IPRO 342 Final Report
Spring 2010

Power Plant Waste Heat Utilization for Greenhouse Applications

Advisor: Blake Davis

1. Executive Summary

The goal of this project was to determine the feasibility of using the heated waste water from the Braidwood Generating Station for use in greenhouse applications. Though extremely efficient, the Braidwood Generating Station, like all nuclear power plants, still wastes two-thirds of all energy generated and pumps 1.5 million gallons per minute of warm waste water into its cooling lake. All of this thermal energy pumped into the cooling lake is wasted. IPRO 342 was looking to change that.

This semester, the IPRO team began to develop greenhouses of many different types that could take advantage of this waste water heat and use it constructively as a heat source for the greenhouses. With Exelon Nuclear as a sponsor, the team has researched all aspects of their project such as greenhouse design, heating layouts, crop selection, and even weather patterns with one goal in mind: *to make one of the greenest forms of energy greener*.

2. Purpose and Objectives

Background and Purpose

Exelon Corporation is one of the largest electric utilities in the United States specializing in energy delivery, energy generation and power marketing. As part of their commitment to reduce global warming, Exelon has a goal to reduce, offset or displace more than 15 million metric tons of greenhouse gas emissions per year by 2020. Specifically, Exelon Nuclear, the sponsor of this IPRO and a business unit of Exelon Corporation, has been a large factor in these goals. Nuclear energy has a very low environmental impact because the process does not release greenhouse gases thought to contribute to global warming, nor does it release gases that could cause ground-level ozone formation, smog, or acid rain.

As Exelon continues its drive to become a leader in environmentally friendly energy, it becomes increasingly important to find creative solutions to reduce environmental impacts. These creative solutions should go above and beyond regulatory environmental policies in order to gain shareholder value. The Exelon Corporation has committed itself to continually improving environmental performance, and in order to have continual improvement with respect to the environment innovative and resourceful approaches must be pursued.

While nuclear energy does not produce as many greenhouse gases as other types of power plants, it still produces large amounts of heat pollution. Since most plants already operate very close to their maximum electrical generation efficiency, one way to reduce this heat pollution is to utilize it for another purpose.

The purpose of this team is to bring together interdisciplinary students in a research project on the economic and technological feasibility of using waste heat from a nuclear power plant to profitably operate greenhouses and caged fish cultures.

Objectives

- Research the economic feasibility of the project
- Evaluate where in the generating process to remove the waste heat while determining what impact this may have on the plant operation
- Research potential ways to utilize the low-temperature water in agriculture
- Select appropriate low-cost greenhouse structures
- Determine the types of profitable crops to grow and the market outlets for the volumes of produce a facility like this could produce
- Design a prototype greenhouse and caged fish farming system that can be utilized at Exelon's Braidwood Generating Station
- Update research on similar projects using current economic data
- Determine the capitalization and operational requirements for the facility
- Present the research and prototype to Exelon
- Work effectively as a team to produce our highest caliber of work through consistent communication, research, and desire for quality

3. Organization and Approach

In order to begin this project the team had to acquire basic knowledge about greenhouse and nuclear power plant operation. Senior management and engineers from Exelon Nuclear presented a lecture on the logistics of the nuclear power plant and pertinent information on waste heat. The students also took a tour of the facilities of the Braidwood Generating Station in order to further develop an understanding of the systems and the site.

The large group then split into smaller groups based on individual background and interests. These subgroups included a research, mechanical systems, crop, and greenhouse design group.

The research subgroup analyzed previous projects that used similar applications of waste heat to power greenhouses. The group used online databases to find studies that had been previously conducted and updated those results using current economic and cultural parameters. Projected cost savings compared the cost of natural gas as a heat source to the cost of designing a system to utilize the waste heat. The group constructed a summary describing how much could be saved using waste heat and found that the project would ensure cost savings in the current scheme, as well as further savings from 2015 to 2030 using projected costs of natural gas.

The mechanical systems subgroup focused primarily on the heating system, and later on the various other systems that would be necessary to make the greenhouse operate. This subgroup's goal was to determine a heating system that could keep the greenhouse warm enough to support plant growth throughout all seasons and then to optimize that system so that the required temperature could be maintained. The group researched various types of heating systems that utilize waste heat. It was necessary to determine a heating system that was both efficient and low cost. Subsequently, several types of heating systems were modeled that used low temperature waste heat. Upon discovering that many of these previously used systems were unable to provide enough heat to the proposed greenhouse, the group proposed a combination of the previously modeled systems that seemed feasible. Computer programs were employed to make visual aids for the heating system design and thermal plume of the system. In addition to designing a heating system, the group researched irrigation, ventilation, extra lighting, and dehumidification systems. When determining the specifics necessary to the Braidwood site various agencies and companies in the area were contacted to determine the necessary steps needed to provided water or electricity by these companies.

The crops subgroup focused on two major areas of research: traditional greenhouse farming and caged fish farming. The group acquired significant information by visiting a local greenhouse. The design parameters of the fish cages were primarily based on previous projects. The group determined the species of fish that have been successfully farmed in a caged environment as well as their growth needs, including optimal water temperatures and cage placement Feeding, harvesting, and grading schedules were compiled to maximize production. This group focused on determining crops that could grow within the achievable temperature ranges of the greenhouse. Furthermore, the crops subgroup researched the lighting, water, soil and temperature requirements for the crops.

The greenhouse design subgroup had the task of designing the greenhouse. This group researched two main types of greenhouse design: water and land-based. Research was done on previous greenhouse designs and materials used to choose a design that had a relatively simple and known construction process. Materials selection and site placement were also determined by this subgroup. Lifetime cost analyses were completed for the materials of the greenhouse to determine an inexpensive yet durable structural design. The responsibilities of this subgroup also included the final greenhouse images and model which incorporated elements from the three other subgroups' research. The software program AutoCAD was used on a weekly basis to model the structures and make 3D renderings in order to give others a visual understanding of the evolving greenhouse design. These drawings were used in the final presentation and brochures.

4. Analysis and Findings

At the beginning of the semester, two suggestions were made for utilizing the waste heat discharged from the Braidwood Nuclear Plant. The first proposal was to use the water in the cooling lake directly for a fish farm that could operate year round, since the lake never freezes. The second, and main objective of the project, was to develop a greenhouse design that could be heated solely by the waste heat, thus removing any need for expensive oil or natural gas heating systems.

Fish Farm

According to data collected by the Braidwood Generating Station, the coolest pond temperature never goes below about 50 degrees, even in the middle of winter (see Appendix D). The fact that the cooling lake never freezes over provides an opportunity for creating a fish farm that can operate year round, so members of the crops subgroup researched this possibility extensively to determine how this could be done feasibly.

The fish cages would be constructed from a galvanized steel frame with plastic ¼ in netting fastened to it. The small size of netting is necessary if the cages are going to be stocked with fingerlings, which is the most cost effective method. The cages, if designed well, have a life expectancy of ten years. For flotation as well as accessibility, a modular system of interlocking polyethylene cubes (see Appendix C) would be a better option than a more typical dock, because it creates a self-contained structure that can be moved within the lake to different water temperature regions. The cages must also be positioned in an area where they have at least two feet of clearance between the net and the bottom of the lake, and have the greatest possible water circulation to allow for the removal of waste and to keep the oxygen levels in the cage within an acceptable range.

Due to the temperature of the water available year round in the cooling pond, the most suitable fish for production is Nile Tilapia. This species can thrive in water temperatures between 75-95 °F, and optimal growth occurs between 73-79 degrees F. During acclimatization, the fish should be introduced into water that is at least 70 degrees F. Tilapia must be sourced from an out of state supplier. In order to allow for consistent growth and results and keep fighting at a minimum, the cages would be stocked with males at a high density.

The fish will need to be fed twice a day, when the water temperature should be monitored as well. To minimize the risk of a disease outbreak, the CO_2 levels, pH, nitrate and nitrite of the water should also be checked frequently. Since the fish will grow best when they are all within the same weight range, they should also be graded and sorted every four weeks. The target market weight of the Tilapia is one pound. The optimal density of fish within each cage is one fish for every two gallons of water, so the cages should be sized accordingly.

