GNG5140

Design Project User and Product Manual

Sustainable Food Storage

Submitted by:

Team – Sustainable Food Storage

300190376 Can Cui

300242585 Rushi Patel

7300100 Lotty Pontones Ledon

8609464 Zhi Zheng

April 18th, 2022

University of Ottawa

Table of Contents

List of Figures

List of Tables

List of Acronyms

Table 1. Acronyms

Acronym	Definition
DRFH	Deep Roots Food Hub
HVAC	Heating, Ventilation, and Air Conditioning
TOFB	The Ottawa Food Bank
IoT	Internet of Things

1 Introduction

This User and Product Manual (UPM) provides the information necessary for users who want to store food to effectively use the root cellar and for prototype documentation. As climate change persists, crop production is threatened year-round, jeopardizing global food security. This report investigates and analyzes an existing food storage prototype in Eastern Canada: an above-ground vegetable root cellar designed by local grassroots organization Deep Roots Food Hub. Deep Roots Food Hub (DRFH) is a grassroots non-profit organization based in West Carlton that aims to create a safe and sustainable food system in West Carlton, Ontario [1]. The system takes the form of a prototype root cellar. This above-ground cellar and off-grid storage structure provides small-scale vegetable growers with a sustainable and energy-efficient storage facility after the season, offering longer root crop storage and the possibility of extended sales and/or distribution [2].

The report examines build materials and specifications, parameter controls (temperature, humidity, etc.), current issues, and customer needs. Based on the above, this document will show a good food storage solution for the cellar, using shelves and drawers to distinguish different types of food, and improving space utilization. In addition, this document carries out convective heat transfer calculations for the cellar and proposes ideas for the utilization of new energy sources, such as wind energy and geothermal sources. This document will first introduce the background of the cellar, tell users how to use the cellar, and the possible problems and solutions of the cellar. The document also proposes several options for improving the cellar, such as the use of new energy sources. Finally, this document shows the calculations for the three major systems in the cellar: the storage system, the convection heat transfer system and the energy system. This design is aimed at users who want to take advantage of stored food. Attention should be paid to security incidents such as trespassing, fire, etc., users should immediately contact the emergency hotline for help.

2 Overview

Figure 1. Overview of the root cellar

Climate change poses a major threat to crops growth and sustaining the food consumption of our population. Harvests are reduced with climate change, which means that periods of infertility may be extended if supplies are reduced, or if it takes longer to get an adequate harvest. In many food-insecure regions such as eastern Canada, agriculture and food production are seasonal (summer and fall); leaving people to rely on winter and spring harvests. However, the harvest of our local farmers is not enough to sustain the current Easter population in Canada during these seasons. Therefore, many of the foods we consume must be imported from regions with warmer climates. The above factors are the driving force behind the efficient storage of crops throughout the year. Providing long-term storage for crops in a well-designed environment will reduce the likelihood of having to extend the barren period so that enough crops are available. This will maintain a controlled population through the foreseeable harsher weather conditions and uncertain times, which could include higher food prices due to lower production and higher demand. The cellar designed in this document features an innovative Quonset style metal construction that captures and circulates ground-sourced geothermal heat to maintain a near constant +2°C temperature and 90-95% humidity within the structure's root storage compartment [1]. The cellar in this document can not only meet the requirements of food storage temperature and humidity, but also meet the concept of sustainable development with a low-carbon and environmentally friendly design.

The user's needs include expanding the size of the cellar, using separate rooms to store things, having an efficient heat source, maintaining a consistent temperature, maintaining a consistent humidity, and the generator can be turned on automatically without direct manual operation. The novelty of this cellar design is that it achieves ten sustainable development goals through rational planning of the space inside the cellar and rational use of geothermal sources, such as: no poverty, zero hunger, good health and well-being, decent work and economic growth, industry innovation, sustainable cities and communities, responsible consumption and production, climate action, life on land, and partnerships for the goals [3].

Table 2. Key features and major functions of the root cellar

Key features and major functions	System environment
Building dimensions	40’×24’×10’
Power system	Three solar panels Four 12-volt vehicle batteries A backup gas generator Two 250W heaters
Desired values	Two and four centigrade and the humidity between 90 and 95%
Monitoring devices	A Raspberry pi (microcomputer) that connects to Wi-Fi and Cellular to monitor temperature, humidity, battery levels and fan controls. And there is another software component, written in python, used to query for current temperature in the zones, to calculate averages, and to compare against external conditions.
Methods of heating	Heat can be obtained from underground rocks. Gravel floors can provide warmth from the earth.
Methods of cooling	The first is to open the vents at night to cool the cellar with cool outside air. The second method is to utilize Icehouse Strawpile. The air in the cellar can be cooled by ice cubes, and then returns to the cellar to achieve the purpose of cooling.

2.1 Cautions & Warnings

Before using the cellar, the user needs to know that the energy storage of the cellar system is affected by the weather. Because one of the energy sources for this cellar is solar energy, low energy storage can occur when it is cloudy for long periods of time, which can eventually cause the battery to drain completely. Users need to pay attention to power information in real time and use backup batteries when necessary. In addition, it should be noted that the control system may be disconnected from the Internet, and the user needs to contact the technical center. For security incidents such as unauthorized entry and fire, users should immediately contact the emergency hotline for help.

3 Getting started

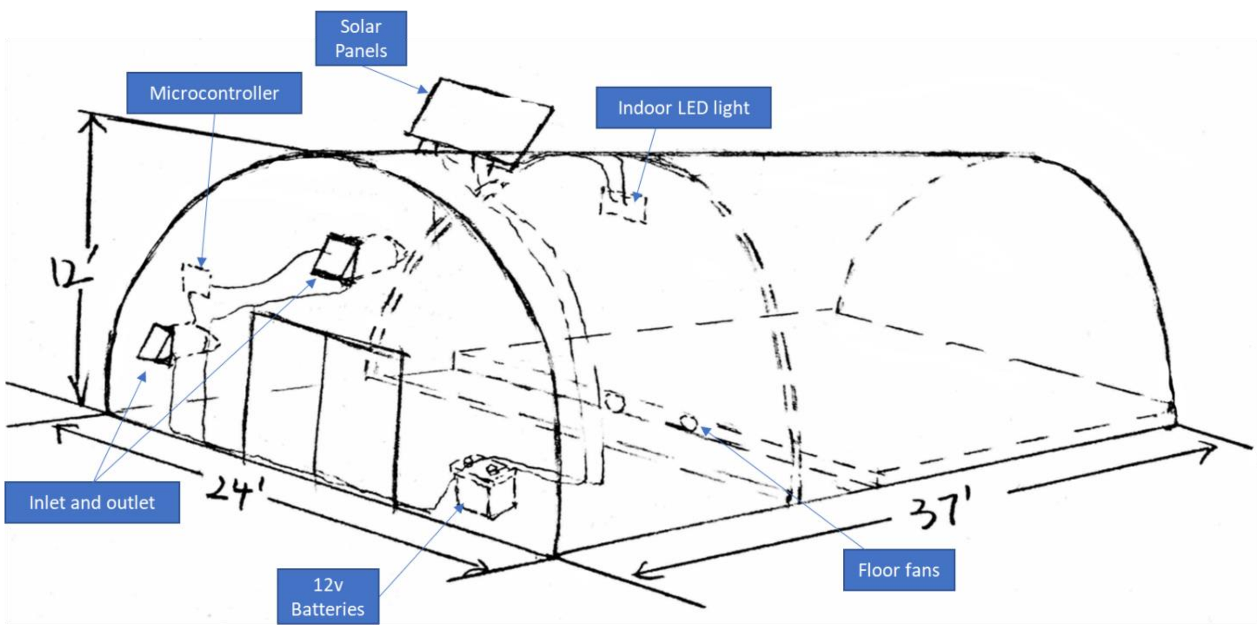

Figure 2. Overview of the root cellar

The above picture shows 3D visual of the overall prototype, due to limited space, the detailed visuals of food storage, wall insulations, and heating/cooling elements are included in the section 3. The prototype uses galvanized steel for the structure, and they are connected by using pins and rivets.

A dividing wall separates the inner space into two sections, the front is an antechamber for equipment storage, and the back is the produce chamber. As agreed with the client, the teams focus will be mainly on the storage method improvement, and the control system is neglected because the current one works very well. Therefore, only the description for control system and its connection with power system are given here. Solar panels are set on the top to provide green energy, and they are connected to vehicle batteries inside the antechamber to store power.

