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GNG 5140 Engineering Design

Project Deliverable G: Final Prototype Report

Group 4 – Sustainable Food Storage

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Abstract

This report investigates and analyzes an existing prototype for food storage in Eastern Canada: an above-ground vegetable root cellar designed by a local grassroots organization called Deep Roots Food Hub. The report documents the description and testing of the final prototype. The team then discusses the revised designs by comparing the performance against target specifications. Then, the scalability, sustainability, quality, and usability aspects of the project are analyzed to find how the prototype can be furtherly improved.

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List of Acronyms

Acronym	**Definition**
DRFH	Deep Roots Food Hub
HVAC	Heating, Ventilation, and Air Conditioning
TOFB	The Ottawa Food Bank

1 Introduction

Higher temperatures, water scarcity, extreme events like droughts and floods, and greater CO_2 concentrations in the atmosphere have already begun to impact staple crops around the world [1]. Maize (corn) and wheat production have declined in recent years due to extreme weather events, plant diseases, and an overall increase in water scarcity [1]. The threat of the varying global climate has greatly driven the attention of scientists, as these variations are imparting negative impact on global crop production and compromising food security worldwide [2].

As discussed, climate change poses an eminent threat to growing our crops and sustaining our population's food consumption. With climate change reducing harvests, this means that the lean period (skipping one or more meals a day to reduce food consumption) may be extended if there are fewer supplies, or if it takes longer to get an adequate harvest. In many food-insecure areas, such as Eastern Canada, agriculture and food production is seasonal (during the Summer and Fall seasons); leaving the population to rely on the harvests for the Winter and Spring seasons. However, the harvests from our local farmers are not enough to sustain the current population of Easter Canada during these seasons. Therefore, a lot of the food we consume has to be imported from warmer climates.

The aforementioned factors are motivators for a working, all-year round crop storage. Providing long-term storage for crops in a well-designed environment will decrease the likelihood of having to extend the lean period, and thus, have enough crops available. This will sustain a controlled population during foreseeably harsher climate conditions and moments of uncertainty, which can include an increase in food prices due to a lower production and higher demand.

The Deep Roots Food Hub (DRFH) is a grassroots, West Carleton-based non-profit organization that aims to create a secure, sustainable food system in West Carleton, Ontario [3]. This system is in the form of a prototype root cellar (see Figure 1).

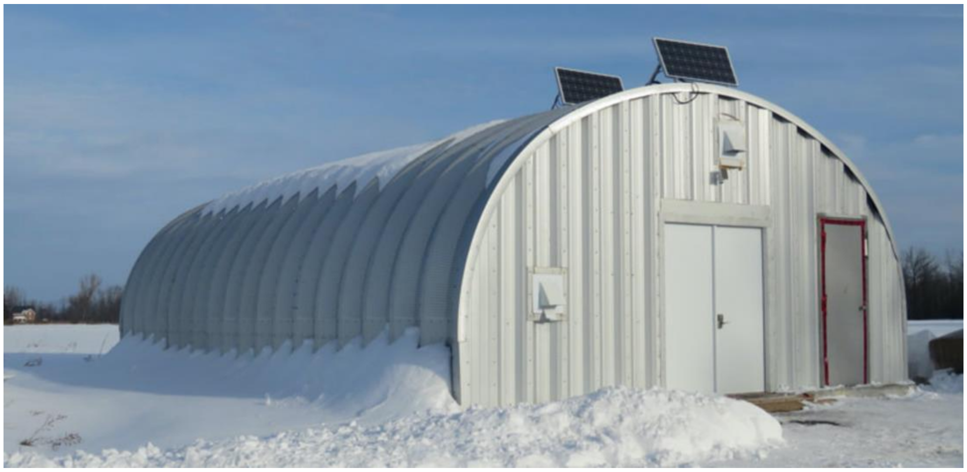


Figure 1. Root cellar exterior (February 2020).

This above-ground cellar and off-grid storage structure provides small-scale vegetable growers with a post-season sustainable and energy-efficient storage facility, providing longer root crop storage and extended sales and/or distribution possibilities [3]. Prior to bringing this prototype design to life in the West-Carleton area, there wasn't a community-based storage space for local root crops. This innovative Quonset-styled metal building is designed to capture and circulate ground-sourced geothermal heat to maintain a near-constant + 2°C temperature and 90-95% humidity within the structure's root storage chamber [3].

There are other more traditional methods of prolonging root crops such as: freezing, canning, and dehydrating. However, these methods involve having to thaw them in order to be readily edible (in the case of freezing), or are laborious in practice (such as the case of canning, which must be done to some root vegetables because of their low acid content).