Crops

At the beginning of the semester, the crops sub-team started with an enormous list of possible crops with the goal of narrowing it down. After getting a better idea of the environmental factors that will be possible within the greenhouse, the team was able to narrow down an extensive list of crops down to six that can be grown and rotated throughout the year. The final list of possible crops is: strawberries, lettuce, peppers, beans, tomatoes, and squash. Each specific crop has pros and cons that are dependent on the exact conditions of the greenhouse (see Appendix D).

Greenhouse

One of the first steps taken in evaluating the feasibility of heating a greenhouse with waste heat was to find past research on the economics and update it to reflect current costs. This part of the project was handled by the research subgroup. The research subgroup focused on two specific papers that analyzed the energy savings from using waste heat and updated sections of those report with current and projected natural gas prices. Both of these reports used different heating systems and general construction than the greenhouse currently being proposed, so the cost savings are only very rough estimates, but they give a general idea of what can be expected (Table 1, Table 2). In both cases, the savings at the current price of natural gas is less than the projected savings when the analysis was first made, but the projected increase in natural gas prices will lead to greater savings in the future.

Table 1: Update of water blanket (in $)

	1982	Current	5 yr average	2015	2030
Natural Gas Savings	654,184	785,021	1,007,443	1,242,950	1,655,086
Added Electricity Costs	39,493	61,518	61,518	61,518	61,518
Fixed and Other Costs	93,489	243,071	243,071	243,071	243,071
Net Savings	521,202	480,431	702,854	938,360	1,350,496

Table 2: Update of 2-acre greenhouse (in $)

	1981		Current		5 year average	2015	2030
Item	Natural Gas	Waste Heat	Natural Gas	Waste Heat	Natural Gas	Natural Gas	Natural Gas
Fuel	79,670		95,604		122,692	151,373	201,565
Electricity	9,600	9,600	14,954	14,954	14,954	14,954	14,954
Supplemental Fuel		3,600		4,320			
Pipeline Amortization		29,600		76,960			
Operating and Maintenance		2,000		5,200			
Total	89,270	44,800	110,558	101,434	137,646	166,327	216,519
Savings		44,470		9,124	34,988	64,893	115,085

The design of the actual greenhouse was based on the primary criterion that the waste heat should be used as efficiently as possible, i.e. since such a large volume of hot water was accessible, the design should be based on inexpensive construction cost rather than thermal efficiency. This led to the decision to base the greenhouse design off of a simple hoop structure covered by a Tufflite IV polyethylene cover as the best compromise between durability and low price. The cooling water discharged from the plant is significantly cooler than normal heating water, so a system to make full use if had to be specially designed. This was the main task of the mechanical/thermodynamics team. Instead of the normal systems that use a low volume of water at a high temperature, the thermodynamics team worked on developing a system that had a high volume of water at a lower temperature. A few weeks into the semester, the thermodynamics team realized the difficulty of providing a high enough volume of water to effectively heat the greenhouse and at their suggestion the general greenhouse design was split into two branches, one developing a more conventional land-based greenhouse, and the other working on a floating greenhouse design. In the case of both the land and floating greenhouses, members of the design team handled the overall design of the greenhouse, as well as site considerations, while the thermodynamics team developed the heating system and also did research on ventilation and irrigation systems.

The main advantage of the floating greenhouse was that it did not require any mechanical heating system, but would be heated by the warm water beneath it. The design did present numerous other problems that needed to be resolved, however. After considering the matter, the design team concluded that a rigid floating frame should be used as the base, for stability reasons, and a normal hoop house structure could be placed on top of this. To increase the heat entering the hoop house, a non-solid floor was decided on, with walkways for workers. The lack of a solid floor means that the planting boxes can be put in actual contact with the water for more effective heating. The proposal is to use discarded 50 gallon drums for the flotation of the greenhouse, as something that is both durable and inexpensive. The drums would be connected in a rigid frame around the perimeter of the greenhouse, which would provide both the flotation for the entire structure and would also create a wall to break any waves from the lake (see Appendix E).

The most difficult issues would be getting electricity and irrigation water to the greenhouses. Two suggestions have been made for this: First, the greenhouse barges could be moored to a solid dock that had hookups for electrical and water, which would allow supplemental lighting in the winter months. This would have the added advantage of making the greenhouses easy to access for maintenance and harvesting, but the disadvantage that they could not be easily moved.

The second option is that the greenhouses would have self-contained irrigation and no electrical system. In this case, the irrigation would be a drip system from a large tank that would need to be refilled periodically. Though this would be more cumbersome for daily maintenance, it would allow the greenhouses to be moved around the lake as the water temperature varied. For this second case, either a boat or a moveable walkway to shore would be needed to access the greenhouses, depending on where they are moored.

Early on in the semester, the greenhouse design team analyzed maps of the Braidwood Generating Station site and determined that the best location for greenhouses on land would be either north or west of the discharge channel. Later, this was narrowed down to the strip of land west of the channel as the proposed site (the orientation of the greenhouses can be found in Appendix D). This provided easy access for heating water, and was mostly open space that could be easily utilized. This site did provide other disadvantages, however. The thermodynamics team discovered that the site was not part of the Braidwood Water Distribution System, but was actually in the Village of Godley. Godley relies mainly on well water, and the municipal water currently in development was only designed to handle the current residential load, so irrigation water would either need to come from the lake or a separate well system.

Throughout the semester, the thermodynamics team researched several different types of heating systems to determine whether they could provide adequate heat. These systems included heat exchangers, underground piping, flooded floor, floating barges, and water channels. Heat exchangers and underground piping, while commonly used, were quickly disregarded because both systems are very expensive to install and perform more efficiently with higher source temperatures than the cooling lake water. The final design was a system of sloped concrete trenches running the length of the greenhouse. The trenches would be filled with running water, and have the planters set in the top of them. Walkways would run between the trenches and would be set 3' below grade so that the trenches were at an easy working height (see Appendix G).

Unfortunately, the systems that adequately provide heat also result in high humidity. Many plants grow well in relative humidity of up to 85%, but at higher relative humidity there are many negative effects. High humidity's can result in reduced transpiration, smaller root systems, mineral deficiencies, and pathogens can infect the plants with greater ease. In order to reduce the problems associated with high humidity, it is necessary to reduce freestanding water on plant surfaces. This can be done by ventilating the greenhouse, heating from the bottom, utilizing thermal screens, and circulating the air.

5. Conclusion and Recommendations

Conclusion

IPRO 342 has developed two feasible greenhouse designs that utilize waste heat. According to calculations, the waste heat water will be able to provide adequate winter heating for both the land and water-based designs. Where the margin of safety of the temperature in the land-based greenhouse is much less, there are still details to be worked out in the floating greenhouse as well.

The economic feasibility of both greenhouses needs to be further researched. While IPRO 342 has determined the group of crops that works best under the conditions provided in our greenhouse designs, we have yet to determine which crops should be grown to maximize profit. In addition, the number of greenhouse structures on the Exelon site also needs to be determined. Nuclear power plants have extremely limited access, and the number of workers allowed to access the greenhouse may be relatively small. The members of IPRO 342 recommend that this project be further researched as an EnPro to further explore the economic aspects of this project.

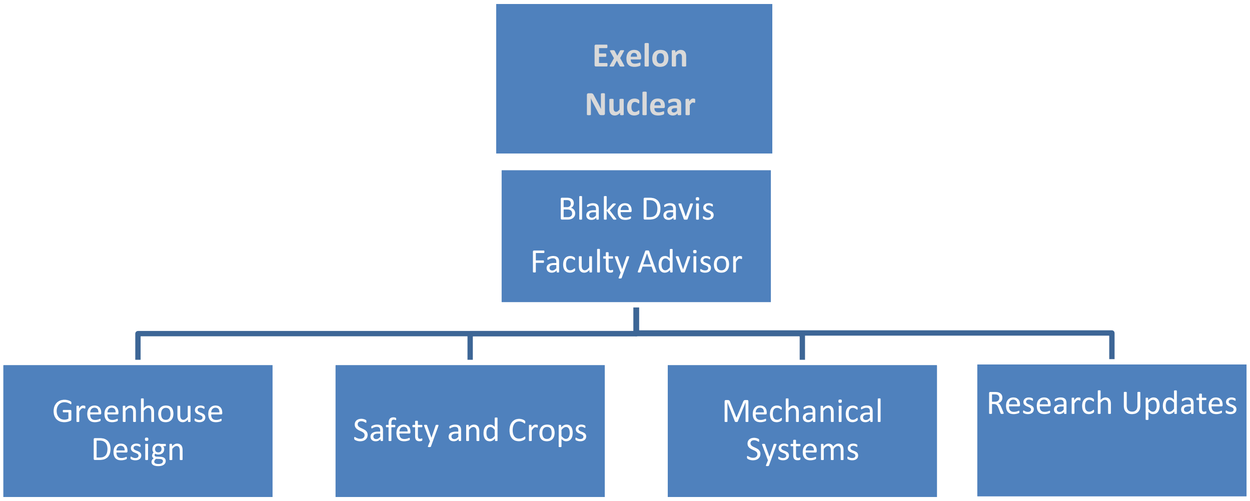
Exelon should consider constructing a small number of these greenhouse prototypes to test the on-site feasibility. This way access, safety, and financial concerns can be addressed as they come up (before a large investment is made). With this on-site testing and feedback, the greenhouses can be improved before their final implementation.

