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Kate Gleason College of Engineering
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Rochester Roots Adaptable High Tunnel

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Abstract

A high tunnel (or hoophouse) is typically a bare-bones, lightweight greenhouse with the sole purpose of extending the growing season further into the winter months using little to no energy. The following proposed high tunnel seeks to achieve year-round growing in the same lightweight structure with the addition of minimal, efficient heating and lighting. Full-scale, transient thermodynamic analysis of the high tunnel was necessary for determining the most effective method of maintaining desired internal temperatures. A scale model was then constructed for the purpose of testing various design possibilities. The end result of this project will be a turnkey design of a high tunnel capable of growing food year-round in a USDA Zone 6a environment.

Picture 1: Students help Rochester Root members in assembling the high tunnel.

Introduction

Urban agriculture is vital for growing urban areas as topics such as food security and sustainability become more important to individuals. Rochester Roots aims to "develop a comprehensive social, educational program, using urban agriculture as the vehicle."[1] This requires a safe and capable learning environment in which these goals can be realized.

The original structure shown in Picture 1 has already proven fruitful for many seasons, and will continue to produce even more food now that it can operate during the November - February months. This high tunnel is located at Clara Barton School #2 in the City of Rochester, and has provided countless opportunities already to local children and young adults who want to learn more about agriculture.

This project, as it is a learning tool, differs in that it will not be a product of years of gardening experience and trial and error. The problem of maintaining adequate temperature is approached analytically, to be verified empirically. Additionally, this project will seek the use of 'green' resources such as rainwater, infrared radiation, and the thermal mass of the earth. The engineering methods used to arrive at the final design are detailed in the sections that follow, as well as details of the features and capabilities of the final design.

Methodology

Figure 1: Systems Breakdown

In order to create an environment conducive to growing, this system must maintain a set of favorable conditions relating to water, light and temperature. The most important (and difficult) of these is maintaining the soil temperature near the surface and the air temperature within the high tunnel at or above 10°C. The second challenge is transmitting adequate light during the naturally low-sunlight, winter months of Rochester. The amount of UV radiation required for satisfactory growth equals 15 mol/day. This light must also be coming from across at least 70% of the spectrum for ideal growth. The last remaining ingredient for a healthy growing environment is plenty of water. A suitably large supply of collected water must be available to provide about 1.0" of rainfall (60 gallons/100 ft^2) per week.

Minimum Temperature	10 (40)	°C (°F)
UV Light Transmission	> 15	mol/day
% of Spectrum Transmission	> 70	N/A

Table 1: Summary of Environmental Requirements

While the main goal of this design is to allow for winter growing by meeting the above criteria, there are a number of additional requirements that must be fulfilled. The previously mentioned requirements only relate to the actual growing of plants but this high tunnel must also be used by the community. This brings up a number of additional requirements pertaining to its accessibility, convenience of working within the high tunnel, safety for all people involved, and also a certain level of resistance to damage.

Removable/Adaptable Panels	Yes/No	N/A
Work Area Available	> 96 (8.9)	ft^2 (m^2)
Irrigation Storage Size	250 (946)	gal (liters)
Changeover Time for 2 ppl.	< 1	hour

Table 2: Summary of Usability Requirements

The only remaining constraint on the design is the budget. Rochester Roots has placed a $15,000 maximum on any possible design. The details of how the final high tunnel design accomplishes these objectives will be detailed in the following sub-sections; one section per subsystem.

Enclose Garden

The high tunnel is being converted from a completely soft covered tunnel to a partially hard-covered and partially soft-covered design. This is done to discourage any vandalism and unauthorized access to the high tunnel; the idea being that a more formidable barrier will deter possible vandalism. The panels must also be adaptable so that the high tunnel functions optimally year round. The high insulation values that come with hard paneling would cause undesirably high temperatures in the high tunnel during the warmer months, which is not allowable. To overcome this, the side walls can be opened and locked in place to allow for drafts and ventilation in the high tunnel whenever necessary.

