Temperature	±0.1℃	±0.2℃
Relative Humidity	±2%	±5%
Air Velocity	±2%	±5%
pH (H+ Concentration)	±0.1 pH	±0.1pH
Electrical Conductivity	±5%	±5%

Table 4.1 Sensor precision and accuracy

P. *Reporting of Parameters:* Sensor reporting to both the display panel and for corresponding feedback is done based on the suggested NCERA-101 guidelines.

This table adapted from the Growth Chamber Handbook (Krizek et al., 1997) indicates the frequency of measurement collection and reporting, as well as the location of measurement.

Parameter	**Units**	**Measurement Location**	**Measurement Period**	**Reporting Format**
Radiation Photon Flux	$\mu molm^{-2}s^{-1}$ (λ_1-λ_2)	At top of plant canopy	Daily	Weekly average (± extremes)
Air Temperature (Shielded and Aspirated)	℃	Within sensor box and throughout growing area	Continuous Measurement	Real time measurements + Hourly Average
Atmospheric Moisture	%RH	Within sensor box	Continuous Measurement	Real time measurements + Hourly Average
Air Velocity	$m\ s^{-1}$	At top of plant canopy	Continuous Measurement	Real time measurement
Carbon Dioxide (mole fraction)	$\mu mol\ mol^{-1}$	Within sensor box	Continuous Measurement	Real time measurement
Watering	liter (L)		At times of water application	Frequency of watering
Electrical Conductivity	$mS\ m^{-1}$	In saturated nutrient solution	Daily	Daily value
pH	pH units	In saturated nutrient solution	Daily	Daily Value

Table 4.2 NCERA-101 Sensor measurement units and reporting

4.8 Safety

As with all engineered systems, it is crucial to consider the health and safety risks associated with the design.

I. *Eye damage from radiation* - Light output from the LEDS has the potential to cause irreparable eye damage. Our system uses high power LEDs, which emit light in the visible spectrum of 380-780 nm at an intensity which can create eye lesions. Because LEDs have such a small emitting surface, the flux is more concentrated in the viewing direction, creating a higher luminance. As a result, the processing of this bright light by the retina can lead to macular degeneration cataracts, pterygium, pinguecula, photokeratitis, climatic droplet keratopathy, or even skin cancer. UV-A, UV-B, and UV-C radiation are all emitted from LED sources, so proper eye protection is important. To reduce the risk of causing eye damage to both CEC staff and visitors, the amount of reflective surfaces within the growth chamber is minimised, with all surfaces being either non-reflective or covered with a semi-gloss spray. Additionally, the growth chamber should be placed in the CEC so that no one person is subjected to prolonged exposure to its light.

II. *Electrocution* - The combination of hydroponics systems which deal with water flow, and the high power nature of both LED systems and temperature regulation systems presents the possibility of electric shock. Leaks from hydroponic lines could infiltrate the sensitive electronics present at the bottom of the system, potentially shorting the system. Spills should be treated with caution, and all electronic components have plastic covers that will direct water around them, instead of into them. All wires have heat-shrink coverings, so that all metal wires are properly insulated and grounded.

III. *Toxins* - Any of the sealants, sprays, or paints used in the fabrication of the growth chamber pose a risk to the health quality of the lettuce produced. Fumes from the drying of paint and seals could leave toxic residue on plant tissue, which could cause illness in anyone who consumes a substantial amount of lettuce from the system. In order to reduce the risk of chemical contamination, all surfaces and seals are allowed to cure for up to 2 months, and as many non-toxic and non-volatile types of sealants are used to reduce the total amount of chemical toxins used in the fabrication of the growth chamber.

IV. *Biological Contamination* - The source of the water used for the nutrient solution is important for the overall health of the system. If water is used that may be contaminated with bacteria, the bacteria colony could grow and elevate to levels where human health is at risk. Thermotolerant coliforms are especially risky, with bacteria such as E. Coli being found in waters. This can be avoided by ensuring all water is taken from approved taps connected to treated city mains, and that all hoses used in the filling and emptying of water tanks is food grade.

V. *Sharp Edges* - As this design has metal construction, fabricated sheet metal and metal fasteners pose a risk to anyone doing maintenance on the growth chamber. Cut sheet metal has sharp edges that can easily lacerate human skin, and the roofing screws used in the fastening of components can stick out, leaving sharp edges that a person could injure themselves on. This hazard is mitigated by cutting back of any exposed metal parts, and covering sharp edges with teflon tape. Anyone working on the machine should wear gloves and exercise caution.