Recommendations

- Determine adequate access and anchoring of the water-based greenhouse design
- Perform structural analysis of both designs.
- Determine the most profitable crops
- Establish the ideal number of greenhouses
- Create a time schedule and cost analysis of the necessary maintenance for greenhouse structures
- Transform IPRO 342 into an EnPro to further test the economic feasibility

6. Appendices

Appendix A: Team Members and Hierarchy



Greenhouse Design	Safety and Crops	Mechanical Systems	Research Updates
Zachary Harbour*	I Zorra*	Gustavo Zarazua*	Tejash Patel*
Krzysztof Bartus	Marisol Aguirre	Matthew Alvarez	Nancy Lima
Brooke Jeffcoat	Andrew Fonk	Joshua Hasbrouck	Fatima Chippo
Kyungmin Nam		Madeline Jensen	Samir Qaisar
Christopher Pope		Emily Kunkel	

Responsibilities: Design proposed greenhouse model, both on land and on water. Decide on greenhouse site location	**Responsibilities:** Decide on viable crops to grow in greenhouse climate. Propose feasibility of fish farming. Contact Exelon for property information.	**Responsibilities:** Decide on heating system for the greenhouse, both on land and on water. Research air circulation and de-humidification techniques.	**Responsibilities:** Study old greenhouse techniques using waste heat. Update old references into current prices.

* Denotes sub-group leader

Appendix B: Team Budget

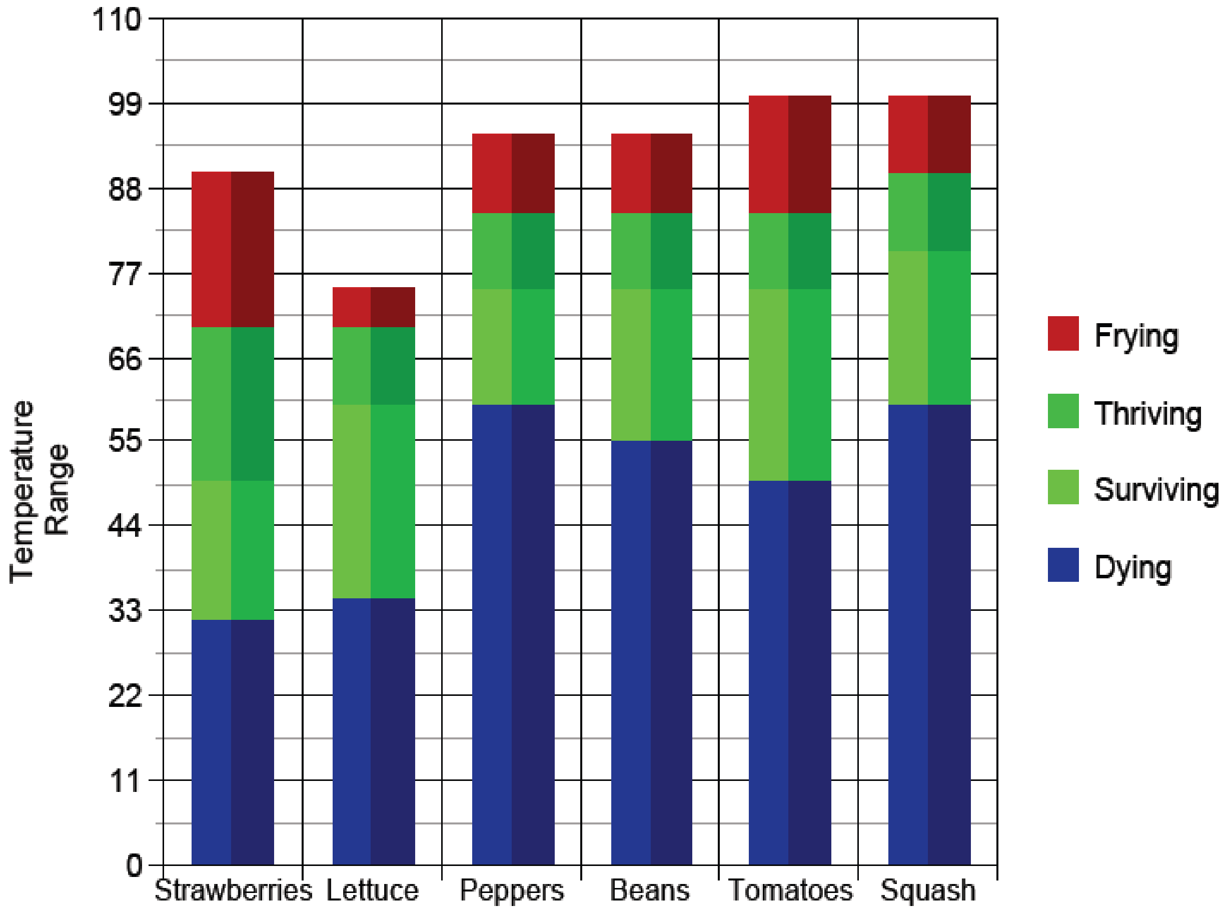
Activity	Budget Cost	Money Spent	Description
Transportation	$50	$165.00	trip to Exelon Nuclear power plant for a plant tour and for site visits–reimburse the three drivers necessary
Heating System Model	$200	$_____	to pay for the water pump, tubing, plastic gloves and heat source to model the heating system
Team Building	$150	$0	Bog rental to get to know the team members better so that the group can work more efficiently or to celebrate the completion of the project at its conclusion
Printing/Supplies	$75	$0	costs of the brochures and posters for the promotion of the project
Greenhouse Model	$75	$______	to make a scale model of the greenhouse including wood frame, steel frame, plastic covering
Totals	$550	$165.00	Amount under: $385.00

This table shows the proposed team budget and how much money was actually spent on that activity and the description of the activity. The bottom shows the overall proposed budget and how much money the group came under budget.

Appendix C: Floating Fish Cage Structure

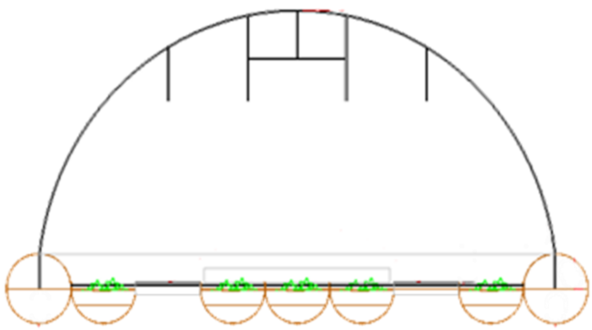
This figure shows the interlocking cube structure of the floating fish cage support. This has a solid walking structure for harvesters to utilize for easier and safer access to the fish cages. This design is called the *Magic-Float* Modular Dock System which is manufactured by Magic Float Enterprise. This design includes separate buoyant cubes that interlock in any design pattern the purchaser chooses.