The roof will be covered in 6 mil polyethylene plastic sheeting held in place by spring lock wires in U-channels. The end walls and side walls will be covered in 8mm Deglas Acrylic paneling. This material is a twin wall design which offers an above average R value of 1.74 and a very high UV transmission of 86%. Deglas Acrylic was chosen over polycarbonate paneling because these two critical values were much lower for polycarbonate, which is also much more breakable.

The panels' edge has been treated with a rubber insulation to form a tight barrier with the metal frame of the high tunnel when closed. When ventilation is necessary, simply unlatch the desired number of side panels and the spring will automatically open them. The tops of the panels are attached to the steel frame via a simple hinge, however the bottoms of the panels are attached with a temperature control self-actuator, produced by Univent. This allows for the panels to open automatically when the temperature rises.

Sustain Adequate Temperature

One of the biggest challenges of year-round plant growth in a USDA Zone 6a environment is maintaining adequate temperature for plants to survive. Even the heartiest winter vegetables such as kale and broccoli cannot live in temperatures dropping below 35°F for very long. To combat this, thermal energy must be added to the system in some way to prevent these hard frosts from freezing the soil and killing the plants. Traditionally, people have been using space heaters in greenhouse-type environments to keep the air and soil temperatures at sufficient limits. This method, however, has been proven to be extremely inefficient, as air's relatively low mass doesn't allow it to store much of the thermal energy being transferred to it. As a result, heat must be constantly added to the system, most of which is lost through low insulation greenhouse walls.

Through analytical means, it has been proven that utilizing the soil as the "thermal mass" in which heat is added is far more efficient than the conventional method of heating the air. The soil's far superior mass allows it to serve as a thermal bank, that is, it will store excess amounts of thermal energy and slowly release it into the system as needed. As a result, more of the energy added to the system stays with the system.

Our proposed method of maintaining adequate temperature consists of three features: **(1)** Subterranean electric heating cables controlled by a thermostat **(2)** Insulation in the soil creating a thermal boundary between our growing environment and the earth **(3)** Low tunnels.

1. Subterranean Heating

Three sections of 600 meter Heatsafe© electric heating cable, buried at a depth of 2' and secured in place with chicken wire, will be used to add thermal energy to the soil underneath the South, middle, and North beds of the high tunnel.

2. Soil Insulation

To more effectively utilize the thermal energy added to our system, Foamular© 150 2" insulation will be placed along the soil boundaries, both along the edge of the high tunnel and at depth of 4'. To allow proper drainage of the soil, a series of 0.5" diameter holes will be placed every 12" along the bottom insulation.

3. Low Tunnels

Low tunnels will be implemented into the system as they are traditionally used, that is, a series of metal hoops will run along the each plant bed with the spun nylon tightly covering them.

Sustain Adequate Light

Lighting is an integral part of plants daily nutrients to help it thrive in a growing environment. Sunlight is the ideal way to provide the energy plants need for photosynthesis, however in the winter months, there is very limited sunlight and less intense rays making it much harder for plants to grow. To accommodate for this, grow lamps are used to provide the amount of sunlight exposure and suitable wavelengths to support plant growth[2]. Grow lights have five attributes that the effectiveness of the system depend on **(1)** Lamps **(2)** Reflectors **(3)** Distance from plants **(4)** Area coverage **(5)** Timers and zoning.

1. Type of Light

The supplemental light will come from 600W metal halide lamps. Metal halide lamps emit "blue" light (wavelength of 450–495 nm), which is desirable when growing "winter vegetables" such as kale, lettuce, and broccoli.

2. Reflectors

Each ballast has a rectangular reflector around the lamp. The reflectors are used to direct the light from the lamps and increase the area that adequate light reaches.

3. Distance from Plants

The distance the lamps are from the plants affects the amount of light the plants get as well as the area covered. For this design, it is recommended that the lamps be two feet from the tops of the plants so that they receive the correct mols/day required. The ballasts also come with an adjustable pulley system allowing for easy adjustment of the distance.