VI. *Tipping* - Major concerns come from the size and weight of the unit when transporting the unit. Tipping of the unit could crush body parts, as such it is advised that two or more workers use proper movement techniques when transporting the growth chamber throughout the location.

VII. *Slipping* - Leaks in the system could wet floors leaving passerbyers prone to slipping. Any spills or leaks should be immediately addressed, with proper signage over spills to reduce the risk of people slipping and falling.

4.9 Cost and Economic Considerations

Economic factors of the Autonomous Controlled Environment Growth Chamber are shown in Table 4.3 below. Detailed calculations of these costs are given in Appendix 2.

Total cost to date	$785.44
Estimated cost to completion	$9,000.00
Total estimated cost	$9,785.24
Cost of operation (per year)	$318.24
Payback period (years)	25.50
Cost per head during payback period	$2.99
Cost per head after payback period	$1.36

Table 4.3: Economic considerations of the Autonomous Controlled Environment Growth Chamber

If the price of lettuce per head in the greater Montreal area is assumed to be $3.00, the payback period for the ACEGC is 25.50 years. After the payback period is over, the cost of production per head of lettuce is estimated to drop to $1.36/head. Because of this, the chamber at its estimated development and operation cost is not only feasible from a design perspective, but has limited financial incentive as well, given the assumption that materials will last throughout the calculated payback period. It should be considered that economies of scale would apply to this system in the case of scaling up.

4.9.1 Additional Economic Considerations

The application of the Autonomous Controlled Environment Growth Chamber has much potential from an educational perspective, but could be applied on a larger scale given that it is economically viable. Smart Greens is a company which uses LEDs and hydroponics to grow plants in storage containers for areas in northern Canada that cannot support growth of fresh produce outdoors. Eric Bergeron, owner of Smart Greens, estimates that even without the automation of Smart Green's indoor farms, indoor vertical farming technologies can save as much as $600,000 per year when compared to conventional small greenhouse farming techniques (Kelly, 2016). As manufacturing costs decrease, this is a market well-suited for the Autonomous Controlled Environment Growth Chamber.

4.10 Environmental Considerations

The ACEGC has many components which are environmentally beneficial, including significantly lower resource allocation per head of lettuce produced than conventional methods, reduced energy consumption when compared to growth chambers using incandescent or high intensity discharge (HID) bulbs, and reduced use of fossil fuels in the transportation of produce.

I. *Resource allocation* - Currently, approximately 38.6% of suitable land and 70% of drawn freshwater is used for agriculture worldwide. As the world's population grows and food demands increase, there is a need for increased biomass production with a decrease in resource use. In arid areas such as Arizona, up to 69% of freshwater reserves can be devoted to agriculture alone. Studies on resource reduction through hydroponics have found that in arid areas like these, yield of hydroponic lettuce can be up to 11 times greater per area, when compared to conventional farming. Additionally, hydroponics can comparatively reduce water consumption by up to 1300% (Barbosa et al., 2015). Implementation of the ACEGC for environmental purposes could have a significant effect on resource mitigation. There are, however, some drawbacks to implementing the ACEGC on a wider-scale.

II. *Energy consumption* - Detailed calculations for energy consumption are presented in Appendix 2. The energy required to operate the ACEGC for one year is estimated to be 3401.35 kWh/year, which is about a third of the total energy that an average American consumes in a year (U.S. Energy Information Administration, 2017). The prototype, which will remain in Montreal, will have power supplied by Hydro-Québec. This power is from hydroelectric dams, and does not have the direct negative environmental effects that other sources of energy, such as coal, oil, or natural gas, do. The extremely large energy consumption, however, would have a significant negative environmental impact if the chamber was moved somewhere which relied on less sustainable energy production methods.

III. *Transportation* - One environmental benefit provided by the ACEGC is the reduction in fossil fuel usage as the need for transported lettuce decreases with production. Because the ACEGC is only one unit producing 234 heads of lettuce per year, this reduction will be small, but may help offset a fraction of the energy consumption required, particularly in areas with non-sustainable power sources.

IV. *R134a* - R134a is a halogenated refrigerant that contains chlorine and fluorine atoms, whose emissions contribute greatly to atmospheric quality deterioration. R134a emissions increase greenhouse gases that contribute to climate change and global temperature rise, as well as ozone depletion (Mohanraj et al., 2009). One way to reduce the harmful impacts of refrigerants would be to substitute R134a for a more environmentally-friendly alternative. Mohanraj et al. (2009) concluded that R152a is an adequate substitute with less damaging effects. For ACEGC development in the future, alternatives like this could be used to improve overall environmental impact.