<u>Appendix D:</u> Internal Temperatures Data for Crop Survival

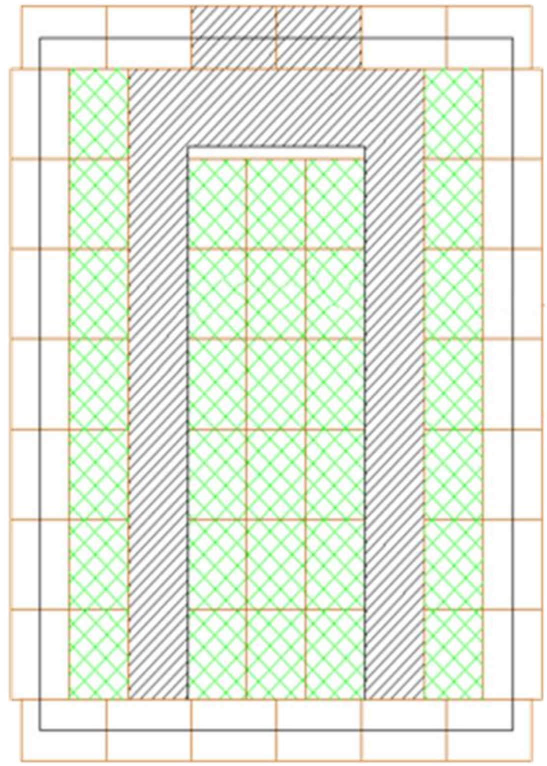


This chart shows internal temperature information for the six most realistic crops for this project. Both cold weather (Strawberries and Lettuce) and warm weather (Peppers, Beans, Tomatoes, and Squash) are shown. Having a rotation of both cold and warm weather crops extends the operation time of the greenhouse, allowing cold weather crops to be grown in the middle of the winter. The dark green region of the chart shows the temperature range that is idea for each crop, while the lighter green shows a range of temperatures in which the plant will survive, but not as well. The red and blue denote areas in which it will be impossible to grow specific crops for long periods of time.

Appendix E: Floating Greenhouse Structure



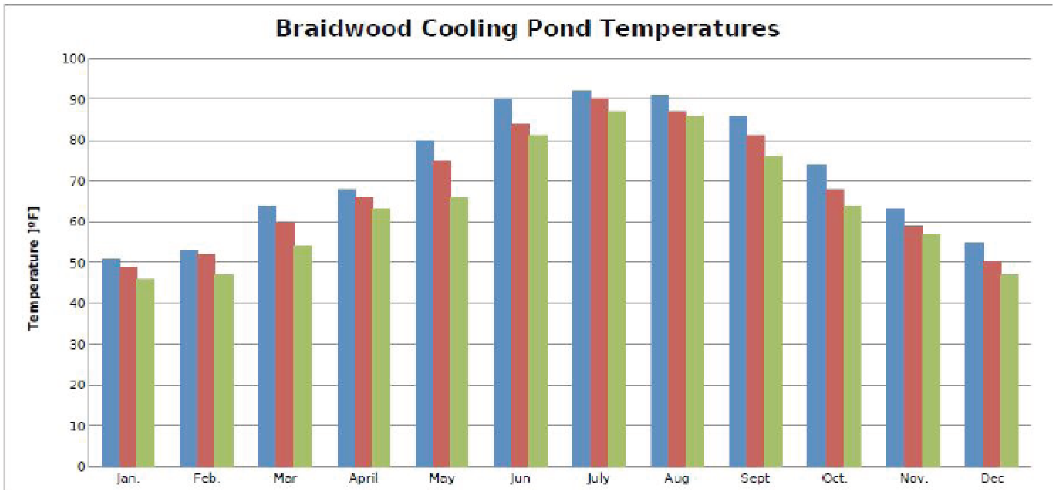
End Section



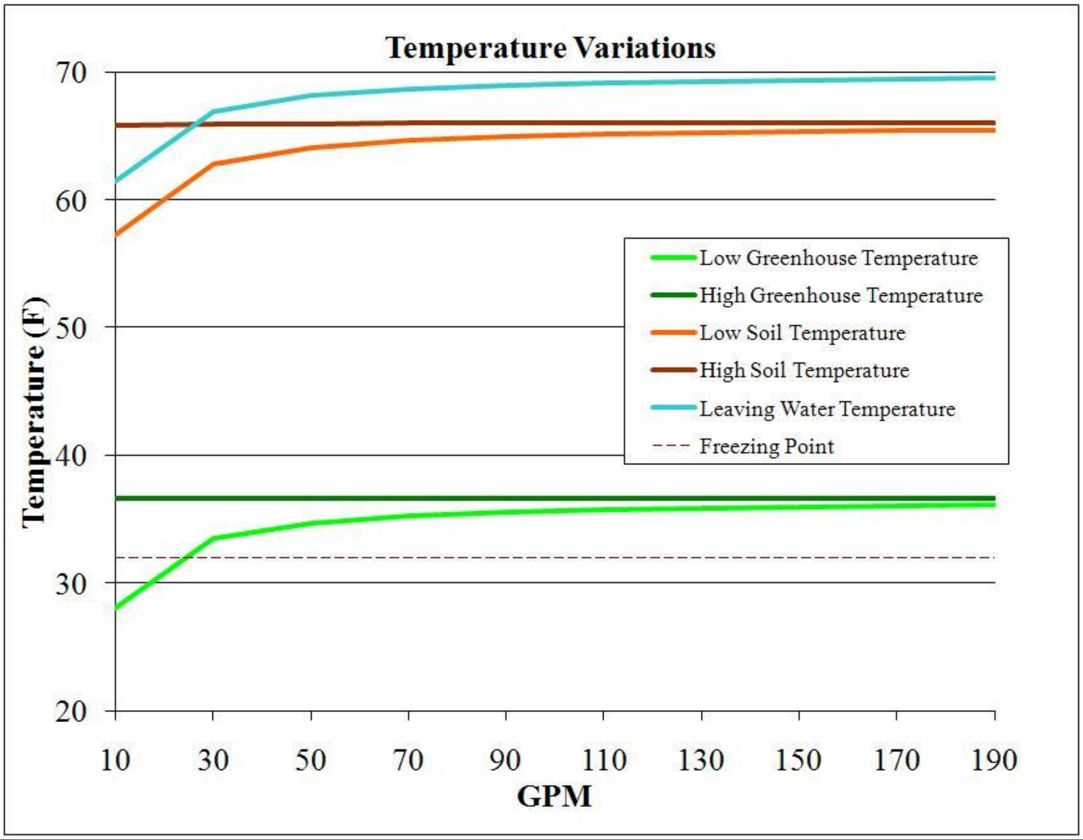
Plan View

These two figures show the end section and plan view of the floating greenhouse structure. As shown, there will be a steel hoop house structure on top of a rigid structure of empty barrels or drums. Tethered between the two sides are cables that will attach to planter boxes so as to hold them in place. The planter areas are marked by the green box weave pattern. The black diagonal striped pattern shows where there will be a rigid concrete walkway for workers to access the plants by. The barrels around the perimeter will provide the main source of buoyancy for the greenhouse structure.

Appendix F: Mechanical Systems Raw Data for Land Based Trough Heating System

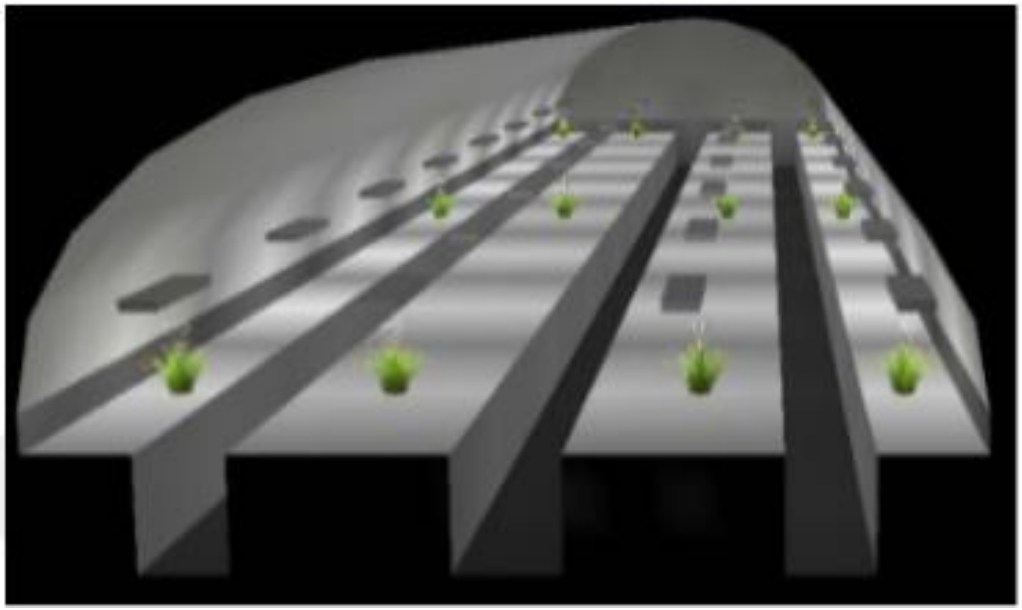


This chart shows the Braidwood plant cooling lake temperature averages over from 1998-2009. This is recorded based on the entrance temperature of the water from the lake going into the facility. The blue lines denote the maximum temperatures for each month, while red is average and green is minimum. The temperature of the water exiting the facility is approximately 10^{o}C higher than the lake temperature. Thus the temperature of the channel in which the plant returns the water can be found by adding 10^{o} to the numbers shown in this graph. The hot water channel temperatures are what are being studied for the use in the heating system.