4. Area Covered

As mentioned above the distance the lamps are from the plants affects the area covered. A distance of two feet from the plants would create the layout shown in Figure 2. This layout would require a minimum of twelve ballasts so that every area receives adequate light. The layout was designed to optimize the area a single ballast can provide energy to so that the fewest number of ballasts were needed. The yellow squares represent where the reflectors are hung and the areas that get the full energy from the lights. The white squares represent the areas that get the overlapping residual lighting however these areas are still getting the required amount of energy needed to sustain plant growth.

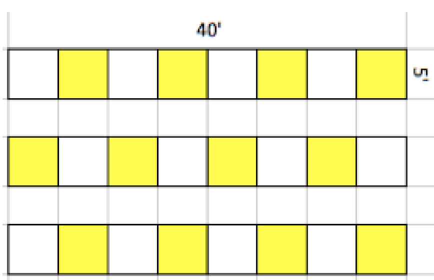


Figure 2: Layout of Lighting System

5. Timers and Zoning

The system will be on a set of two timers. These timers are split between two sections of the growing area to allow for "zoning" the lighting those areas receives. This means that two sections of the high tunnels can receive lighting for different durations during the day. This is important because some plants do not require as much lighting as others.

Provide Water

Sufficient water, in addition to adequate lighting and temperatures, needs to be provided to allow plants to grow and thrive. Even if water is provided, if it is not enough to meet the needs of the growing space, the plants' growth will be stunted and their production minimal.

A need of 1" of water a week (60 gallon/100 ft^2) was identified as an industry standard. The high tunnel measures 20'x48', therefore a minimum need of about 288 gallons a week was calculated with that number increasing as the temperature increases. By analyzing the Typical Meteorological Year data[3] for the past ten years in Rochester and balancing the size and cost of the tanks led to the design choice of two 550 gallon water tanks.

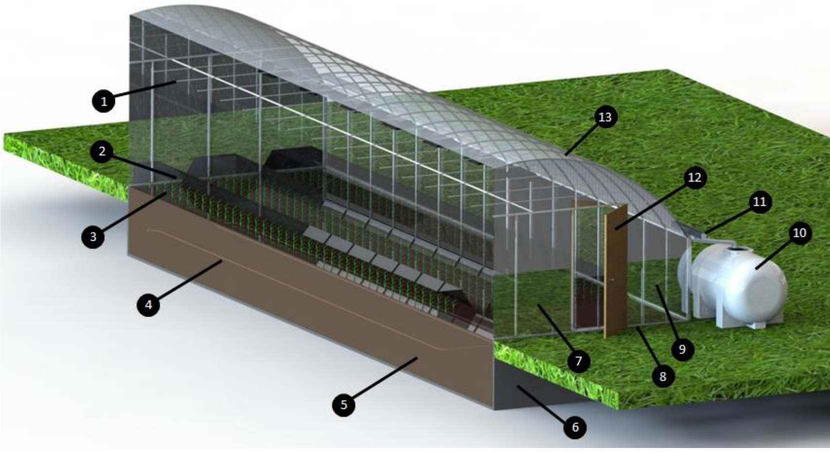
Gutters will be mounted at an angle along the edges of the high tunnel roof. These gutters will catch water runoff from the roof and will transport that water to the storage tanks at the front of the high tunnel. In 2012, a team at

Iowa State University created a design for carrying water out to the tanks and allowing for overflow that was geared toward a more serious grower and this design is based heavily on that.[4]

Once water is stored, it flows from the two tanks to a central point, where it is filtered and then pressurized by use of a centrifugal pump. The pressure is then reduced slightly with a regulator before flowing in to a header main line that extends the width of the high tunnel. Branching off of this main line is drip lines with emitters punched every 12” to allow water flow out at slow controlled pace of. To address the threat of below average rainfall, and the necessity to water in the winter, an adapter will be placed in between the pump and pressure regulator to allow an outside water source to be attached. The rain catchment system must be disassembled prior to the first major snowfall and the tanks must be completely drained to ensure there is no damaged to the system as a result of snow weight, or freezing water.