On the front wall, a microcontroller is mounted on it to control inlet, outlet, fans, and all sensors inside the chamber. All electrical wires are taped on the wall to avoid tangling. The intake air fan from outside will run if the outside air is cooler than the inside air, but only if the inside air is above the target range, and the outlet fan exhausts the warm air from inside. The floor fans are only turned on when indoor temperature is below targeting range and the underfloor temperature is between or above the range. To efficiently use the produce chamber space, several food storage methods are proposed and compared in section 3.

3.1 Set-up Considerations

The structure and materials of the cellar: The greenhouse storage cellar is composed of three parts: the cellar body, the roof and the management room. It is semi-underground, built in a north-south direction, and the materials are civil structures. The tiling material of the cellar shoulder is 200 cm×150 cm×5 cm foam board (that is, polystyrene board), with a total of 120 m^2, which needs to be sealed and fixed, and only one piece is left at the front, middle, and back of the top of the cellar aisle. Foam board is used as an artificial control adjustment measure for temperature increase, ventilation and moisture dissipation.

3.2 User Access Considerations

The root cellar is made of galvanized steel structure. The dimension is 40'×24'×10'. And the foundation is made of poured concrete, which is 10''×18'' deep. The geothermal isolation is made of 2'' high density foam, which is covered with 12'' of granular "A" gravel. This extends 5' from poured concrete foundation. The inside walls of the cellar are made of sprayed foam, which provides R60 thermal insulation. The wall on the side of the cellar door is double-layer batt insulation, which can provide R40 insulation. The floor of the root cellar is made of 3/4'' plywood and 2'' Styrofoam sheet.

3.3 Accessing the System

To access the root cellar, you need to contact our client Dr. Barry Bruce at 1team4health@gmail.com and arrange a time for a visit.

3.4 System Organization & Navigation

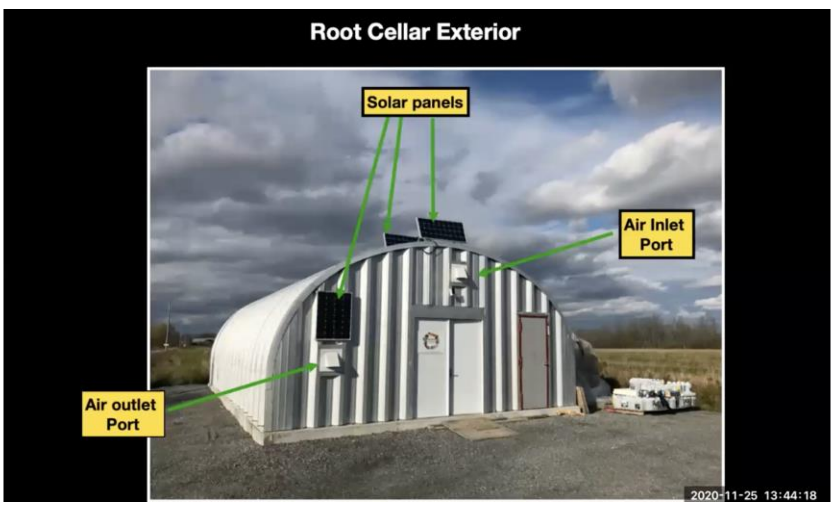

Figure 3. Front of the root cellar

On the entrance of the root cellar there is Air inlet and outlet. Just behind the outer wall there is a power system and motherboard that controls everything in the root cellar. A Raspberry pi (microcomputer) that connects to Wi-Fi and Cellular to monitor temperature, humidity, battery levels and fan controls. And there is another software component, written in python, used to query for current temperature in the zones, to calculate averages, and to compare against external conditions.

This leads to automated decisions on whether air should come in from outside (cooling) or should be circulated from under the floor (heating), or be circulated within the ice cube chamber (cooling in spring), or simply turn on circulation fan (air flow to reduce chance of mold growth and to balance temperatures in main chamber). The off-grid design utilizes three solar panels and four 12-volt vehicle batteries to capture and store energy. A backup gas generator for emergency situations is stored inside the root cellar, the client has been using it quite often to support two 250W heaters due to the frequent cold fronts in this winter.

3.5 Exiting the System

When you exit the system make sure to perform following actions:

1. Turn off all the lights.
2. Make sure that the generator is turned off.
3. Check the battery backup power.
4. Clean the dust on the solar panels
5. Refill gas in the generator.
6. Make sure the door is properly closed and insulated

4 Using the System

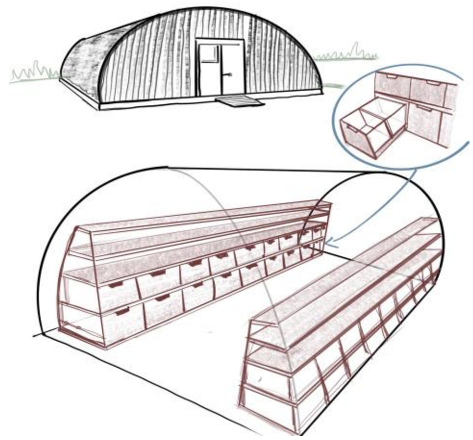

Figure 4. Storage example

The following sub-sections provide detailed, step-by-step instructions on how to use the various functions or features of the root cellar.

4.1 Drawer

Drawers in the last 2 rows of the storage so that it is easy to access vegetables. It can also make restocking drawers easier. Drawers has a grove that should be used as a handle. Handle has been specifically made like this to avoid the damage and maintenance.

Figure 5. Storage drawers

4.2 Walking Space

We have kept about 4 feet on space on both side of middle rack for easy walking. Even when all the drawers will be open there still will be 3 fts. of walking space. This space is enough when there are about 5-10 people in the root cellar at the same time.

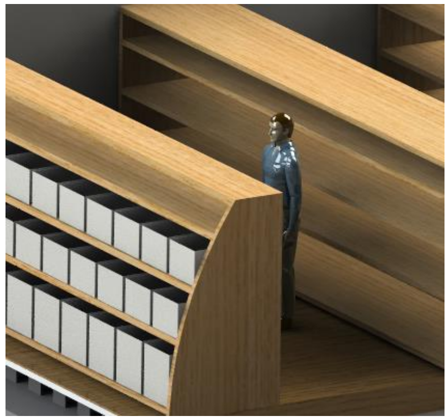

Figure 6. 3D model of the storage space

4.3 Height of racks

We have kept the height of top shelve to be about 6 feets, so it can easily be accessed by all people. There is enough space on the top to keep extra backets to maximize the storage space.

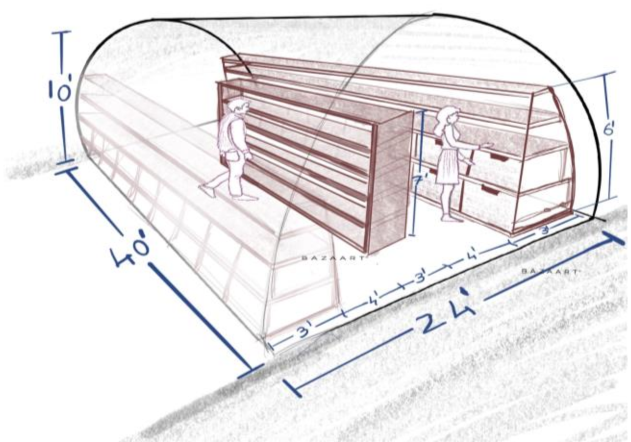

Figure 7. Early design for the storage

4.4 Airflow

½ feet of space at the back of racks for easy air flow. Air flow is important to keep vegetables fresh. We have also kept about 2’’ of space on sides to for extra air flow for the vegetables.

Figure 8. 3D model of the storage space 2

4.5 Handle

A cut out in plywood of the drawers for easily opening drawers. Traditional handles can easily break, thus we have decided to keep a grove for opening the drawers that will last longer.