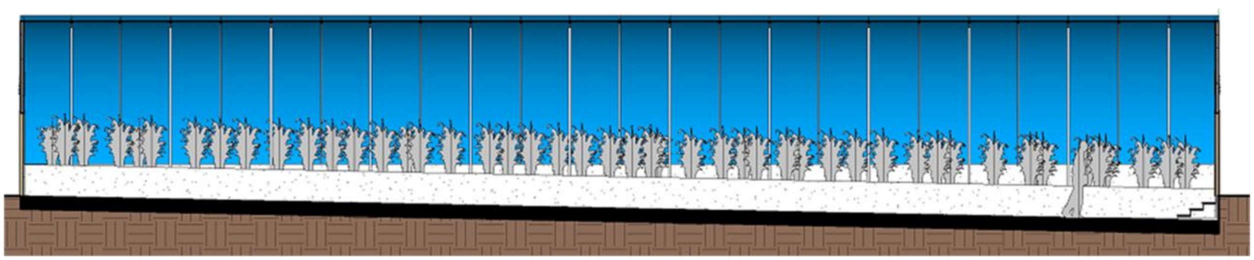


This graph displays the data evaluated for the water channels heating system. The average outside temperature ranges from -10F to 20F in the winter in Chicago, so these values were used as a worst case scenario when calculating if this system was viable for the winter. The outside air temperatures were paired with possible U-values for the Tufflite IV greenhouse covering, since the actual U-value of Tufflite IV was difficult to accurately determine. Based on the heat loss from the greenhouse, the water flow rate (in Gallons per Minute) in the channel was calculated to keep the soil temperature between ~55F and ~67F. The greenhouse air temperature was also evaluated during this calculation and the goal was to keep the air temperature inside the greenhouse above freezing in order to prevent the crops from freezing over. The resulting flow rate was approximated at 100 gallons per minute through each channel.

Appendix G: Land Based Greenhouse Structure and Visual Representations

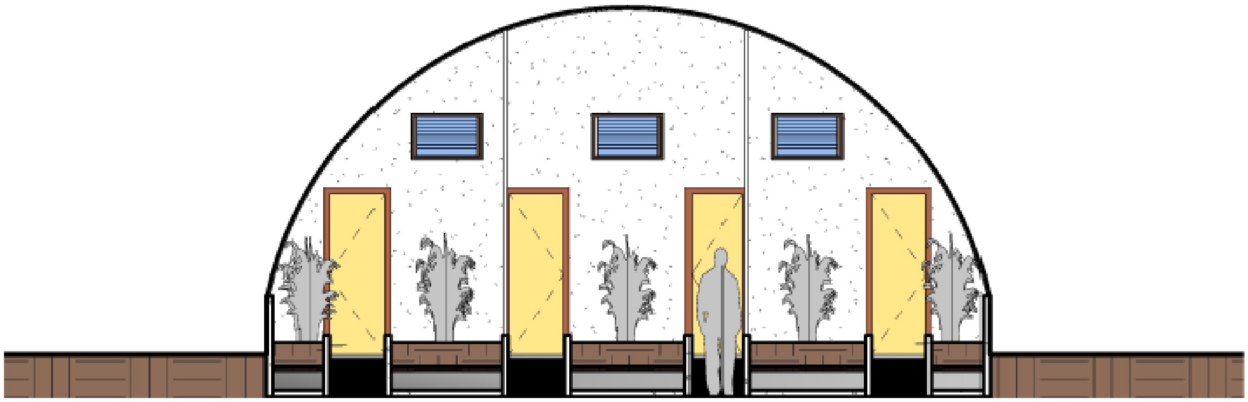


This figure shows the inside special representation of the water channel design. In this case, the plant beds in the water would be located at ground level and the walkways would be located about 1-1.5' below ground. This figure also shows the location of extra lighting that would be used for winter months to give the plants supplemental artificial light during months with few hours of light.

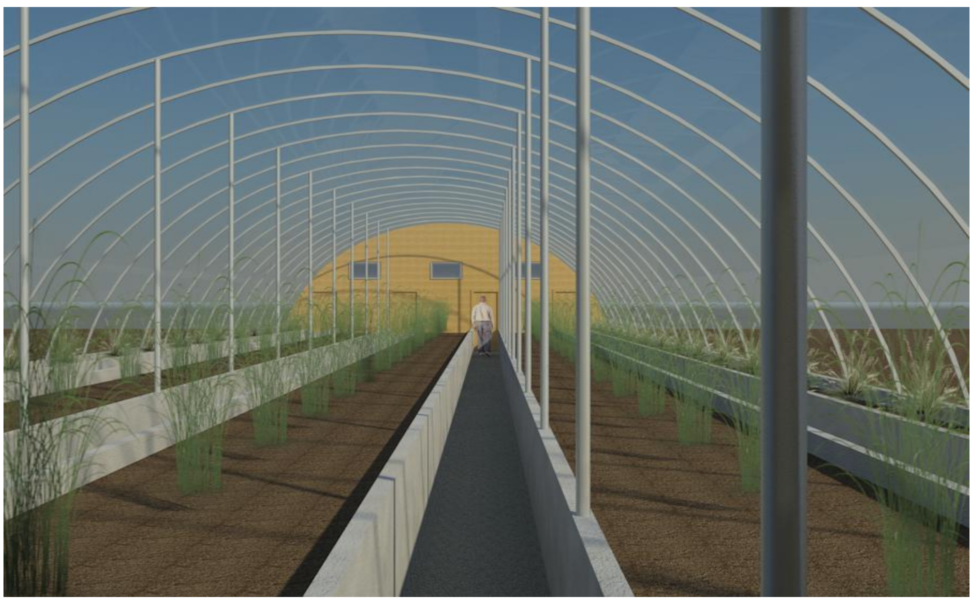


Side Section

This figure shows the longitudinal or side elevation of the greenhouse structure. As shown, the ground will be slopped along with the walkways and troughs inside. It will be sloped a total of two feet over the course of the 96 foot long greenhouse. The slopped design allows for gravity to move the water through the greenhouse while avoiding pumping costs. There are stairs at the end due to the fact that the interior walkway will be located below ground level at the one end.

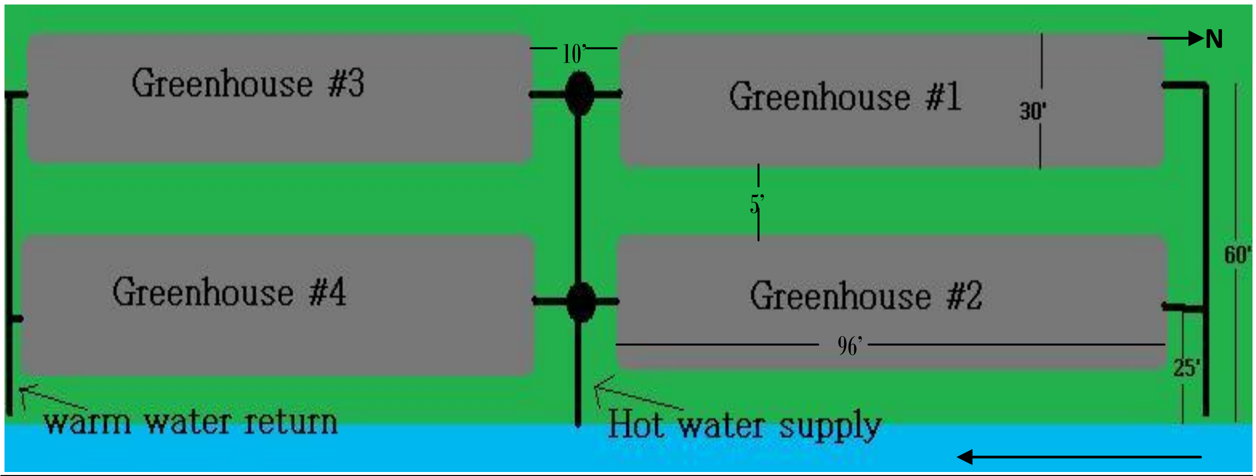


This figure shows the side section of the greenhouse. As shown, there are walkways between the five troughs that are located below the troughs to have the plants be at waist height for the workers. A ventilation system is also shown in this figure.