Final Design Summary

The 3D model pictured in Figure 3 represents the final design. The features discussed have been labeled.



Item No.	Description
1	600W Metal Halide Lighting Luminaries
2	Low Tunnel Covers
3	Plants
4	Heating Coils
5	Soil
6	Soil Insulation
7	Deglas Acrylic Non-Adaptable Front and Back Panels
8	Steel Frame
9	Deglas Acrylic Adaptable Side Panels
10	550 Gallon Water Tank
11	Gutters
12	Door
13	Polyethylene Sheeting

Figure 3: Cutaway of Final High Tunnel Design with Feature List

Scaled Test Facility

Before the full-scale design is implemented, testing must be done to verify that the design choices made are credible and produce the desired results. To do this, a scale model of the high tunnel was developed to experiment with various features of the full-scale design. Shown in Figure 4.

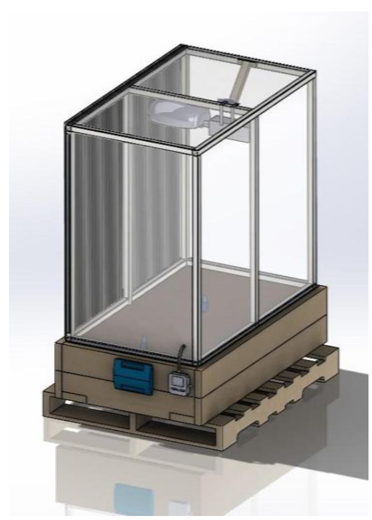


Figure 4: 3D Model of Test Facility

The budget for the test facility comes from the Multidisciplinary Senior Design office and totals $1000. The test facility consists of a simple wooden box that has been screwed to a stand pallet for ease of transportation. A metal frame was cut and welded; it fits snuggly inside the wooden box. Different prototype polycarbonate panels were attached to the two available spaces on the hard panel side (pictured facing away in Figure 4). This test facility contains soil heating cables in the middle layer of soil; about a 6” depth from the surface. The wire was zip tied to a wire mesh as shown in Picture 2. In order to verify the effectiveness of the soil heating cables, two lengths were installed: the calculated length of 10m and a conservative estimate of 3.5m.

Picture 2: Heating Coils in Test Facility Before Covered in Soil

Experiments and Results – Scaled Test Facility

Several tests were planned that would verify the effectiveness of the heating cables and light fixture. These all have the same method of testing: observe the change in temperature over time from steady state room temperature to steady state freezer temperature. Four Measurement Computing USB dataloggers were used to collect data from just below the soil surface, the center layer of soil, just above the base of the soil box, and the internal air temperature as well.

The first trial produced poor results; the soil box reached and remained at the freezer temperature. After inspecting the setup it was clear that the transformer had tripped and no power was getting to the thermostat. The second trial was started after the soil box had reached room temperature. After another two days the dataloggers were collected and the results were the same: no heat from the cables. It was evident after this point that there was an electrical problem within the thermostat. The power light on the thermostat showed power was going to the thermostat, but no power was reaching the cables. The coupling from the thermostat to the heating cables turned out to be broken. Both the positive and the negative wires were not connected or were pulled out of their contacts. Considering the care that was taken during the installation, the only possible conclusion is shoddy craftsmanship.

Once the problem was diagnosed and fixed, a new trial began. Due to time constraints, the test facility was not brought back to room temperature, but remained at 3° C when the tests began. The expected results here are to see the soil temperature rise from 3° C to > 10° C. Figure 5, below, shows the temperature behavior over time.