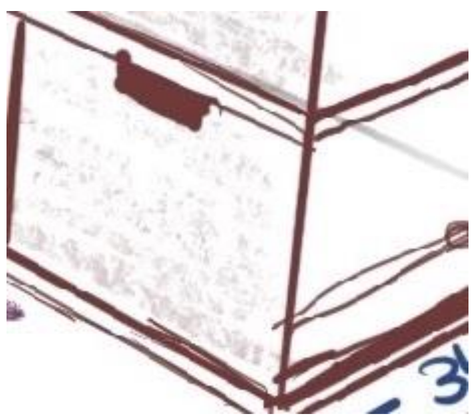

Figure 9. Drawer handle

4.6 Shape

Curved Spaced rack design to maximize space. Curved space of the racks matches the interior of the root cellar, it helps us to increase the amount of vegetables it can store. Thus, due to this space we were able to reach the intended storage of about 15000 pounds of food.

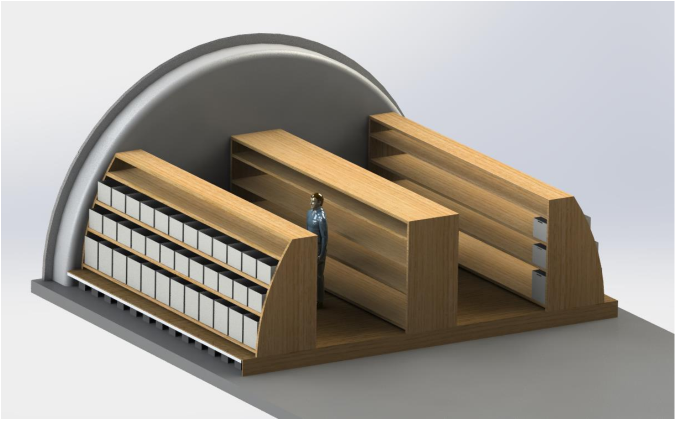

Figure 10. 3D model of the storage space 3

5 Troubleshooting & Support

This section documents the possible errors that may happen during the operation, and how the errors can be resolved or avoided.

5.1 Error Messages or Behaviors

As mentioned before, the root cellar uses vehicle batteries for energy storage, and they also support the fans and control systems in the evening. Low energy storage can happen when there is prolonged period of cloudy days, and this could eventually lead to the batteries being drained completely. The expected behaviors are listed as follows:

1. Lights and fans cannot be turned on.
2. The battery does not accept electricity from the solar panels when there is sufficient sunlight.

Another issue may happen during the operation, is the control system disconnects itself from the internet or fails to control the fans and the sensors. The expected behaviors are:

1. No real time data on the IoT dashboard.
2. One or more sensors' reading is not available for more than a day.
3. Fans are inactive when indoor temperature is out of the preset range.

5.2 Special Considerations

The batteries provide a base amount of power for the charge controller to function. In the event that the batteries become drained, it will not provide power to the charge controller, the charge controller will turn off, preventing the solar panels from charging the batteries once sunlight is available to the panels. To boost the batteries, there is an available battery booster pack sitting beside the batteries. The steps are as follows:

- Connect the battery cable to the proper terminals.
- Connect the battery cable to the booster pack.
- Once connected, the display on the battery cable will show the charge on the battery, in volts.
- The booster will charge the batteries until the batteries reach 13 volts.
- At this time the charge controller should be powered on.
- Remove the battery cable from the booster first and then from the batteries.
- Push the blue button on the battery booster pack to determine the remaining available boost capacity. If necessary, take the booster pack home and recharge with the available USB cable.

For issues with the control system, the user first needs to reset the system and see what happens. If one or more components still does not work, the user shall inspect the connection and detect any damaging or loosing on the cables. If the issue persists, the user shall contact the technical support, the procedure is described in section 5.4.

5.3 Maintenance

To avoid the complete drainage of the batteries, the user needs to monitor the battery voltage data on the IoT dashboard, the power generator shall be turned on when battery level appears to be less than usual.

To avoid damaging the solar charge controller on sunny days due to too much voltage input, the user needs to monitor the LED on the solar charge controller, and steps shall be taken when it blinks green very fast. The procedure is:

1. Disconnect the positive cable from the solar charge controller to the batteries to power off the charge controller.

2. Reconnect the positive cable from the solar charge controller to the batteries. The charge controller will turn on.

3. If the LED is still blinking fast, simply disconnect the positive cable from the solar panel to the charge controller (using a Phillips screwdriver) and reconnect. The LED should be green and blinking slower. Also, the LED for the battery should be solid green once it has been charging for some time.

5.4 Support

For further troubleshooting of specific components, user can read the corresponding user manuals. For persistent issues with the control system, the user shall contact the technical support. Name and contact information are not included here due to privacy concerns, but they are easily available by contacting the client.

To report an issue, email exchange is the preferred method. The user needs to include the following information: when the issue was discovered, estimation of how long it has happened, which specific area in the root cellar, photo evidence, and any step that has already been taken before contacting the support.

For security incidents like trespassing or fire, the user shall contact the emergency hotline immediately to ask for help.

6 Product Documentation

6.1 Optimization of Storage

Table 3. Dimension values for the main produce chamber, entrance/antechamber, and entire root cellar. Dimensions are listed in feet units as W, L, and H, which stand for width, length, and height.

Main produce chamber (usable food storage area)				Entrance/Antechamber (utilities, air inlet and outlets, and storage batteries housed here)				Entire root cellar (main produce chamber + antechamber)			
W	L	H	Total (sqft)	W	L	H	Total (sqft)	W	L	H	Total (sqft)
22.5	20	11.25	**5,062**	22.5	11.5	11.25	**2911**	24	37	12	**10,656**

The precise dimensions of the root cellar were measured by the team on March 23 and are updated in Table 1. Note that food is stored on the plywood floor inside the produce chamber, and the floor has a length of 18 feet as shown in the figure below, it sits on Styrofoam boards and concrete bricks.

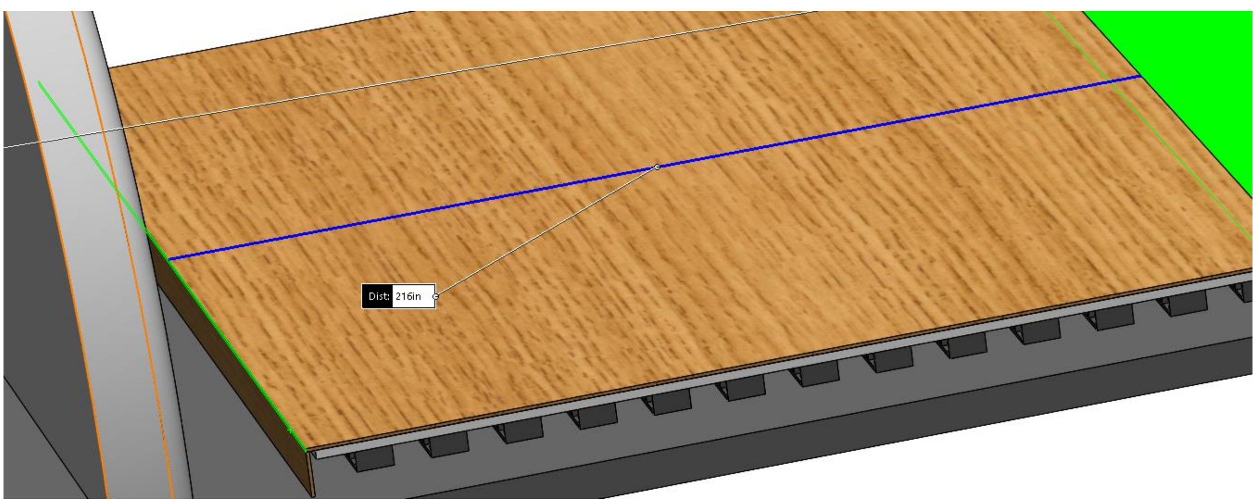

Figure 11. Plywood floor length

The client has already stored some plywood boxes and coroplast boxes in the produce chamber. We had estimated that in the main produce chamber (the only place in the root cellar where the produce will be stored), there is enough space for 24 plywood boxes (see Figures 4-5). Since each plywood box can hold 16 coroplast boxes, that brings the total coroplast boxes to 384. Each coroplast box can store 18-24 kg of produce. If we take the average (21 kg), all the coroplast boxes can hold up to 8,064 kg of produce. The client has mentioned that he estimates the cellar can hold 50,000 kg of food. So, this design is not sufficient as it can only support about 16% of the aforementioned.