V. *Recycling* - The system aims to recycle as much as possible. The growth medium can be repeatedly recycled, only being replaced once annually. The hydroponic system is semi open, so the system will only be flushed once every 7 to 10 days.

4.11 Social and Ergonomic Considerations

Because the focus of the ACEGC prototype is for educational purposes in the Macdonald Farm Community Engagement Center, the primary focus of the chamber should be ease of access and friendly user interface. The LCD panel used to control the growth chamber should be easy to understand and easy to operate, without extensive knowledge of lettuce growing conditions or training on ACEGC operation. To achieve this, a focus will be placed on perfecting a simple and easy-to-use user-interface (UI). Additionally, because the chamber will be operated primarily by untrained or partially trained users, the ACEGC should be easy to troubleshoot, and relatively easy to fix basic problems. A focus in this design has been placed on reducing potential complexities and ensuring simplicity and durability.

A key component of controlled environment growth chambers is their ability to bring fresh produce to communities of people which may not otherwise have access to locally-grown vegetables. The ACEGC has potential in broad applications as a community staple in areas such as the Northern Territories, or Antarctic research stations. These applications further place an importance on ease of use and access, and show that there is indeed a market for *autonomous* growth chambers which require no human labor or training to operate.

4.12 Chamber Specifications per NCERA-101 Standards

As per NCERA-101 standards, reporting of growth chamber specifications should be reported in a manner that defines the parameters and capabilities in a standard fashion. That method is seen below:

I. Requirements

The growth of lettuce at the Macdonald Campus Farm Community Engagement Centre requires a well maintained and consistent controlled environment for the display of the physiological growth of the horticultural crop; lettuce. For the proposed growth, accurate and consistent control of light intensity, day length, temperature, relative humidity, carbon dioxide, nutrient application, irrigation, and airflow is needed, according to the requirements for lettuce growth. For purposes of definition, the words “growth chamber” will mean the total system, and the words “growing area” will mean the 0.848m^3 volume within the growth chamber where plants are grown. “Growth height” is the maximum distance between the light bars near the display window and the netcup - PVC assembly in which the lettuce is grown.

II. *Physical Construction*

Materials - Because the growth chamber is subjected to high humidities, it is constructed of rustproof materials such as aluminum, stainless and coated steels, and plastic.

Size - The growth chamber must not be too large, given its installation within the Community Engagement Centre, and thus must be sized appropriately. The growth chamber has the specified dimensions: Width: 1.375m, Depth: 0.687m, Height: 1.905m

Interior and Exterior Finish - The exterior is finished with semi-gloss white paint. An infographic panel with information on the exhibit is located at the top of the front of the growth chamber. The interior is finished with non-toxic semi-gloss white spray paint on all non-plastic surfaces. These finishes will not degrade after years of service, and will offer uniform reflectability of light.

Insulation - Expanded polyurethane insulation is used for thermal resistance between the growth chamber interior and the external temperatures. The insulation properties are not crucial as the chamber will operate at near-ambient temperatures, but expanded polyurethane insulation offers a cost effective solution that will allow temperature control of daytime and nighttime temperatures. Expanded polyurethane has an approximate k factor of 0.10 to 0.11.

Floor - The growth chamber floor is painted sheet metal, with drainage holes for any spills or condensate from the system.

Doors and Seals - Access to the growth chamber is available through the front panel. Plants should be interacted with through the automatic plant retrieval system, but if more interaction is required with the system for maintenance, the entire front panel is on a hinge that can be opened.

Lamp Bank - 5 Red/Blue LED bars will provide light for the system with a non-barrier system. LED bars are located right next to the Lexan plastic window, providing a distance of 16” from the LEDs to the substrate.

III. *Environmental Control*

Temperature - Range from 25℃ with lights on (Daytime) to 19℃ with lights off (Night Time) with a maximum differential of ±2℃. The maximum temperature variation across the growing area is no larger than ±0.5℃.

Humidity - Humidity is regulated between 50%-70%.

Light - Requires 550 $\mu molm^{-2}s^{-1}$ PPF with 0.40m distance from LEDs to plant, with 100% wattage to the LED bars.

Airflow - 6 lateral fans pull air horizontally, with 1 fan pushing cooled air downwards. This achieves an average air flow of $0.30ms^{-1}$.

IV. Controls, Monitoring, and Recording

A diurnal cycle for temperature and lighting is required for plant growth, controlled by a micro-computer running LabVIEW software. Reporting of all environmental parameters is done through interfacing of sensors to the microcomputer, and all values are available for display on the computer touch screen.