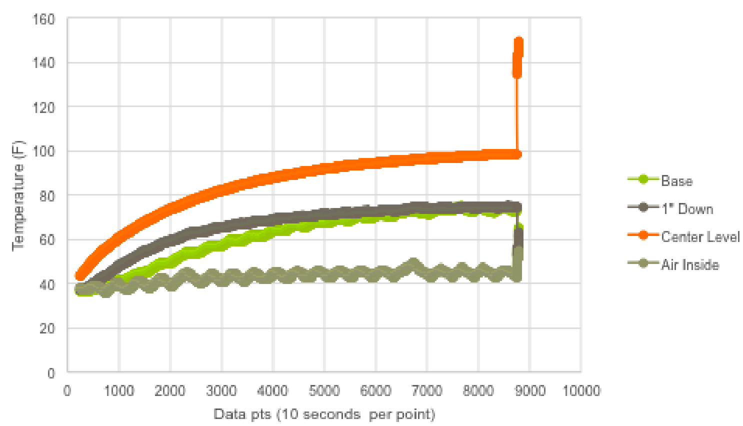


Figure 5: Test Results

Simulation Result

To analyze this system, a full-scale, transient thermodynamic model for both the existing structure and the new design. A thermal circuit of the high tunnel was created that takes into account all thermodynamic processes from the soil to the atmosphere. It is pictured below in Figure 6.

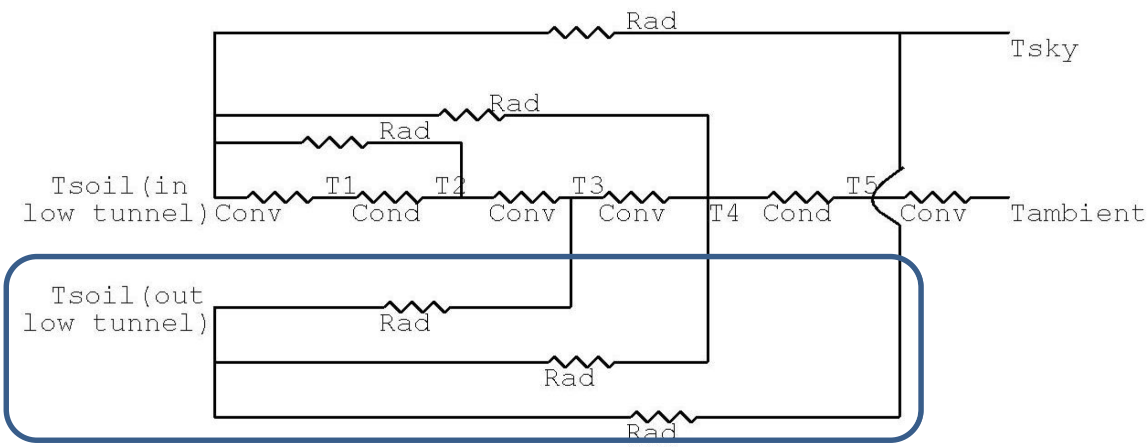


Figure 6: Thermal Circuit of the High Tunnel

The lower portion (boxed) of the thermodynamic model is ignored in order to solve this circuit. The area being ignored consists of walkways and the work area at the end of the high tunnel. Temperature data for Rochester was acquired from the National Solar Radiation Database, and was used as the outdoor air temperature. Initial values for indoor air temperature, soil temperature inside and outside, were all set equal to the first temperature of the typical metrological year. The simulation was run from October through February, as those are the only relevant months for the project. The results of this model are shown before and after the upgrade in Figures 7 and 8.