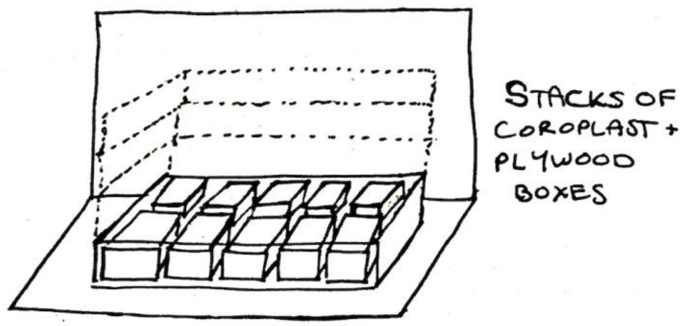

Figure 12**.** Sketch of the plywood box with space for coroplast boxes. The dashed lines represent the other plywood boxes that would be stacked.

Figure 13. Plywood box with coroplast boxes inside. The box is located near the back of the root cellar.

To increase this percentage and get closer to 100% (which represents 50,000kg, or full capacity), the team came up with an innovative storage method. The images below show the placements of the storage shelves and their configurations. The dimensions are also updated in the left columns of the 6 to 7. Three plywood racks are placed on the floor, and the two side racks can support 12 coroplast boxes on each bottom level, while usage of the top level is left for the client to decide. A thorough calculation of how much food these racks and boxes can hold is in the test section. A stress test is also included to ensure that the plywood structures do not fail when they are carrying heavy loads.

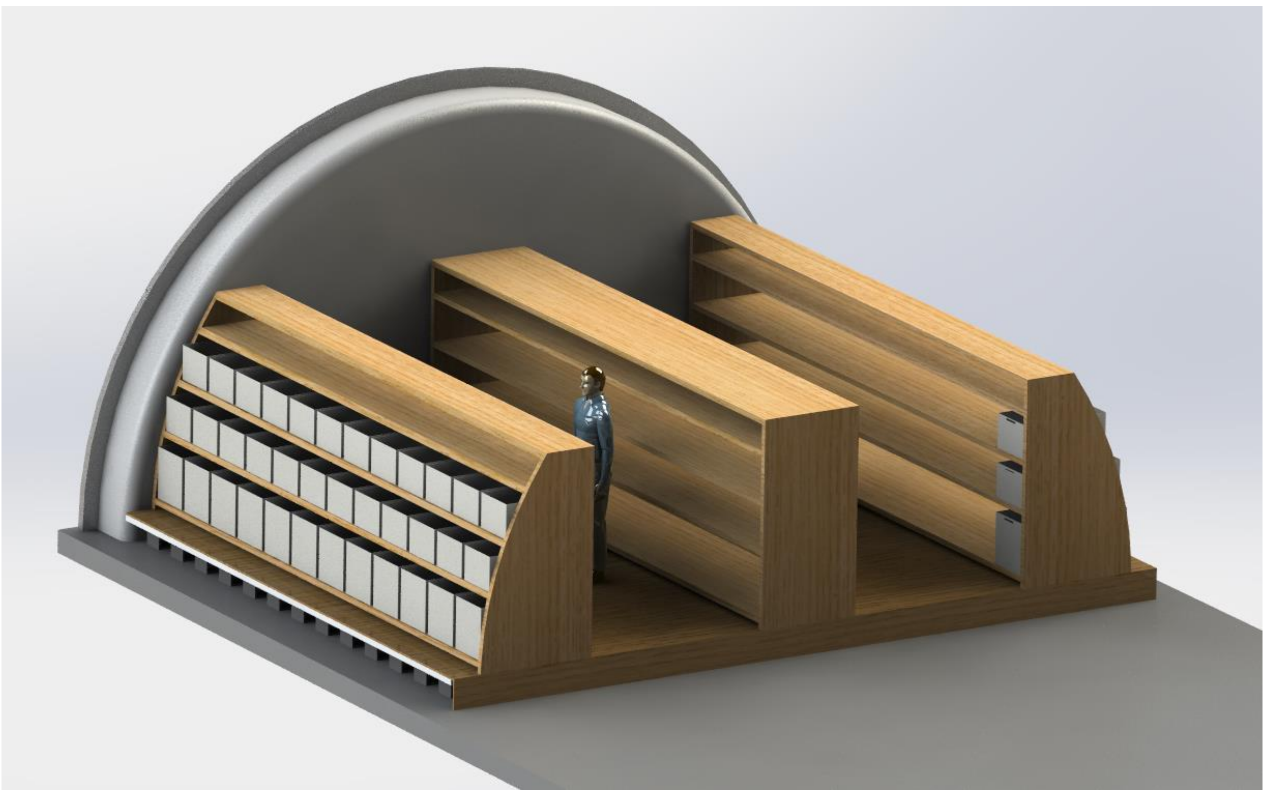

Figure 14. CAD model of the produce chamber after optimization

a	18'
b	11'
c	24'
d	¾'
e	1'
f	3 ½'
g	6'
h	5 ½'
i	3'
j	6'
k	¾'

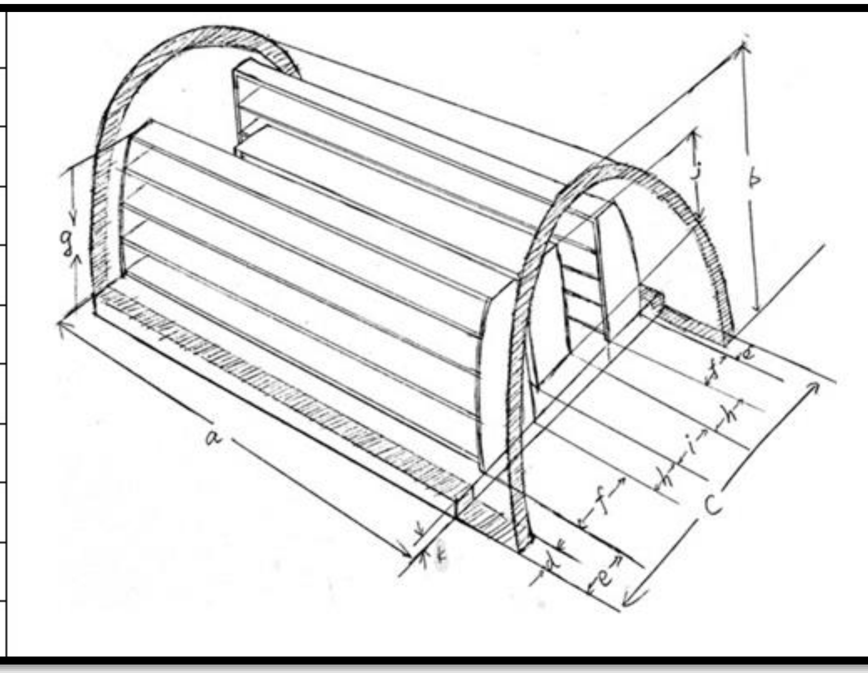

Figure 15. Placements of the racks in produce chamber and general dimensions

a	18'
b	3 ½'
c	6'
d	1 ½'
e	2''
f	2''
g	21''
h	15''
i	15''
j	9''
k	16''
l	1 ½''
m	18''
n	12''
o	12''
p	3''