The controlled environment in the root cellar is better at providing fresher and readily-available foods (no waiting for food to thaw – which could take hours depending on the environment), and extending the life of root crops.

The main objective of this report is to document the revision of the prototypes and their test results. This report will discuss in detail the testing results against target specifications, and how the prototype can be improved by applying the knowledge learned in class.

2 Global Solution Concept

2.1 Overview

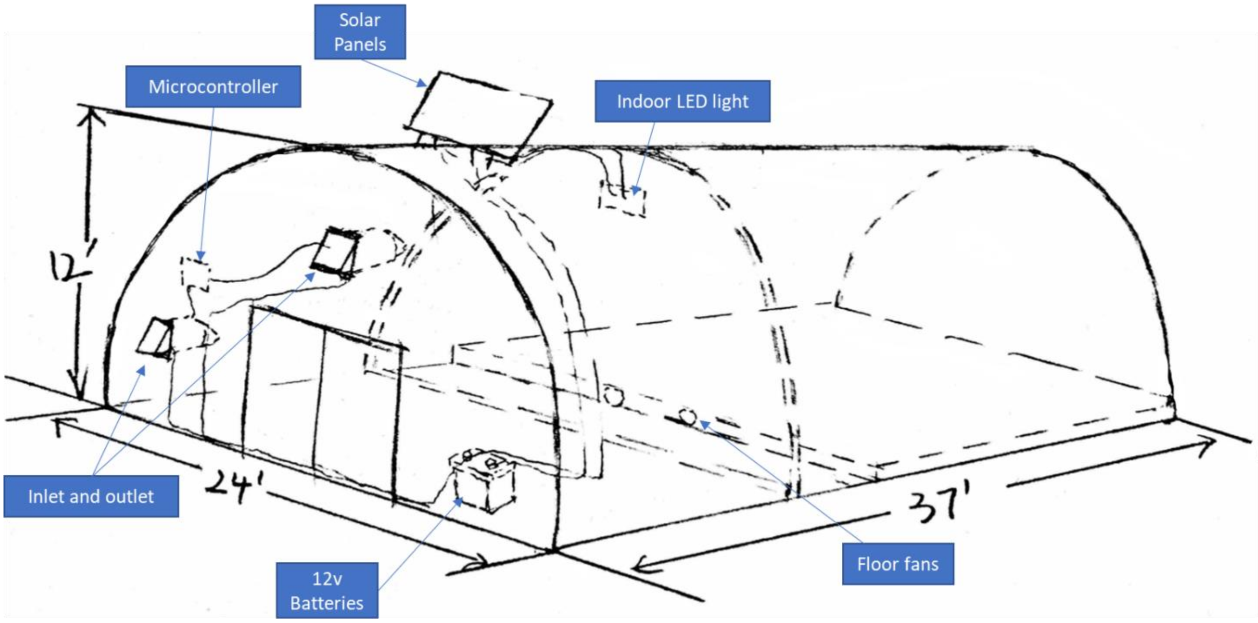


Figure 2. 3D view of the root cellar

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 section 2.2 and 2.3. 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 is 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, a detailed storage plan is proposed and verified. Another objective is to help the root cellar stay off-grid, so several energy harnessing methods are proposed. In addition, the next section also has a verification of the picked insulation materials, and heating and cooling elements, which are crucial for keeping the indoor temperature in range.

2.2 Optimization of Storage

Table 1. 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.