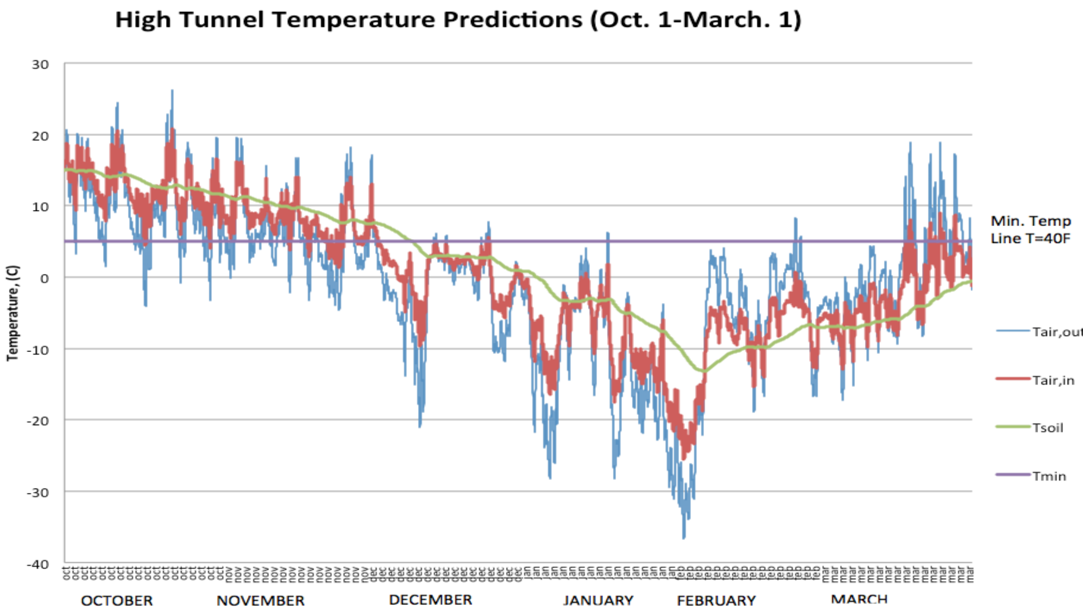


Figure 7: High Tunnel Temperature Simulation- Current State

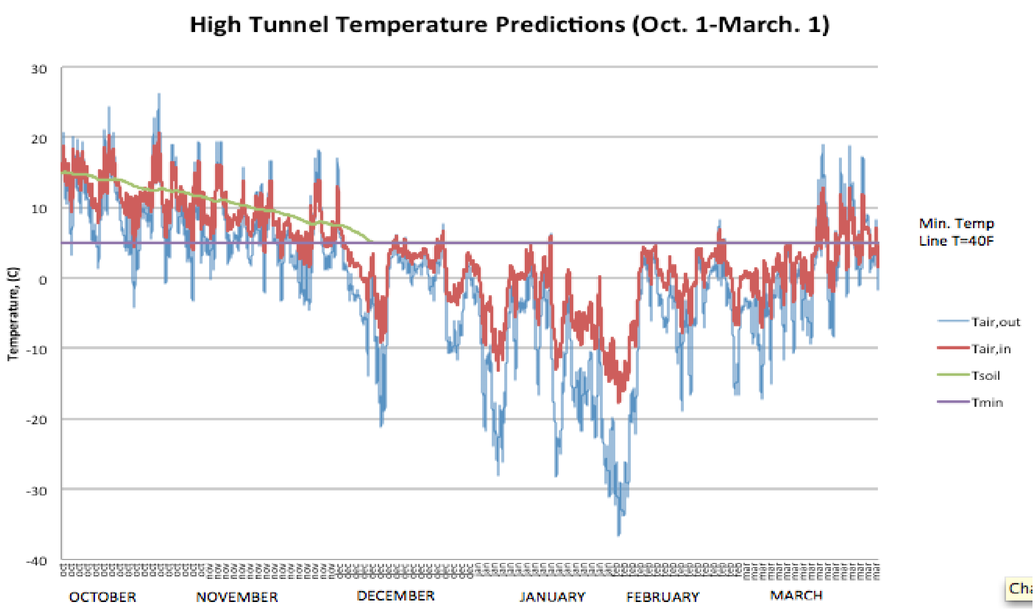


Figure 8: High Tunnel Temperature Simulation- New Design

Conclusions and Recommendations

When considering the main objectives of this project, it is evident that the new design will satisfy the of an in-depth thermodynamic simulation as well as a scaled test facility, the proposed design will maintain soil temperatures above the target 10° Celsius. By insulating the soil underneath the high tunnel, and putting all heat energy into that thermal mass, there is much less heat loss during the crucial winter months. Additionally, the requirements of protecting the high tunnel and adapting to warmer weather is satisfied by the side panels. The auxiliary light and water storage capacity finish this sustainable growing environment.