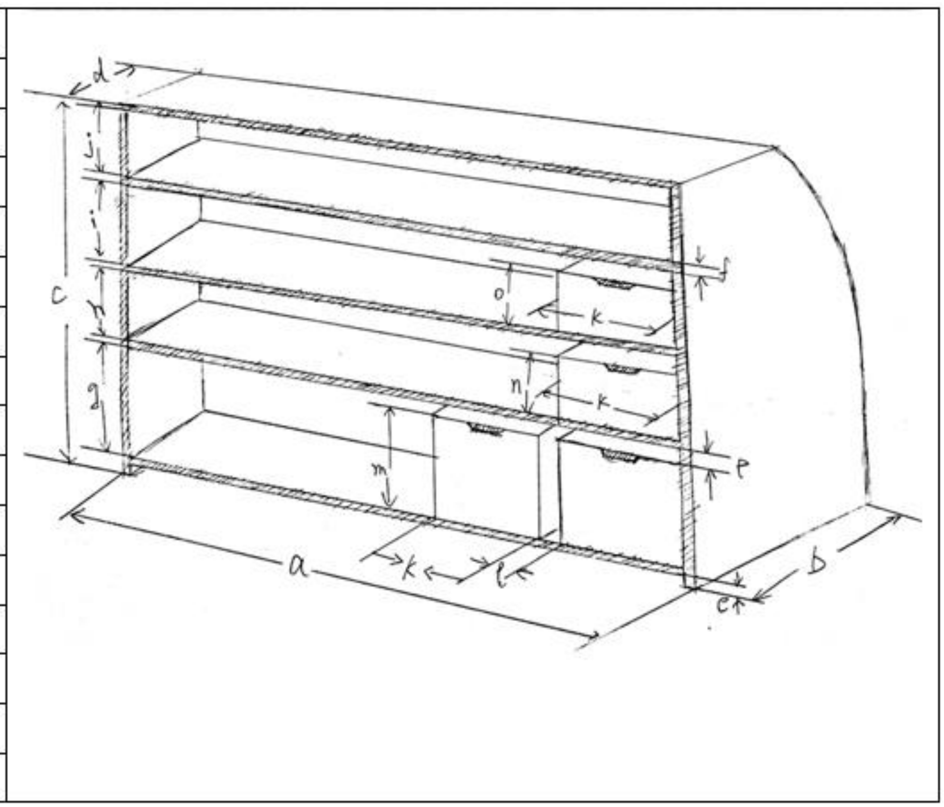

Figure 16. Side rack configuration

a	18’
b	6’
c	3’
d	2’’
e	2’’
f	21’’
g	15’’
h	15’’
i	9’’

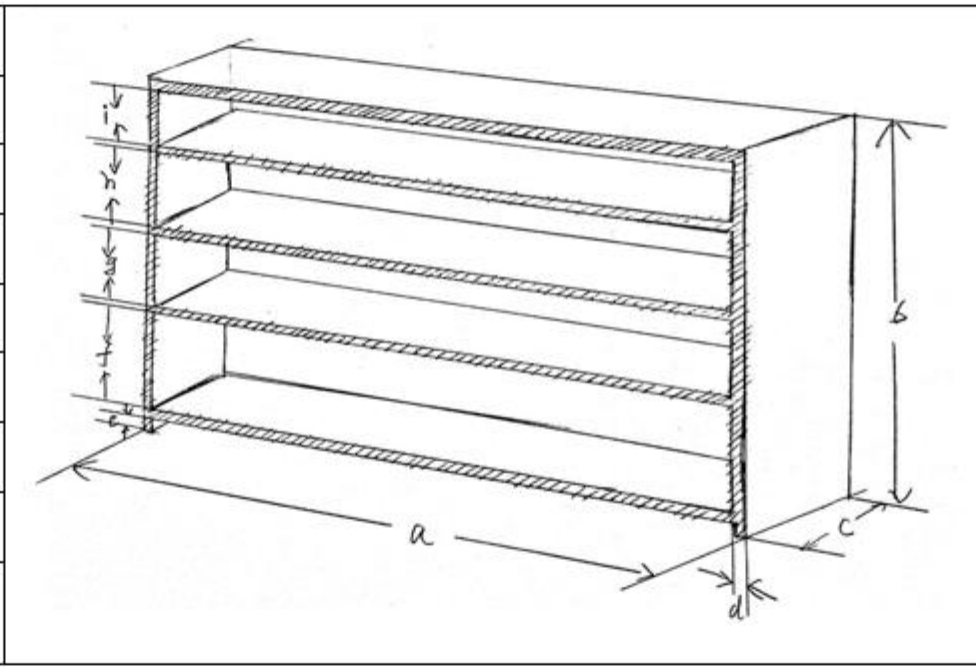

Figure 17. Middle rack configuration

6.1.1 BOM (Bill of Materials)

The racks and boxes were not built so we do not know the exact cost for them as the labor charge might take a big role, but an estimation shows that the raw materials cost less than $1000.

6.1.2 Equipment list

Equipment like saws, ruler, nails, and hammer might be needed to build the racks, but these designs were not built so we cannot give a certain list of equipment.

6.2 Power System

To help the root cellar stay off-grid, a few power system improvements are proposed here. And the estimated power generation values can be found in the testing section. These are the proposed ideas and are not fully realized in final prototype, so no instructions and bill of materials are given.

6.2.1 Wind Energy

Figure 18. Wind turbine

Canada's geography makes it ideally suited to capitalize on large amounts of wind energy. It has one of the highest wind flows in the world. Unlike solar energy, wind energy can be collected 24/7.

6.2.2 Additional Solar Panels

Figure 19. Solar panel

Addition of a few more solar panels can be done. If the space on roof of root cellar is not enough then the solar panels can be installed on the space around root cellar.

6.2.3 Ground Source

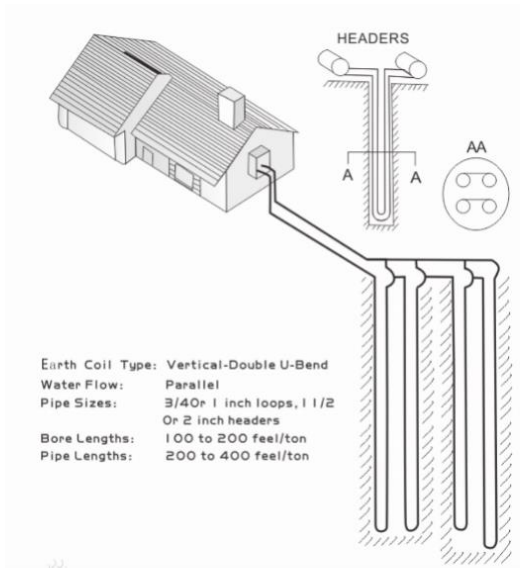

Figure 20. Geothermal heating network

Another option is to create a geothermal heating network. The idea is to install geothermal wells about 50 meters below the cellar. The underground heat exchanger buried underground forms a loop to exchange heat with the earth. In winter, pipes can transport water heated by geothermal energy to the cellar to warm it; in summer, pipes can transport cooled water to the cellar to cool it down. Geothermal heating will reduce greenhouse gas emissions and also reduce cellar heating bills.

6.3 Heating and Cooling System

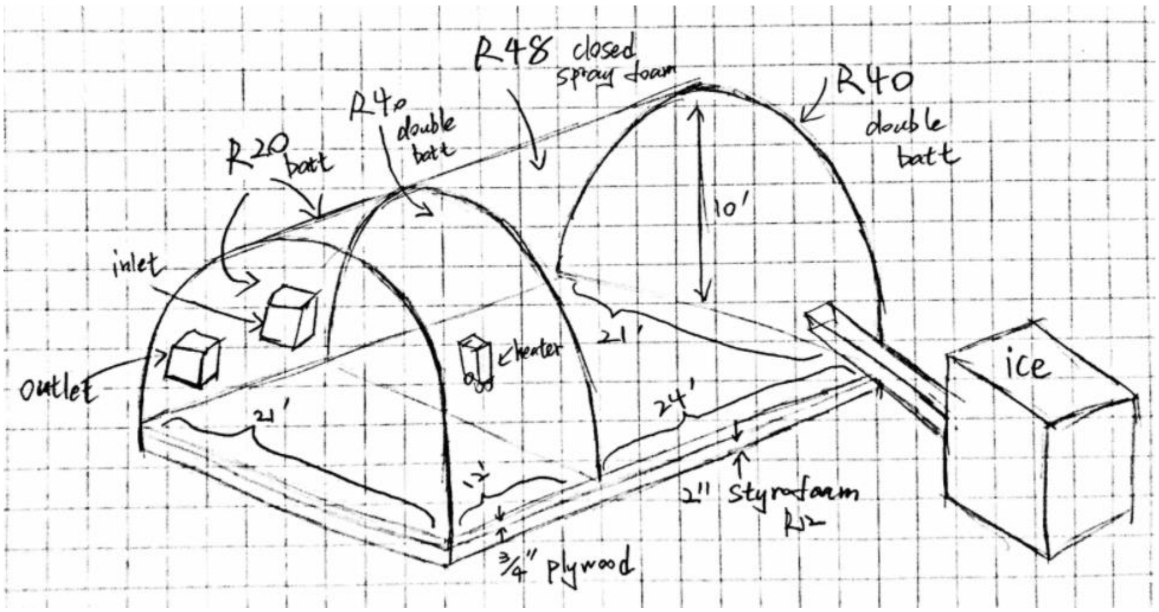

Figure 21. Detailed view of the HVAC system.