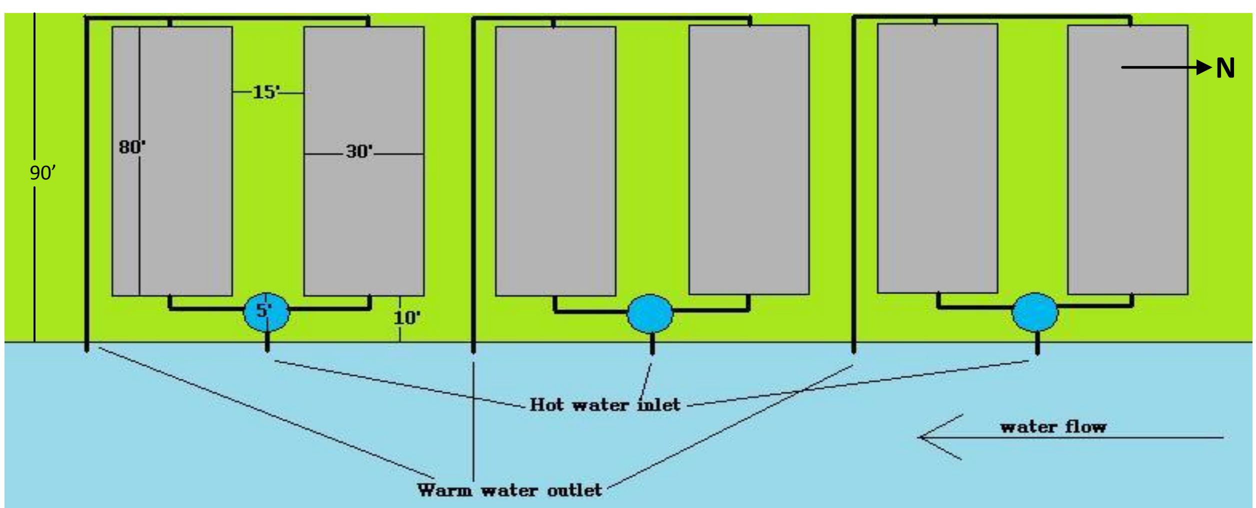
This figure shows the 3D rendering of the interior of the greenhouse. Shown are the troughs in which the plants are located, the walkways that are below trough level, and the steel structure of the hoop house. The person is shown inside to give a realistic visual representation and proportionality of the greenhouse itself to a human.

Appendix G: Spatial Layout of Land Based Greenhouses



--Figure 2--

This figure represents the orientation that the greenhouses would take if their size was 96'x30'. This orientation was chosen because the width of the land is only about 80-90' thus a 96' greenhouse could not fit facing the other direction. Since the hot water inlets to the greenhouses are 25' and 60' away from the hot water channel, this is not an ideal orientation because of all the heat loss across the pipe on the way to the greenhouse.

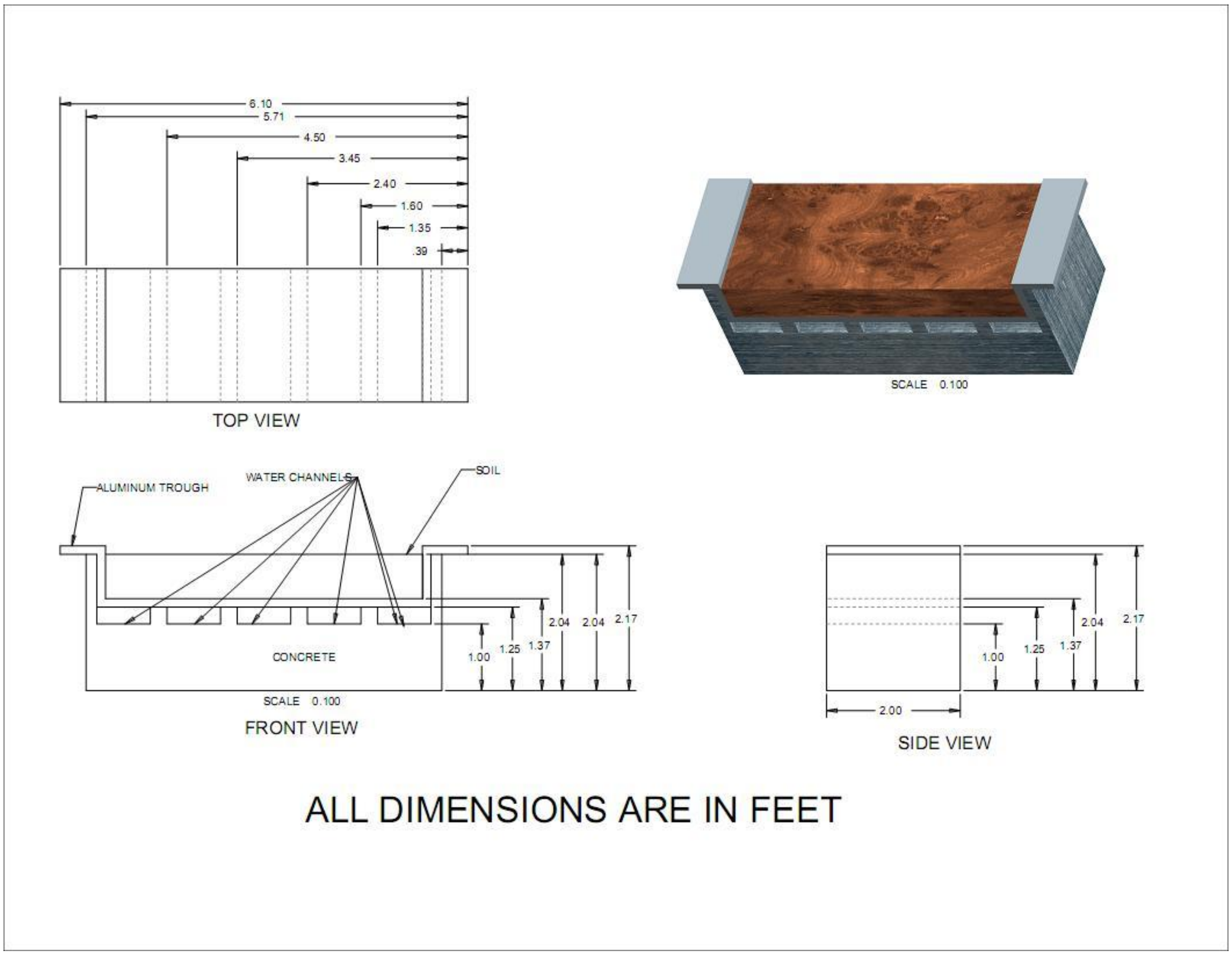


--Figure 3--

This figure represents the orientation that would be optimal for the heat transfer in the greenhouses. Since the hot water inlet of the greenhouses is as close to the hot water channel as possible, it provides the lowest amount of heat loss which means better heating efficiency. Since the land is only 80-90' wide though, the greenhouse size would have to be cut down to 80'x30' instead of the usual 96'x30'.