Though the objectives of the project have been met, there are always ways to improve. Most prominently, finishing the variety of heating tests would verify the efficacy of the heating cables and the lighting. These tests would consists of items such as testing heat sinks and black bodies, testing different lengths of heating cables, and testing the heat benefits from auxiliary lighting. Further progress can also be made in general product selection; using different distributors could result in a lower overall build cost. Lastly, the creation of a specific build manual would be helpful for potential customers/recipients of this high tunnel package. Though the method of achieving the requirements has been completed, there are still minor construction details that would be covered in a build manual.

Appendix

Table 3: Bill of Materials for Heating System

Component	Quantity	Make/Model	Estimated Cost	Where to buy?
4' Soil Excavation and return	N/A	N/A	$2,000	
Foamula 150 2" Thick	(47) 8'x4' Sheets	Foamula 150 2" (R=10)	$893	Home Depot, Menards.com
Heatsafe Heating Cable	215 meters X(3)	HHS1 Heating Cable (110V High Output Per Meter)	$3,228.15	Heatsafe.com
Pre-punched Metal Strip Per meter	61 meters X(3)	PPS/A Heatsafe Pre-punched Metal Strip	$150.00	Heatsafe.com
Thermostatic Controller	1	AT-A Heatsafe Thermostatic Controller (Adjustable Thermostat)	$37.54	Heatsafe.com
Strip Free End Seal	3	SF-E Heatsafe© Strip Free End Seal	$7.32	Heatsafe.com
Cable Connector (Type F)	3	CCF/F/FS Heatsafe© Cable Connector Type F	$10.77	Heatsafe.com
Cable Connector Male (Type B)	3	CCM/B/RP Heatsafe© Cable Connector Male Type B	$10.77	Heatsafe.com
RCD and Mains Plug	3	PL/US Heatsafe Plug	$12.75	Heatsafe.com
Cable Connector Female (Type C)	3	CCF/C/RP	$10.77	Heatsafe.com
Cable Connector Male (Type A)	3	CCM/A/RS	$10.77	Heatsafe.com
Cable Connector Femal (Type D)	3	CCF/D/RS	$10.77	Heatsafe.com
		Total=	$6,383	

Table 4: Bill of Materials for Panels

ITEM NO.	DESCRIPTION	Part #	COST	SOURCE
1	8mm Deglas Acrylic	CPC-DG8 40	$2,300.00	Greenhouse Megastore
2	Sun Master 6 MIL (1 Layer) 50 ft	108658	$212.40	Growers Supply
3	Foam Insulating Tape	64614-0002	$167.50	FoamTape.net
4	Piano Hinges (4 ft x 24)	1581A521	$155.76	Mcmaster
5	SPRING LOCK HOLDER	102197	$107.88	Growers Supply
6	SPRING	102198	$25.80	Growers Supply
8	Sealing Tape		$8.70	
9	Low Tunnels	GR-RC1506-	$42.00	
			$3,020.04	