The main component of HVAC is wall insulation, but regardless of how well the root cellar is insulated, there will always be some heat conduction. Therefore, after determining the heat transfer from walls in winter and summer, additional heating and cooling elements shall be added to compensate the heat gain/loss so that the indoor temperature can stay between 2-4^{o}C. For ventilation purpose, the root cellar also has air inlet and outlet on the front wall. When the outside temperature is cooler than inside (and indoor temperature > 4 ^{o}C), both ports will be turned on until the room temperature stabilizes, this method is normally used during warm winter evenings. For hotter days, client will turn on a DIYed strawbale ice chamber to blow cold air into the chamber. The ice chamber contains 2000 pounds of ice, and it is insulated with R60 straw bale. As shown in Figure 13, warm air from outside and produce chamber is let into the ice chamber to get cooled before being fed into the produce chamber. For heating in winter, two 250W heaters are selected.

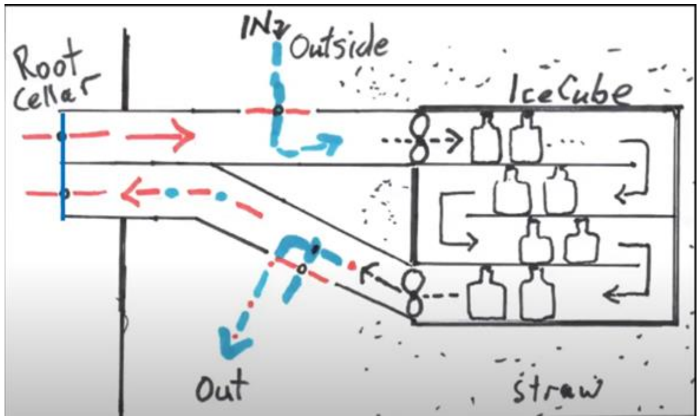

Figure 22. Schematic of the ice chamber.

Figure 12 shows the insulation materials being used on each wall. The insulation is R40 (double batt) for the rear wall and the wall dividing the main chamber from the antechamber. The front wall and side walls are R20 in the antechamber. The spray foam (8 inches thick) is about R 48, on the side walls of the produce chamber only. The gravel and the produce chamber are separated by 8’’ tall concrete bricks, R12 Styrofoam pads, and ¾’’ plywood. The construction material for the hard wall is 1/8’’ galvanized steel. Figure 14 shows that the insulations are installed on the hard wall by using metal and plastic pins.

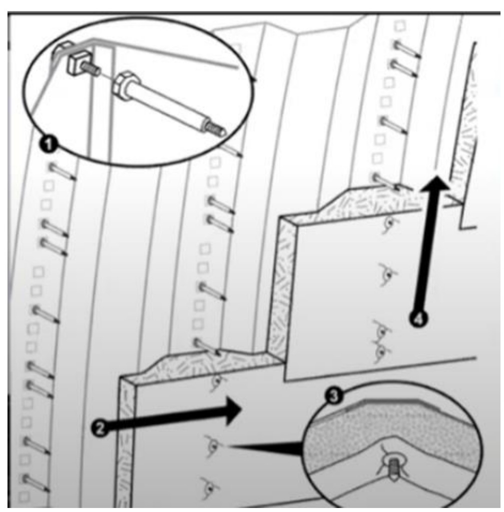

Figure 23. Wall insulation installation.

To furtherly reduce the overall heat transfer with the outside, the half inch thick R15 vacuum insulated panels can be installed on the existing insulations. These panels offer excellent thermal resistance, and they are thinner than the existing insulations. Testing result shows that they can reduce the overall heat transfer by nearly 100W. The price for this material requires direct quote from manufacturer, so there is no bill of material for it.

The IceCube chamber is well insulated, so no new insulation method is proposed. The ice chamber can run nearly 2 days until the ice completely melts during early spring days. To improve the cooling efficiency, two dampers can be installed in front of the inlet and outlet fans. The idea is to shut down the airflow and turn off the fans temporarily when the ice chamber temperature is above 4^{o}C, the dampers can be opened again to allow airflow once the internal temperature drops to 3.8-3.5 ^{o}C. This ensures that the outlet air temperature is always lower than the produce chamber temperature and reduces unnecessary heat gains from the excessive intake air, the power usage is lowered because of shorter running time of the fans. No analytical testing for this improvement because the internal temperature is affected by many uncontrollable parameters like intake air humidity and pressure, which varies drastically every day.

6.4 Testing & Validation

6.4.1 Storage test

- **Produce weight estimation**

The total volume of the drawer: L*B*H

1. The data of the length, width and height of the first layer: 42inch, 18inch, 16inch

The data of the length, width and height of the second layer: 38inch, 16inch, 12inch

The data of the length, width and height of the third layer: 32inch, 16inch, 12inch

The data of the length, width and height of the fourth layer: 20inch, 18inch, 9inch

2.The volume of the first layer is 12*16*42*18=145152 inch^3

The volume of the second layer is 12*38*12*16=87552inch^3

The volume of the third layer is 12*12*16*32=73728inch^3

The volume of the fourth layer is 12*20*18*9=38880 inch^3

3.The volume of the middle drawer is (18+12+12+9) *18*12*3*12=396576 $inch^3$

4.The sum of the volume is (145152 + 87552 + 73728 + 38880) *2+ 396576 =1087200 $inch^3$=629.17ft^3=17.82m^3

As an example, the food stored in the cellar is potatoes, and the space utilization is assumed to be 100%. The density of potatoes is 1.0-1.2g/cm^3, so the weight of food that can be stored in the cellar is calculated to be 17820kg.

- **Stress test**

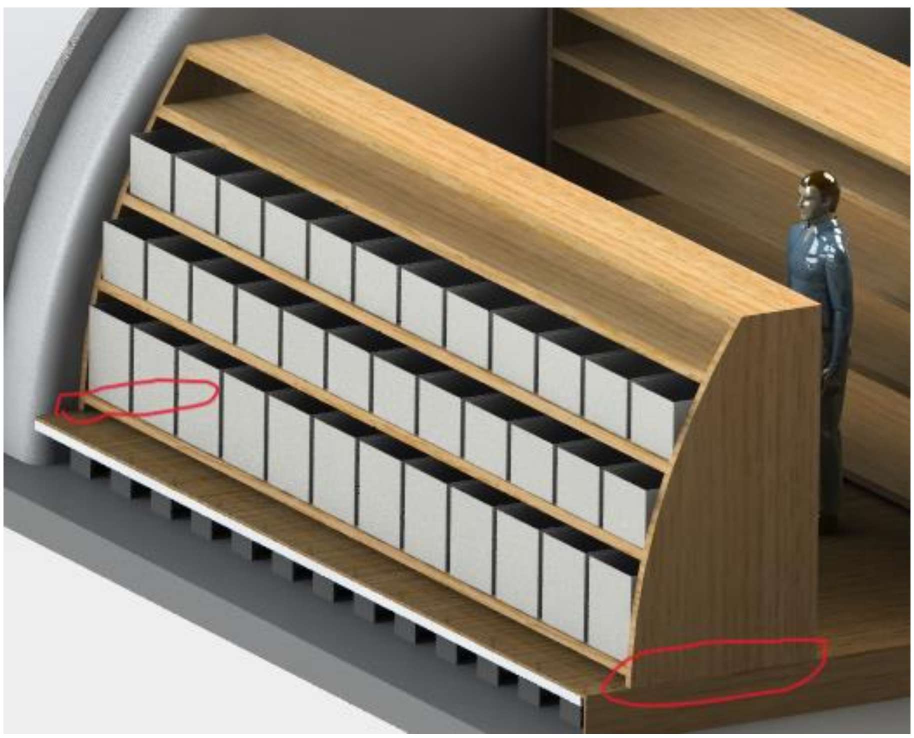

Figure 24. Side rack selected for testing (red line circles the standing areas)

The stress test was carried out by using SolidWorks (model is available in the design files). After inspecting the structure of the racks and the floor, it is obvious to see that the largest pressures happen at the standing areas shown in the figure above because those two small areas bear the whole weight of the rack. Therefore, if the plywood at the standing areas can pass the stress test, the rest structure will automatically be within the safe range.