Appendix H: Mechanical and Heating Systems

The mechanical team modeled the transfer of heat from the water into the greenhouse using various thermodynamic equations. The end result was to determine the feasibility of heating a land based greenhouse. First, the values were calculated in *Engineering Equation Solver* (EES). The units of the calculations were in British units: Rankine, foot, hour, pound mass. A system of equations that described the transfer of thermal energy of the water through the greenhouse was derived. For example, thermal resistances were calculated and utilized in an overall heat transfer equation. Built in function of EES were also used to determine Nusselt number correlations required for the heat transfer calculation. Lastly, the main assumption in the calculation dealt with one dimensional steady state heat conduction. Basic dimensions of the cross section of a ninety-six foot trough can be seen below.



Please take into consideration that the concrete base of the trough is nearly one foot thick. Further design, structurally, is required.

The greenhouse house was modeled using conservation of energy.

$$\sum_{i=1}^{n} Q_{in,i} + \sum_{j=1}^{m} Q_{out,j} = 0$$

The equation above says that the heat added to a system must equal what goes out. Heat outward is considered negative. The next operation in the analysis was to determine the thermal resistances, such as convection, due to wind blowing over a building or conduction through the aluminum sheet in the trough system. The following formula is used for calculating the thermal resistance due to conduction.

$$R_{conduction} = \frac{t}{kA}$$

The equation above is mostly used in the trough system. Moreover, the same equation is converted to cylindrical coordinates to account for greenhouse heat conduction or heat losses. The 'k' in the equation above represents the thermal conductivity of the material, which is specific thermal property. 't' represents the thickness of the material that which thermal energy is transmitted through. Finally, 'A' is the cross sectional area or the face of the material exposed to a heat load. Examples of thermal resistances due to heat conduction consist of the Tufflite liner of the greenhouse, the concrete base, aluminum trough, and the soil. Heat loss due to convection can be represented as the following equation.

$$R_{con\,vection} = \frac{1}{hA}$$

Thermal resistance due to convection is important, especially for the water flowing through the troughs and air flow over the Tufflite cover. Built in EES function solved for the convection coefficient 'h.' This convection coefficient is specifically characterized by a Reynolds and Prandtl number correlation that is derived through experimental methods. The build in EES function used in this case is referred to as *Nellis and Klein* correlation for duct flow. All thermal resistances are summed accordingly to the following equations.

$$\mathrm{U} = \frac{1}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{R_n}}$$

The overall EES code consists of 78 variables and 78 unknowns. Four variables were incremented accordingly, such as the Braidwood seasonal air temperatures, Exelon cooling pond temperature, volumetric flow rate, and height of the water channels. For instance, the volumetric flow rate varied from 10 gal/min to 90 gal/min per channel, while water temperature, height of the channel, and outside air are remained constant. This allowed the mechanical team to understand the system response due to changes in temperatures about the length of the trough system. For instance, the inside air temperatures of the greenhouse can be found as well as soil temperature variations about the length of the trough can be found. Finally, for visual purposes, a temperature distribution of a two foot long section of the water trough was made in Pro/Engineer Mechanica.

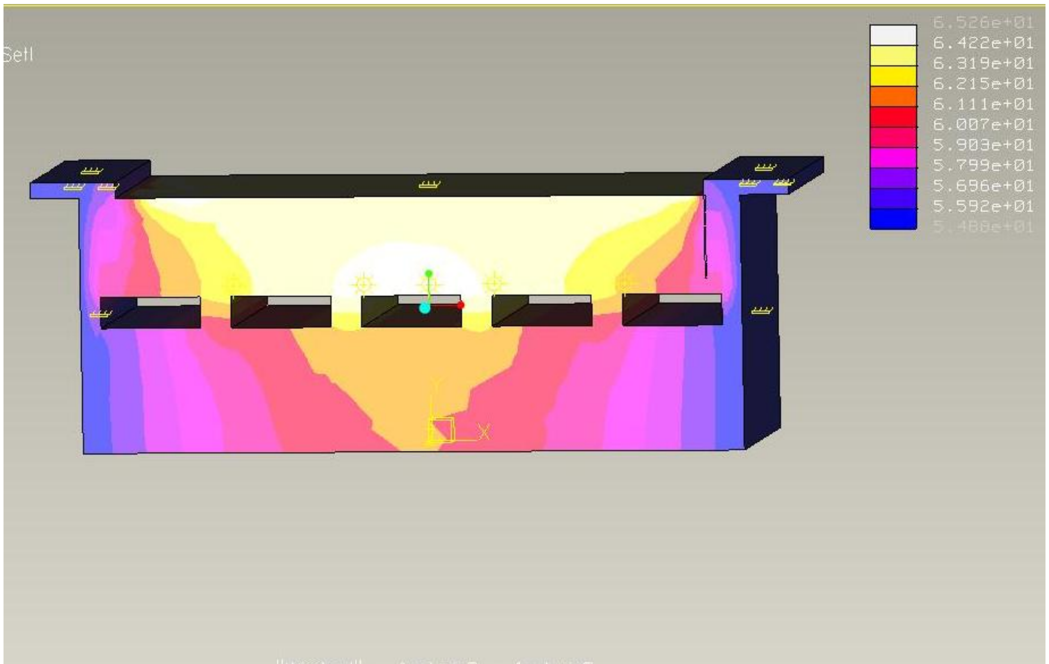


Figure: Temperature Distribution

The temperature distribution in image was created by applying convection and constant temperature boundary condition on the surface of the concrete (see first image of this section). A constant heat load was applied under the aluminum trough. The temperature scale indicated a maximum temperature of 65 ºF at the very center of the trough. The reason for this is due to the low temperature of the air inside the greenhouse as well as convection due to fans moving air on the inside. This results in a two dimensional heat conduction with a heat flux pointing upward and outward from the water channel to the top soil. Values in the analysis are based on the calculated results. Lastly, the thermal analysis was limited due to computational limits. However, a simple temperature distribution of the cross section for the entrance region is consistent with the calculations made in EES. Therefore, it is suggested by the mechanical team, that the ninety-six foot trough be divided into forty-eight two foot long sections to study the temperature profile about the length of a single trough.

```
"Units"
"Area = ft^2"
"Density = lbm/ft^3"
"Length = feet"
"Mass Flow Rate = lbm/hr"
```

"Pressure = psia"
"Specific Heat = Btu/lbm-R"
"Temperature = degrees Rankine"
"Thermal Conductivity = Btu/hr-ft-R or Btu/hr-ft-F"
"Thermal Resistance = Btu/hr-ft^2-R"
"Velocity = ft/min, ft/s, ft/hr"
"Volumetric Flow Rate = gal/min, GPM"

"Conversions"
"1 ft = 0.3048 meters"
"1 GPM = 0.13368 ft^3"
"1 W/mK = 0.57779 Btu/hr-ft-F"

Concrete_Width = 3 / 12 "3inch concrete width"
Channel_Width = 5 - (2*Concrete_Width) "Soil width"
Channel_Depth = 0.25 "Depth of Water channel"
Channel_FlowArea = Channel_Width * Channel_Depth "Flow face area"
Channel_Length = Greenhouse_Length / Factor "Length of each channel"
cp_Water = Cp(Water,T=T_WaterEntering,P=Pressure_Water)
cp_OA = Cp(Air,T = T_OA)
cp_v = cp_OA * rho_OA

D_Greenhouse = Greenhouse_Height "Greenhouse Diameter"

{Factor = 2} "If Factor = 1, then a total of 4 channels are used that run the length of the Greenhouse. If Factor = 2, then a total of 8 channels that run half the length of the Greenhouse"

Greenhouse_Length = 96 [ft]
Greenhouse_Width = 30 [ft]
Greenhouse_Height = 13 [ft]
Greenhouse_SA_Cylinder = (2*PI*Greenhouse_Height*Greenhouse_Length)/2 "Cylindrical exterior surface area of greenhouse"
Greenhouse_SA_Ends = PI*(Greenhouse_Height^2) "Surface area or greenhouse ends"
Greenhouse_Volume = (PI*(Greenhouse_Height^2)*Greenhouse_Length)/2 "Interior Volume of greenhouse"
Greenhouse_ACH = 1 "Greenhouse air changes"
{GPM = 60} "Select GPM and look at temperatures, Greenhouse air and Soil temperatures specifically"
GPM_Total = (4 * Factor) * GPM "Total GPM per greenhouse"