V. Alarm System

Alerts that the system has plants ready for harvest, or that environmental parameters have exceeded the maximum allowed, will be displayed on the computer screen for maintenance works to acknowledge and address accordingly.

VI. Operating Conditions

The growth chamber will be operated year round, with biannual downtime to ensure all functions are working as required and to perform any necessary maintenance to the growth chamber.

5. Conclusion

Moving forward with the design process, more challenges will surface that will be addressed accordingly. This report has laid out a framework for the concept design of the Automated Controlled Environment Growth Chamber, and should allow for the easy completion of fabrication. Analysis of the major parameters allowed for systems to be designed in a way that would allow easy operation and maintenance of the chamber. Upon completion of the chamber, the consideration and integration of economic, environmental, ergonomic, and social factors should help the growth chamber to operate and educate for a long time.

6. References

1 Micron - 10 Micron - 20 Micron - 40 Micron - Water Filters. (2017). *H2owarehouse.com*. Retrieved 29 January 2018, from http://www.h2owarehouse.com/info-micron.htm

Allen, R., Pereira, L., Raes, D. and Smith, M. (2004). *Crop evapotranspiration*. Rome: FAO.

Aqua Ultraviolet (n.d.). *Fresh water UV sizing chart.* Retrieved from http://www.aquaultraviolet.com/sites/default/files/brochures/UV%20Charts%20Salt%20and%20Fresh%20Water.pdf

Australian Department of Economic Development. (2017). Tipburn in lettuce. Retrieved April 01, 2018, from http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/vegetable/tipburn-in-lettuce

Bamsey, Zabel, Zeidler, Gyimesi, Schubert, Kohlberg, Mengedoht, Rae, Graham. (2015, July, 12-15). *Review of Antarctic Greenhouses and Plant Production: A Historical Account of Food Plants on the Ice.* Paper presented at the 45th International Conference on Environmental Systems. Bellevue, Washington. doi: ICES-2012-060

Bamsey, Zabel, Zeidler, Poulet, Schubert, Kohlberg, Graham. (2014, July, 13-17). *Design of a Containerized Greenhouse Module for Deployment to the Neumayer III Antarctic Station.* Paper presented at the 44th International Conference on Environmental Systems. Tucson, Arizona. doi: ICES-2014-122

Barbosa, G. L., Gadelha, F. D. A., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb., G. M., & Halden, R. U. (2015). Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponics vs. Conventional Agricultural Methods. *Environmental Research and Public Health, 12*(6), 6879-6891. doi:10.3390/ijerph120606879

Brechner, M., Both, A.J. (n.d.). Cornell controlled growth environment: Hydroponic Lettuce Handbook. Retrieved from http://www.cornellcea.com/attachments/Cornell%20CEA%20Lettuce%20Handbook%20.pdf

Cahill, J.F., Castelli, J. P., & Casper, B. B. (2002). Separate effects of human visitation and touch on plant growth and herbivory in an old-field community. *American Journal of Botany, 89*(9), 1401-1409. doi:10.3732/ajb.89.9.1401

Conviron. (n.d.). Featured Installations. Retrieved April 01, 2018 from http://www.conviron.com/featured-installations

Crane. (2015). BevMax Media: User's Guide. Retrieved April 01, 2018 from https://www.dsvendinginc.com/images/pdf-manuals/BevMax-6-Media-Generic-Touch-User-Guide.pdf

Despommier, D. (2011). The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. Journal of consumer production and food Safety, *6,* 233-236. doi: 10.1007/s00003-010-0654-3

Downs, R. J., Krizek, D. T. (1997). Air Movement. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 87-104).

Energy Star. (n.d.a) Commercial Refrigerators and Freezers. Retrieved April 01, 2018 from https://www.energystar.gov/productfinder/product/certified-commercial-refrigerators-and-freezers/results?scrollTo=596&search_text=&product_type_filter=Vertical+Transparent+Door+Refrigerator&total_volume_cu_ft_filter=15+-+%3C30&product_orientation_vertical_chest_filter=Vertical&brand_name_isopen=&refrigerant_type_filter=R-134a&markets_filter=United+States&zip_code_filter=&product_types=Select+a+Product+Category&sort_by=energy_use_daily_energy_consumption_kwh_day&sort_direction=asc&currentZipCode=H3A&page_number=0&lastpage=0

Energy Star. (n.d.b). Crane Merchandising Systems: DN3800-6. Retrieved from https://www.energystar.gov/productfinder/product/certified-vending-machines/details/2280286