Property	Value	Units
Elastic Modulus	11000	N/mm^2
Poisson's Ratio	0.394	N/A
Shear Modulus	600	N/mm^2
Mass Density	500	kg/m^3
Tensile Strength	32	N/mm^2
Compressive Strength	39	N/mm^2
Yield Strength	900	N/mm^2
Thermal Expansion Coefficient	0.9	/K
Thermal Conductivity	0.2256	W/(m·K)
Specific Heat	1386	J/(kg·K)
Material Damping Ratio	0.9	N/A

Figure 25. Mechanical properties of the plywood

Here one side rack is selected for testing, it carries about 5660kg of produce which is 55524N.

The standing area is 42’’ x 2’’ x 2 = 168 inch^2 = 0.1082 m^2

So, the distributed pressure on the standing area is 55524N / 0.1082 = 513160 Pa

After applying the materials properties and the pressure values to the CAD model, a static stress study was performed.

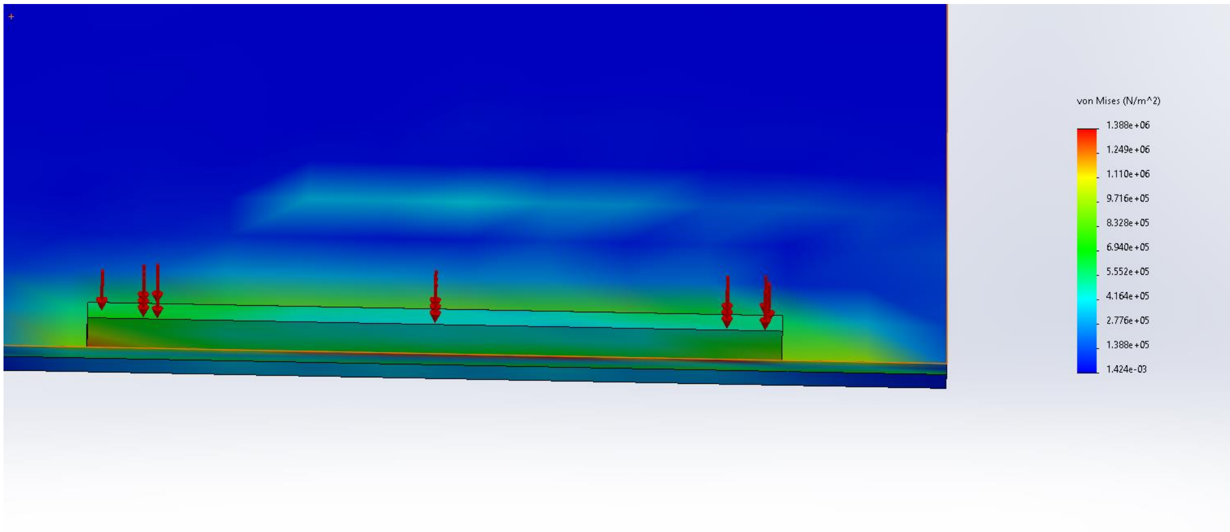

Figure 26. von Mises stress distribution graph by SolidWorks

The figure above shows the von Mises stress over the model, and the contacting area between the rack and the floor bears the largest stress which is 1.388 MPa. By comparing this value with the compressive strength and shear modulus of plywood, it gives a safety factor of 20 and above. And SolidWorks reported that the largest deformation is 0.000148m, the values is less than 1mm. In summary, the structure is safe to use because the stress does not lead to any failures.

6.4.2 Power System Test

- **Wind turbine calculation:**

Q = Qty

W = Watt of wind turbine

H = Hours of operation

C = Capacity factor

Two 800W wind turbine running only 2 hours per day at 15% efficiency can produce:

Q * W * H * C = 2* 800 W x 2 Hours x 15% (0.15) = **240W**

Two 800W wind turbine running only 8 hours per day at 15% efficiency can produce:

Q * W * H * C = 2* 800 W x 8 Hours x 25% (0.15) = **960W**

2 Wind turbine in worst case scenario can produce minimum **240W**

- **Solar panel calculation:**

  Increasing the count of solar panels to 10 (100W each)

  Hence, energy generation would range from 350W – 850W.

  Worst Case scenario: 350W

  10 Solar cells can produce a minimum of **350W** in worst case scenario.

- **Ground source calculation:**

- **Design parameters**

Cellar area 10164sqft.

1. Outdoor design parameters

Summer outdoor temperature tw=27℃

Winter outdoor temperature tw=-10℃

2. Design parameters of the cellar

Cellar temperature t=2℃, relative humidity φ=90%-95%

3. Pipeline design

The underground pipeline adopts high-density polyethylene (HDPE) pipe, the diameter of the pipeline is φ35mm, and the total length of the drilling hole is determined by the heat exchange required by the cellar. In this design, U-shaped pipelines in series will be used. The diameter of the well is 150mm, the depth of the well is 50m, and the diameter of the U-shaped pipeline is generally φ50mm. COP1=5.9 and COP2=4.2 under the working conditions of this design example.

- **Calculation of underground heat transfer**

1. The underground heat exchange can be calculated by the following formula:

Q1'= Q1*(1+1/COP1) kW (1)

Q2'= Q2*(1-1/COP2) kW (2)

Where Q1'--heat emitted to soil in summer, kW

Q1--summer design total cooling load, kW

Q2'--heat absorbed from soil in winter, kW

Q2--winter design total heat load, kW

COP1--cooling coefficient of water source heat pump unit under design conditions

COP2--the heat supply coefficient of the water source heat pump unit under the design condition

2. According to formulas (1) and (2), we can get

Q1'= Q1*(1+1/COP1)=0.573*(1+1/5.9)=670 W

Q2'= Q2*(1-1/COP2)=0.752*(1-1/4.2)=572 W

- **Underground heat exchange design**

Generally, the heat transfer capacity of vertical single U-shaped buried pipe is 35~55 W/m (well depth).

The lower limit of the heat transfer capacity can be taken in the design, that is, 35W/m (tube length). The specific calculation formula for the U-tube design is as follows:

L=Q1/35 (3)

Among them, L--total length of vertical shaft buried pipe, m

Q1--heat released to soil in summer, W

The denominator "35" is the heat dissipation per m tube length in summer, W/m

Calculated according to formula (3)

L=670/35=20m

Ground source heat pumps tend to be expensive to install and require more space because deep digging is necessary to obtain stable subsurface temperatures. In Canada, most of the shaft depths are 50~100m, and the team chose a shaft depth H of 50m. A word of caution: 20 meters is less than 50 meters, so the team's design is not suitable for this cellar. But it has reference significance for the expanded cellar in the future.

6.4.3 Heating and Cooling System Test

As discussed before, a layer of R15 vacuum insulated panels can be added to furtherly improve the heat transfer, therefore new heating and cooling loads were calculated. The ice chamber calculation is included as it was specifically request by the client.

- Heating and cooling loads

  The picture below uses the revised prototype parameters for calculating heating and cooling loads. The result is produced by using the MATLAB tool developed for heating and cooling calculations for the root cellar, this tool can be found in the design files. For the working principle of this tool, see the HVAC calculation document.

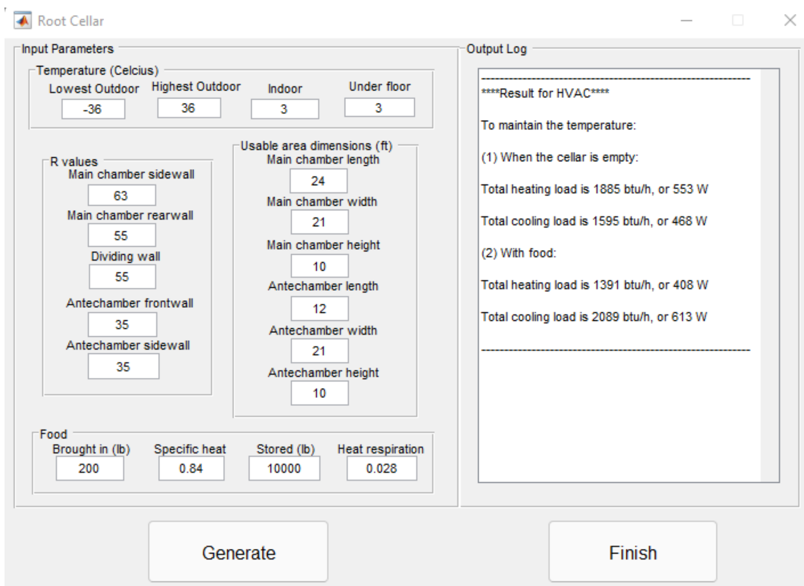

Figure 27. Root cellar heating and cooling loads

- Ice chamber

  This section is the calculation for the IceCube chamber. The storage size is 4'x4'x4' and it is constructed by using 10mm Coroplast sheets. The outside is insulated by using 48'' thick straw bales, which equals to R60 thermal resistance (excluding the side faces the produce chamber). 242 windshield washer fluid containers with a volume of 3.78L (total about 907.2kg) of water is already frozen in plastic containers. For the simplicity of finding the minimum time before ice completely melts into water, it is assumed to be at 0^{o}C (or 32 ^{o}F) and only the heat of fusion is considered.