ITEM NO.	DESCRIPTION	QTY.	COST
1	1 1/4" SQUARE STEEL TUBING - 51 7/8"	6	$150.00
2	1 1/4" SQUARE STEEL TUBING - 48 3/4"	2	
3	1 1/4" SQUARE STEEL TUBING - 22 1/2"	4	
4	1 1/4" SQUARE STEEL TUBING - 27"	5	
5	STANDARD 40" x 48" x 5" PALLET	1	$0.00
6	2" x 6" x 52" LUMBER	6	$35.00
7	2" x 6" x 30" LUMBER W/ CUTS	2	
8	2" x 6" x 30" LUMBER	2	
9	1" x 3" x 8" W/ CUTS	8	
18	Foam Rubber Insulating Tape	1	$16.00
28	Piano Hinge - 30"	2	$17.94
29	Liquid Nail Caulk	1	$9.00
30	Foam Sealant	1	$8.00
25	TARP - 22 FT^2	1	$8.00
26	1 LB BOX OF WOOD SCREWS	1	$9.00
27	1 LB BOX OF METAL SCREWS	1	$6.00
10	SPRING LOCK HOLDER	2	$22.28
11	SPRING LOCK HOLDER - 40"	2	
12	SPRING LOCK HOLDER - 48 1/2"	2	
31	Clear Patch Tape	1	$4.00
14	PLASTIC SHEETING - 42.4 FT^2	1	$26.66
19	HEATSAFE THERMOSTAT	1	$181.00
20	HEATSAFE COILS	1	
13	DIRT ~600lbs	1	$0.00
15	8MM Polycarbonate Panel	1	$100.94
21	Thermocouples/Dataloggers	4	$0.00
32	Gutter Material	1	$86.00
33	Prototype Hinge	1	$75.00
28	Additional Costs + Shipping	1	$13.69
		TOTAL	$768.51
		+/- Orig.	$110.61

Table 5: Bill of Materials for Test Facility

Lighting BOM	QTY	Cost per	Source	Total Cost
Ballast	12	$130.00	Home Depot	$1,560.00
600 W Metal Halide Bulb	12	$30.00	Home Depot	$360.00
Reflectors	12	$50.00	Home Depot	$600.00
Timers (optional)	2	$40.00	Home Depot	$80.00
Light Meter (optional)	1	$100.00	Home Depot	$100.00
				$2,700.00

Table 6: Bill of Materials for Lighting

Table 7: Bill of Materials for Water System

Description	Qty	Cost	Extended Cost	Source
#9 wire	1	9.88	9.88	Lowes
1/4" bolts with nuts	12	3	3	Lowes
115 V Demand Pump	1	189	189	Amazon
2 brass spigots	2	10.99	20	Lowes
200 mesh filter (3/4")	1	13.85	13.85	Amazon
3/4" Hose/Faucet Connector	1	2.8	2.8	Leevalley
4"x4" wood post	1	13.57	13.57	Lowes
downspout adapter to fit drop outlet	2	4.97	9.94	Lowes
downspout elbow	2	2.34	4.68	Lowes
Downspouts 10'	2	8.34	16.68	Lowes
Drip tubing with emitters (1/2")	3	29.97	89.91	Amazon
Drop outlets	4	5.88	23.52	Lowes
End clamps (pack of 4) (1/2")	2	6.71	13.42	Amazon
Filter to pump adapter	1	4.4	4.4	Fastenal
Garden hoses (3/4")	2	15	30	Lowes
gutter end caps	4	3.28	13.12	Lowes
gutter mounting brackets	12	3.28	39.36	Lowes
Gutter seal lubricant	1	5.74	5.74	Lowes
Headerline (3/4")	1	22	22	Amazon
Lumber to act as support board(2x4)	2	3.27	6.54	Lowes
Mounting screws (#10 x 1")	4	12	12	Lowes
Norwesco 550 (67" x 42")	2	399	798	Tank-depot
Pressure regulator(40psi)	1	11.5	11.5	Dripworks
Pump container	1	150	150	Sprinkler Warehouse
Raingo 10' sections	12	6.98	83.76	Lowes
Screws to attach boards and gutter brackets				Lowes
slip joints	10	4.28	42.8	Lowes
Vinyl inflatable ball	2	5	10	Lowes
Y connector	2	10	20	Amazon
			1659.47	

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Picture: Jan MacDonald; http://tinyurl.com/lybnts9

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