Fu, W., Li, P., & Wu, Y. (2012). Effects of different light intensities on chlorophyll fluorescence characteristics and yield in lettuce. *Scientia Horticulturae, 135*(24)*,* 45-51. doi:10.1016/j.scienta.2011.12.004

Geerling, J. (2015). Raspberry Pi Zero - Power Consumption Comparison. Retreieved April 01, 2018 from https://www.jeffgeerling.com/blogs/jeff-geerling/raspberry-pi-zero-power

Hammer, P.A., Tibbitts, T.W., Langhans, R. W., & McFarlane, J. C. (1978). Base line growth studies of 'Grand Rapids' lettuce in controlled environments. *American Society Horticultural Science, 103,* 649-655.

Hicklenton, P. R., & Heins, R. D. (1997). Temperature. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 31-42). Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

How Does an NDIR CO2 Sensor Work?. (2012). *CO2 Meter*. Retrieved 23 February 2018, from https://www.co2meter.com/blogs/news/6010192-how-does-an-ndir-co2-sensor-work

Hydro-Québec. (2018). Rate LG: General rate for large-power customers. Retrieved April 01, 2018 from http://www.hydroquebec.com/business/customer-space/rates/rate-lg-general-rate-large-power-customers.html

Hyperphysics. (n.d.). *Relative Humidity*. [online] Available at: http://hyperphysics.phy-astr.gsu.edu/hbase/Kinetic/relhum.html [Accessed 3 Feb. 2018].

IGA.(2018). Romaine Lettuce. Retrieved April 01, 2018 from https://www.iga.net/en/product/lettuceromaine/00000_000000000000004640

International Committee for Controlled Environment Guidelines (ICCEG). (2008, March). *Measuring and Reporting Environmental Parameters for Experiments in Plant Tissue Culture Facilities.* Retrieved from https://www.controlledenvironments.org/wp-content/uploads/sites/6/2017/06/TC-Guidelines-Brochure-version-A4.pdf

Kelly, L. (2016). Container farms enable indoor growing. Retrieved December 2, 2017, from https://www.northernontariobusiness.com/industry-news/green/container-farms-enable-indoor-growing-371708

Kozai, T. (2013). Resource use efficiency of closed plant production with artificial light: Concept, estimation and application of plant factory. Proceedings of the Japan Academy, Series B, Physical and Biological Sciences, *89(10),* 447-461. doi: 10.2183

Kozai, T., Fujiwara, K., Runkle, E. (2016). *LED Lighting for Urban Agriculture.* doi: 10.1007/978-981-10-1848-0

Krizek, D.T., Sager, J.C., Tibbits, T.W. (1997) Guidelines for Measurement and Reporting of Environmental Conditions. In R. W. Langhans & T. W. Tibbits (Eds.), *Plant Growth Chamber Handbook.* (pp. 207-216) Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

LECA. (2011). Sustainability. Retrieved on March 3, 2017, from http://www.leca.ae/Sustainability

Lidlum. (2014). Lidlum Agro LA3064. (LED Innovation Design, Inc., Ed.). Retrieved April 01, 2018 from http://www.lidlum.com/wp-content/uploads/2015/09/LA3064-EN.pdf

Loblaws. (n.d.). Lettuce & Leafy Vegetables. Retrieved April 01, 2018 from https://www.loblaws.ca/Food/Fruits-%26-Vegetables/Vegetable/Lettuce-%26-Leafy-Vegetables/plp/LSL001001002008

Macdonald Farm Community Engagement Centre / Centre d'engagement communautaire de la ferme Macdonald. (2017). Agricultural and Environmental Sciences. Retrieved 10 January 2018, from http://www.mcgill.ca/macdonald/alumni/giving/cec

Marhaenanto, B. (2001) Proceedings of the World Congress of Computers in Agriculture and Natural Resources :136-46. ISSN: 1892769220

Martineau, V., Lefsrud, M., & Naznin, M. T. (2012). Comparison of Light-emitting Diode and High-pressure Sodium Light Treatments for Hydroponics Growth of Boston Lettuce. *HortScience, 47*(4), 477-482.

Massa, G. D., Kim, H. H., Wheeler, R. M., & Mitchell, C. A. (2008). Plant Productivity in Response to LED Lighting. *HortScience, 43*(7)*,* 1951-1956.