Other assumptions:

- ice chamber is turned on during a warm winter day, daytime temperature is at 6^oC (or 42.8^oF), evening temperature is at -2^oC
- the produce chamber air enters the duct at 5^oC, it then mixes with outside air before entering the ice chamber.
- the air is supplied at 1750CFM. It is impossible to predict the volumes of airflow from two inlets without using proper measurement tool, so the mixed air temperature is assumed to be at 5.5^oC (41.9°F), and it leaves the ice chamber at 3^oC (37.4°F).
- The heat transfer process is isochoric because the volume of air being fed is constant, so the heat capacity of air is about 0.717 kJ/(kg ^oC).

Here, there are two heat gains to calculate: one is heat absorption from the intake air, and the other one is heat absorption from the outside.

- Intake air:

Stored ice volume = 907.2 (kg) / 917 (kg/m^3) = 0.989 m^3 = 34.93 ft^3.

Volumetric flow rate of air = 1750CFM = 0.826 m^3/s

Mass flow rate of air = 0.826 (m^3/s) * 1.273 (kg/m^3) = 1.05 kg/s

Heat gain from intake air q1 = mass flow rate * heat capacity * temperature difference =

1.05 (kg/s) * 0.717 kJ/(kg ^oC) * (5.5 - 3 ^oC) = 1.882 kJ/s = 1882 W

- Outside air:

Surfaces covered by straw bale

$$U1 = 1 / (Rsi + R1 + R2 + Rso)$$

Same as before,

Rsi is 0.68136 ft2·°F·h/BTU

Rso is 0.34068 ft2·°F·h/BTU

R1 is the R60 straw bale

R2 is the thermal resistance of 10mm Coroplast sheets (polypropylene) which is 0.516 ft^2·°F·h/BTU.

$$U1 = 0.0161\ Btu/h/(ft^2*F)$$

The contact area with outside air is A1 = 4*4*4 = 64ft2

Surface without straw bale

$$U2 = 1 / (Rsi + R2 + Rso) = 0.51\ Btu/h/(ft^2*F)$$

The contact area with outside air is A2 = 4*4*2 = 16ft2

The total heat transfer with the outside is:

$$q2 = (U1*A1+U2*A2) * (42.8F-32F) = 99.26\ Btu/h = 29.09W$$

- Time it takes to melt the ice:

To melt the ice, the total heat absorption is = weight of ice * heat of fusion = 907.2kg * 333.55 kJ/kg = 302596000 J

Time = heat absorption / (q1+q2) = 302596000 / 1911.09 = 158337s = 43.9 hours

This means that it would take less than 2 days to completely melt the ice when the outdoor temperature is constantly at 6^{o}C, and at the same time the produce chamber is kept at below 4^{o}C. Compare the intake air heat gain and the summer heat gain from previous section, it shows that the ice chamber works well for cooling.

With the same process, assume outside air is at 11 ^{o}C during daytime for April, the air mix enters at 8 ^{o}C, it would produce a total heat transfer of 3945W, the time it takes to melt the ice is

21 hours. Assume outside air is at 23 ^{o}C during daytime for May, the air mix enters at 14 ^{o}C, it would produce a total heat transfer of 8396W, the time it takes to melt the ice is 10 hours.

7 Conclusions and Recommendations for Future Work

Prior to taking part in this project, none of our group members had much knowledge of food insecurity and farm-level food waste. By meeting with the client and interacting with him, we learned the inspiration behind his project: an off-grid root cellar to store farmer's produce during the off-season (winter). The client let us know of the pain points and items to improve, some which we worked on during the semester: 1) increasing the energy using different power systems, 2) providing calculations for improvements to existing equipment in the cellar, and 3) design an optimized storage solution to increase the amount of produce that can be stored. The first and last items involved taking into consideration the UN sustainability goals in our designs as they were important to the client and to us. Very quickly we learned that there were a lot of items and avenues we could work on to help the client. However, due to time constraints (3-month course), the team decided to prioritize our time with designing a storage solution. Some of our time was also spent generating the numbers and calculations that different sustainable power sources could provide. Additionally, calculations to improve the existing IceCube chamber were also conceived. All in all, our time invested in the 3 aforementioned items were 60%, 20%, 20%, respectively. Our storage solution was visualized in SolidWorks and for future work, the next step would be to build a small section of the curved racks inside the cellar and test various factors such as: how much food crops/produce the levels can store, how easily (strength needed) for the drawers to be pulled out when at full weight/volume capacity, the quality of air flow, temperature and humidity at the different levels, resistance and durability of the materials (coroplast and plywood), and cost of materials and construction, amongst others. If we had a few more months to continue the project, we would also like to implement a virtual tracking system of the produce inventory in the root cellar that can be accessed by anyone who is storing their produce in the chamber. This inventory would be tracked as produce is entering and leaving the cellar and can be achieved by using the Internet of Things. Additionally, we would like to do more research on which root vegetables would be the best to store on the lower levels (colder) and on the upper levels (warmer – heat rises). By knowing this, a system of produce location on the racks can be further implemented to increase their longevity based on the temperature they thrive at. All in all, we are very excited to have participated in this project and have met and learned so much from Dr. Barry Bruce. We wish the next team good luck in this project and to have fun! It is, after all, a great project to work on as root cellars will provide much-needed storage of food for a more sustainable future and a healthier population.

8 Bibliography

[1] Deep Roots' Root Cellar. (2020 February). Retrieved from http://www.deeprootsfoodhub.ca/community-root-cellar.html

[2] Deep Roots Food Hub An Off-Grid Root Cellar and How a Root Cellar Could Support Human and Planetary Health Presentation to CACOR. (2020 November 25). Retrieved from https://canadiancor.com/wp-content/uploads/2020/11/BB-final-final-edits-Root-cellar-for-CaCor.pdf

[3] United Nations Department of Economic and Social Affairs Sustainable Development. Retrieved from https://sdgs.un.org/goals

9 APPENDIX I: Design Files

Table 4. Referenced Documents

Document Name	**Document Location and/or URL**	**Issuance Date**
Heating_cooling_ MATLAB_tool.zip	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBczgvIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--d99ff62668b3f236829c498c7e07114c078f10cb/Heating_Cooling_MATLAB_Tool.zip	April 16th, 2022

Root_cellar_drawing.zip	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBczQvIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--9db0846d0e0551e17c49fb049dd273d92ac66240/Root_cellar_drawing.zip	April 16th, 2022
Heating_cooling_calculation_steps.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBdEEvIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--a6ce981f7943c8a95c976dc152aa766abee5a2c8/Heating_cooling_calculation_steps.pdf	April 16th, 2022
Deliverable_B.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBc2hBIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--01ca96585049774023ca3e8ffa33367d735ce0cb/Deliverable_B.pdf	April 16th, 2022
Deliverable_C.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBc2RBIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--d0a0fe9a83efc586310d9833f8db0abfb3991d04/Deliverable_C.pdf	April 16th, 2022
Deliverable_D.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBc1pBIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--df5e82619280395774b3ddd60cf0a6d99dc00ce2/Deliverable_D.pdf	April

		l 16th, 2022
Deliverable_E.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBc1ZBIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--a0ac3762763a139f3245180c1304a08d6ebc28e4/Deliverable_E.pdf	April 16th, 2022
Deliverable_G.pdf	https://makerepo.com/rails/active_storage/blobs/redirect/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaHBBc2xBIiwiZXhwIjpudWxsLCJwdXIiOiJibG9iX2lkIn19--f69a9c74f297143d075ff2bed393089c30c94254/Deliverable_G.pdf	April 16th, 2022