{Height = 8.8}

k_Air = 0.1336 "Btu/hr-ft-R"
k_Aluminum = 136.4 "Btu/hr-ft-R"
k_Soil = 2 * 0.57779 [Btu/hr-ft-F] "Depending on soil moisture content k varies from 0.16 to 4 W/mK, increasing with moisture. Taken as 2 W/mK for calculcation"
k_Tufflite = 0.21* 0.57779 [Btu/hr-ft-F] "From sources, k = 0.21 W/mK. 1 W/mK = 0.57779 Btu/hr-ft-F"

Pressure_Water = 30 "assumed water pressure"

```
Pressure_OA = 14.7

R_Water = 1 / h_T "Thermal resistance of water film"
R_Aluminum = Thickness_Aluminum / k_Aluminum "Thermal resistance of aluminum"
R_Soil = (Thickness_Soil / k_Soil) * 5.678263 "Thermal resistance of soil, 1 m^2-K/W = 5.67827 hr-ft^2-F/Btu"
R_Air = Thickness_Air / k_Air "Thermal resistance or air. Greenhouse modeled as rectangular, with an average height calculated as 8.8ft"
R_Tufflite = (Thickness_Tufflite / k_Tufflite) + (1/h_OA) "Calculated R-Value for Tufflite. From sources, R-Value = 0.4348 hr-ft^2-R/Btu"
R_Tufflite = 1 / U_Tufflite "Calculate U-Value. From sources, U-Value = 2.3 Btu/hr-ft^2-R. Calcaluated at ~1.8 (Due to effect of h_OA)"
RelRough = (0.001 + 0.00333) / 2 "Average relative roughness of concrete"

rho_OA = Density(Air,T = T_OA,P = Pressure_OA)
rho_Water = Density(Water,T=T_WaterEntering,P=Pressure_Water)

{T_OAF = -10} "Variable outside air temperature, can range from -10F to 30F during winter months when the discharge temperature is 70F at the low end up to ~80F"
T_OA = ConvertTEMP(F,R,T_OAF) "Convert  outside temperature to degrees Rankine"
T_WaterEntering = ConvertTEMP(F,R,T_WaterEntering_F)
T_Greenhouse = (T_GreenhouseE + T_GreenhouseL) / 2 "Average greenhouse temperature"
T_GreenhouseSurface = (T_GreenhouseSurfaceE + T_GreenhouseSurfaceL) / 2 "Average greenhouse outside surface temperature"
Thickness_Air = 8.8 "Greenhouse modeled as rectangular with this height"
Thickness_Aluminum = (1 / 8) / 12
Thickness_Soil = 10 / 12 "10inch soil depth"
Thickness_Tufflite = (5 / 1000) / 0.3048 "5mm thick tufflite plastic cover"

Velocity_OA = 15 [mi / hr] * 5280 [ft / mi] * (1 [hr] / 60 [min]) "Assumed outside wind speeds"
Velocity_Water_ft_s = Velocity_Water / 60 [s / min] "Calulates velocity of water through individual water channel in ft/s"

"Correlations"
CALL DuctFlow( 'Water', T_WaterEntering, Pressure_Water, m_dot_Water, Channel_Depth, Channel_Width, Channel_Length, RelRough: h_T, h_H, DELTAP, Nusselt_T,  f, Re) "Determine h-value for water film in channel"
CALL External_Flow_Cylinder('Air', T_OA, T_GreenhouseSurface,  Pressure_OA, Velocity_OA, D_Greenhouse: F_d\L_OA, h_OA, C_d_OA, Nusselt_OA, Re_OA) "Determine h-value for air film over exterior of Greenhouse"

"Design Equations"
GPM = Velocity_Water * Channel_Width * Channel_Depth * (1 / 0.13368) "Set the GPM and solve for water velocity in ft/min"
m_dot_Water = rho_water * Velocity_Water * (60 [min] / 1 [hr]) * Channel_Width * Channel_Depth "Find mass flow rate or water in ft^3/hr"
Q_Transfer = (4 * Factor) * m_dot_Water * cp_Water * (T_WaterEntering - T_WaterLeaving) "Find T_WaterLeaving"
```

Q_Transfer = (((U_Tufflite * (T_Greenhouse - T_OA)) * (Greenhouse_SA_Cylinder + Greenhouse_SA_Ends)) + (cp_v * Greenhouse_Volume * Greenhouse_ACH * (T_Greenhouse - T_OA))) * 1.2 "Energy Balance, Sum of the heat transfer from channels = Heat loss from Greenhouse"
Q_TransferDPE = ((T_WaterEntering - T_OA) / (R_Water + R_Aluminum + R_Soil + R_Air + (R_Tufflite + (Factor/h_OA)))) "Heat Flux from channel"
Q_TransferDPL = ((T_WaterEntering - T_OA) / (R_Water + R_Aluminum + R_Soil + R_Air + (R_Tufflite + (Factor/h_OA)))) "Heat Flux from channel"
Q_TransferDPE = ((T_WaterEntering - T_GreenhouseSurfaceE) / (R_Water + R_Aluminum + R_Soil + R_Air + R_Tufflite)) "Heat Flux from channel to find Surface temperature at outside of greenhouse at the entrace of the greenhouse"
Q_TransferDPL = ((T_WaterEntering - T_GreenhouseSurfaceL) / (R_Water + R_Aluminum + R_Soil + R_Air + R_Tufflite)) "Heat Flux from channel to find Surface temperature at outside of greenhouse at the exit of the greenhouse"
Q_TransferDPE = ((T_WaterEntering - T_GreenhouseE) / ((R_Water/Factor) + R_Aluminum + R_Soil + (Height / k_Air))) "Solve for Greenhouse temperature at entrace of channel"
Q_TransferDPL = ((T_WaterLeaving - T_GreenhouseL) / ((R_Water/Factor) + R_Aluminum + R_Soil + (Height / k_Air))) "Solve for Greenhouse temperature at exit of channel"
Q_TransferDPE = ((T_WaterEntering - T_SoilE) / (R_Water + R_Aluminum + R_Soil)) "Solve for Soil temperature at entracne of channel"
Q_TransferDPL = ((T_WaterLeaving - T_SoilL) / (R_Water + R_Aluminum + R_Soil)) "Solve for Soil temperature at exit of channel"

"Standard Units"
{T_WaterEntering_F = 70} "Discharge water temperature, 70F used as lowerst case, can range from ~70 to ~100, winter - summer"
T_WaterLeaving_F=ConvertTEMP(R,F,T_WaterLeaving)
T_Greenhouse_F=ConvertTEMP(R,F,T_Greenhouse)
T_SoilE_F=ConvertTEMP(R,F,T_SoilE)
T_SoilL_F=ConvertTEMP(R,F,T_SoilL)
T_GreenhouseE_F=ConvertTEMP(R,F,T_GreenhouseE)
T_GreenhouseL_F=ConvertTEMP(R,F,T_GreenhouseL)
T_GreenhouseSurfaceE_F=ConvertTEMP(R,F,T_GreenhouseSurfaceE)
T_GreenhouseSurfaceL_F=ConvertTEMP(R,F,T_GreenhouseSurfaceL)

Appendix I: Contacts

Joe Cosgrove
Head of Godley Park District
815-458-2787

Victor Gloria
Principal Regulatory Specialist at Exelon Generation Company
630-657-3736

Rob Grigetti
Operator of Water Plant and Water Distribution System in Braidwood
815-458-2333

Tom
Braidwood DNR Office
815-237-0063

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Appendix K: Description of The IPRO Program

The Interprofessional Projects (IPRO®) Program at Illinois Institute of Technology

An emphasis on multidisciplinary education and cross-functional teams has become pervasive in education and the workplace. IIT offers an innovative and comprehensive approach to providing students with a real-world project-based experience—the integration of interprofessional perspectives in a student team environment. Developed at IIT in 1995, the IPRO Program consists of student teams from the sophomore through graduate levels, representing the breadth of the university's disciplines and professional programs. Projects crystallize over a one- or multisemester period through collaborations with sponsoring corporations, nonprofit groups, government agencies, and entrepreneurs. IPRO team projects reflect a panorama of workplace challenges, encompassing research, design and process improvement, service learning, the international realm, and entrepreneurship. (Refer to http://ipro.iit.edu for information.) The IPRO 342 team project represents one of more than 40 IPRO team projects for the 2010 Spring semester.

Appendix L: Acknowledgements

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