Menzies, J.G., Ehret, D.L., Koch, J.W. Hall, K.A. Seifert, C., J. Bissett, and Barr, D.J.S. (2005). Fungi associated with roots of cucumber grown in different greenhouse root substrates: *Canadian Journal of Botany, 83*(1), 80-92. doi: 10.1139/B04-153

Merill, B. (2011). *Hydroponic system grow crops with less water, no soil.* From the University of Arizona. Retrieved on October 17, 2017, from https://swes.cals.arizona.edu/environmental_writing/stories/2011/merrill.html

Mohanraj, M., Jayaraj, S., Muraleedharan, C. (2009). Environment friendly alternatives to halogenated refrigerants - A review. *Greenhouse Gas Control, 3*(1), 108-119. doi:10.1016/j.ijggc.2008.07.003

National Instruments. (2017). What is LabVIEW? Retrieved on December 1, 2017, from http://www.ni.com/en-ca/shop/labview.html

Olympios, C.M. (1993). Soilless Media Under Protected Cultivation Rockwool, Peat, Perlite And Other Substrates. Acta Hortic. 323, 215-234 doi: 10.17660/ActaHortic.1993.323.20

Peet, M. M., Krizek, D. T. (1997). Carbon Dioxide. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 65-79). Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

Pierson, D. C., Kratzer, S., Strömbeck, N., & Håkansson, B. (2008). Relationship between the attenuation of down welling irradiance at 490 nm with the attenuation of PAR (400 nm–700 nm) in the Baltic Sea. *Remote Sensing of Environment, 112*(3), 668-680. doi:10.1016/j.rse.2007.06.00

Pond Parts.com. (n.d.). 140 GPH Submersible Pump. Retrieved April 01, 2018 from http://www.pondparts.com/Pondmaster-Mag-Drive/140-GPH-Submersible-Pump-p-687.html

Promolife, Inc. (2017). O3Elite. Retrieved April 01, 2018 from http://o3elite.com/

Qiang, L. (2013) The research and design of modern agricultural greenhouse environment test system. The research and design of modern agricultural greenhouse environment test system. *Advanced Materials Research 610*(1), 1047-50. ISSN: 1022-6680

Raschke, K. (1960). Heat transfer between plant and the environment. *Annual Review of Plant Physiology, 11,* 111-126.

Raspberry Pi Foundation. (n.d.). FAQs. Retrieved April 01, 2018 from https://www.raspberrypi.org/help/faqs/

Relative Humidity and Your Home - Therma-Stor, LLC. (2018). *Thermastor.com*. Retrieved 4 March 2018, from http://www.thermastor.com/information/Relative-Humidity-And-Your-Home.aspx

Resh, H. (2013). Hydroponic food production (7th ed.). Boca Raton, FL: CRC Press/Taylor & Francis Group.

Sage, R. F., & Zhu, X. G. (2011). Exploiting the engine of C4 photosynthesis. *Experimental Botany* 62(9), 2989-3000. doi:10.1093/jxb/err179

Sager, J. C., & McFarlane, J. C. (1997). Radiation. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 1-30). Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

Scheufele, S. (2017). Lettuce, Downy Mildew (UMass Amherst Center for Agriculture, Food and the Environment, Ed.). Retrieved April 01, 2018 from https://ag.umass.edu/vegetable/fact-sheets/lettuce-downy-mildew

Sparkfun. (n.d.) Display Module - 7” Touchscreen LCD. Retrieved from https://www.sparkfun.com/products/12725

Spomer, L. A., Tibbitts, W. T. (1997). Humidity. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 43-64). Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

The Water Garden. (n.d.) Pond Boss 50 GPH Fountain Pump. Retrieved April 01, 2018 from http://www.watergarden.org/Pond-Supplies/500-GPH/Pond-Boss-50-GPH-Fountain-Pump

Tibbitts, T. W. (1997). Air Contaminants. In R. W. Langhans & T. W. Tibbitts (Eds.), *Plant Growth Chamber Handbook.* (pp. 81-86). Ames, IA, NCR-101 Regional Committee on Controlled Environment Technology and Use.

U.S. Energy Information Administration. (2017). How much electricity does an American home use?. Retrieved April 01, 2018 from https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

West Coast Seeds. (n.d.). Roxy Organic. Retrieved April 01, 2018 from https://www.westcoastseeds.com/shop/vegetable-seeds/lettuce-seeds/butterhead-lettuce-seeds/roxy-organic/

Wilson, J. (2005). *Sensor technology handbook*. Amsterdam: Elsevier.

Woodford, C. (2018). *How do thermocouples work?*. *Explain that Stuff*. Retrieved 16 February 2018, from http://www.explainthatstuff.com/howthermocoupleswork.html

7. Appendices

Appendix 1: Project Expenses and Cost Calculations

Project Expenses			
	Unit Price	Quantity	Cost
Materials and Supplies Bought to Date			
Commercial Display Fridge	$510.00	1	$510.00
Dolly Wheels	$17.50	4	$70.00
22 Gauge 4'x8' Sheet Metal	$60.00	1	$60.00
Red, Blue LEDs and Power Supply	Free - in kind donation	5	$0.00
120mm Cooling Fans	$10.99	6	$65.94
4" Netcups	$1.98	25	$49.50
Semi-Gloss White Spray Paint	$10.00	3	$30.00
		Total:	**$785.44**
	Estimated Unit Price	Quantity	Cost
Remaining Materials and Supplies			
Hydroponic Plumbing	$700.00	1	$700.00
Water and Nutrient Pump	$200.00	2	$400.00
Custom Plexiglass	$1,000.00	1	$1,000.00
HVAC components	$1,000.00	1	$1,000.00
Micro Computer	$700.00	1	$700.00
Sensor Interface	$450.00	1	$450.00
LCD Screen	$150.00	1	$150.00
Input Controller	$100.00	1	$100.00
Sensor Array	$2,500.00	1	$2,500.00
Automatic harvesting arm hardware	$2,000.00	1	$2,000.00
		Total:	**$9,000.00**
	Estimated Unit Price	Frequency Per Year	Cost
Recurring Costs			
Nutrient Solutions	$30.00	4	$120.00
40L Clay Pebbles	$62.01	1	$62.01
Pelleted Roxy Lettuce Seeds (50)	$3.79	5.16 (average)	$19.56
		Total:	**$201.57**

Total initial cost = $785.44 + $9,000.00 = **$9,785.44**

Recurring costs:

Clay pebbles: replaced once per year

Pelleted Roxy Lettuce Seeds: 234 lettuce heads needed per year (see Appendix 2 for calculation). Assuming germination failure rate of 10% (West Coast Seeds, n.d), seeds purchased per year should be (234 heads) x (1.1) = 257.4 seeds = **258 seeds/year**

(258 seeds/year) / (50 seeds/package) = **5.16 packages**

Note: this value does not represent the packages necessary to buy every year, but represents an average over many years

This indicates that over a period of many years, the average cost of seeds per year will be:

(5.16 packages) x ($3.79 per package) = **$19.56/year**

Nutrient solution: 3 quantities every 3 months, or $30.00 every 3 months:

($30.00/3 months) x (4) = **$120.00/year**

Total recurring costs = **$201. 57/year**

Appendix 2: Calculations of cost and energy

If 26 weeks 4 heads/week are harvested, and 26 weeks 5 heads/week are harvested, the expected yearly yield is **234 heads/year**

1. *Energy Consumption:*

P = V x I
Where P = Power (Watts)
V = Voltage (volts)
I = Current (ampere)

Power supply 1: 110V line connected to nutrient pump, LED bar, microcomputer, ozone generator, and LCD screen. Low startup power requirements, on continuously:

I. *Pumps***:** Germination tower: 50 GPH pump, Nutrient Solution: > 100 GPH pump
For estimation purposes, power specifications taken from The Water Garden (n.d.), and Pond Parts.com (n.d.)
Power consumption of a 50 GPH Fountain Pump = **2.7 W**
Power consumption of a 140 GPH pump = **9 W**

II. *LED bars*: Connected to SDR-480-24 rail mount. 5 bars, 4 feet each
Power specifics taken from Lidlum (2014)
Power consumption per bar: 90 W
90 W x 5 bars = **450 W**

III. *Microcomputer*:
For estimation purposes, power specifications taken from Geerling (2015), and Raspberry Pi Foundation (n.d.)
Power consumption of a Pi3 (based on user experience and testing): **1.2W**

IV. *Ozone generator***:**
For estimation purposes, power specifications taken from Promolife, Inc. (2017)
Power consumption of an O_3 Elite ozone generator:
Average input: 1.5 amps
P = V*I = (110V) x (1.5A) = **165 W**

V. *LCD screen:*
For estimation purposes, power specifications taken from Sparkfun (n.d.)

Power consumption of a 7" Touchscreen LCD display model:

Recommended P = (2A) x (5V) = **10W**

Power supply 2: 110V line connected to HVAC system and sensor box. HVAC system has a high startup draw, sensor box has low power requirements overall.

I. *HVAC***:**

For estimation purposes, power specifics taken from Energy Star (n.d.)

Energy consumption of a 15-30 ft^3 vertical commercial display fridge with transparent fronts and R-134a refrigerant = **1.97 kWh/day**

II. *Sensor Box:* Sensor box power requirements comparatively negligible for estimation purposes

Harvesting Arm:

For estimation purposes, power specifications taken from Crane (2015), and Energy Star (n.d.b)

Total energy consumption of BevMax 6 DN3800-6 refrigerated vending machine with XY axes: 3.9 kWh/day

Given the volume of the vending machine is comparable to the volume of the refrigerator, and contains a compressor of similar size, and assuming energy consumption from other factors is negligible in comparison, the energy consumption of the XY arm alone can be estimated:

Estimation for energy consumption of XY axis arm:

= 3.9 kWh/day - 1.97 kWh/day = **1.93 kWh/day**

Harvesting arm will operate 2 days of each cycle: end of germination and harvest

Total energy consumption estimation:

Total energy consumption, assuming 234 heads produced per year:

I. Pumps = (2.7 W) x (.333 hours/day) x (365 days/year) + (9 W) x (.333 hours/day) x (365 days/year) = **1.422 kWh/year**
II. LEDs = (450 W) x (16 hours/day) x (350 days/year (max)) = **2520.00 kWh/year**
III. Microcomputer = (1.2 W) x (24 hours/day) x (350 days/year) = **10.08 kWh/year**
IV. Ozone generator = (165 W) x (1 hour/day) x (350 days/year) = **57.75 kWh/year**
V. LCD screen = (10 W) x (24 hours/day) x (350 days/year) = **84.00 kWh/year**
VI. HVAC = (1.97 kWh/day) x (350 days/year) = **689.50 kWh/year**
VII. Harvesting arm = (1.93 kWh/day) x (2 days/cycle) x (10 cycles/year) = **38.60 kWh/year**

Total = **3401.35 kWh/year**

2. *Cost of Operation:*

At the Macdonald Campus, it is estimated that electricity cost from Hydro-Quebec to a large, commercially-zoned building is \$0.0343/kWh (Hydro-Québec, 2018).
For this rate, operation of the Autonomous Controlled Environment Growth Chamber would cost:

(3401.35 kWh/year)*(\$0.0343/kWh) = **\$116.67**

\$116.67/year + \$201.57/year = \$318.24/year

3. *Payback Period:*

Assuming the cost of one head of romaine lettuce in the Montreal area to cost around \$3.00 (IGA, 2018; Loblaws, n.d.), and the ACEGC is capable of producing 234 heads of lettuce/year:

Potential savings = (234 heads/year) x (\$3.00/head) = \$702/year

Initial manufacturing cost = \$9,785.44, and operation cost = \$318.24/year
Profit/year = \$702.00 - \$318.24 = **\$383.76**

Minimum time to pay off manufacturing cost assuming no material failure : \$9785.44 / \$383.76/year = **25.50 years**

4. *Cost Per Lettuce Head:*

I. *Estimated cost per head of lettuce over payback period, assuming no material failure:*

(234 heads/year) x (25.50 years) = 5967 heads produced
Cost of operation over 25.5 years = (\$318.24/year) x (25.50 years) = \$8115.12
Cost per head of lettuce during payback period:

(\$8115.12 + \$9785.44)/(5967 heads) = \$2.99/head (correct)

II. *Estimated cost per head of lettuce after payback period, assuming no material failure:*

(\$318.24/year)/(234 heads/year) = **\$1.36/head**

Appendix 3: Sizing hydroponic water tanks

1. *Specs*

Germination	1 tower	5 plants
Growth	4 towers	20 plants

Emitters used: 2 L/h
The system will run for 5 minutes, 4 times per day
70% of fertigate recycled

2. *Germination*

$$2\,{}^{L}/_{h} \times 5\ nozzles = 10\,{}^{L}/_{h} = 0.16\ L/min$$

$$0.16\frac{L}{min}\times 5min = 0.83\frac{L}{cycle}$$

$$\frac{4L}{day}\times 30\%\ losses = .25\ L\frac{losses}{cycle}$$

$$0.25\ L\ losses\times 10\ days + 0.83L = 3.33\ L\ minimum\ tank\ size$$

3. Growth

$$2\,{}^{L}/_{h}\times 20\ nozzles = 40\,{}^{L}/_{h} = 0.6\ L/min$$

$$0.6\frac{L}{min}\times 5min = 3.3\frac{L}{cycle}$$

$$\frac{3.3L}{cycle}\times 30\%\ losses = 1\ L\frac{losses}{cycle}$$

$$1\ L\ losses\times 10\ days + 3.3L = 13.3\ L\ minimum\ tank\ size$$