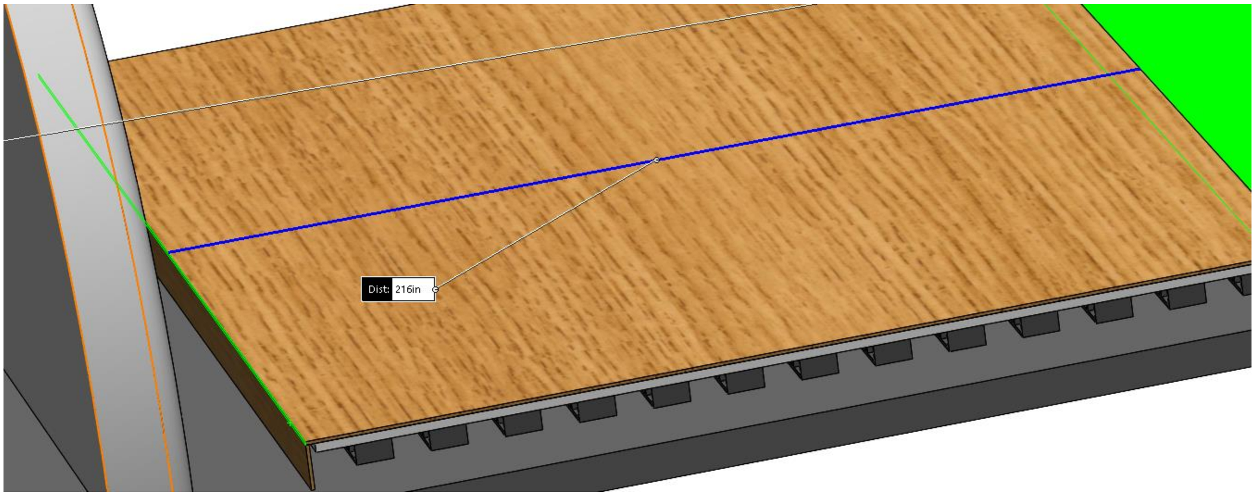


Figure 3. Plywood floor length

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.

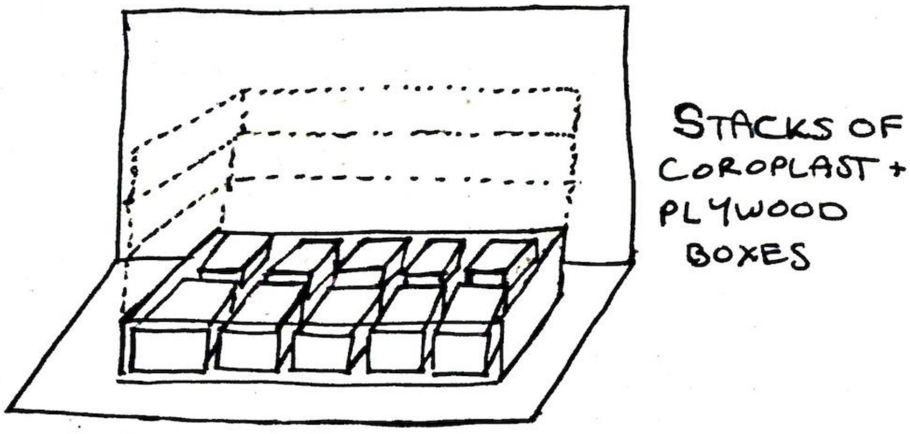


Figure 4**.** Sketch of the plywood box with space for coroplast boxes. The dashed lines represent the other plywood boxes that would be stacked.

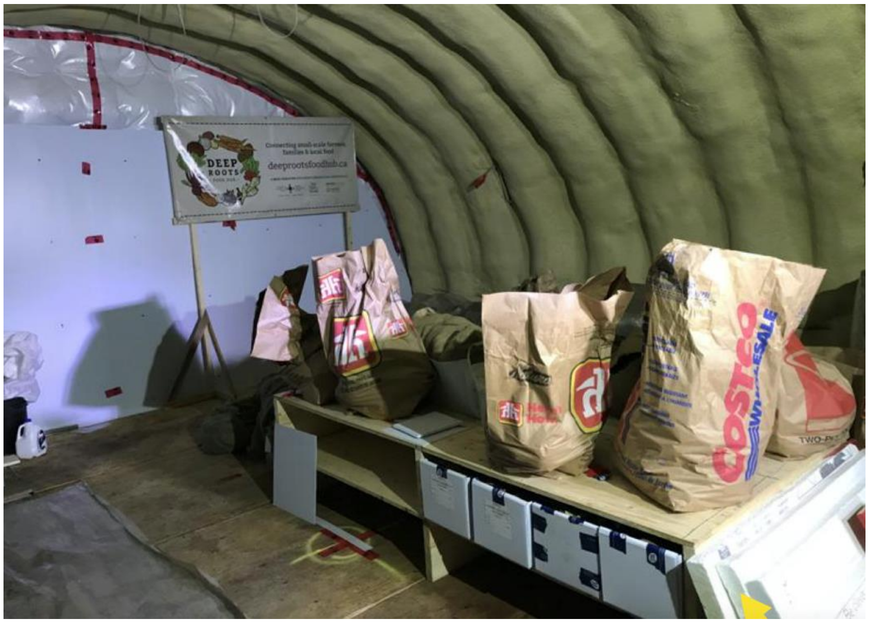


Figure 5. Plywood box with coroplast boxes inside. The box is located near the back of the root cellar.

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.

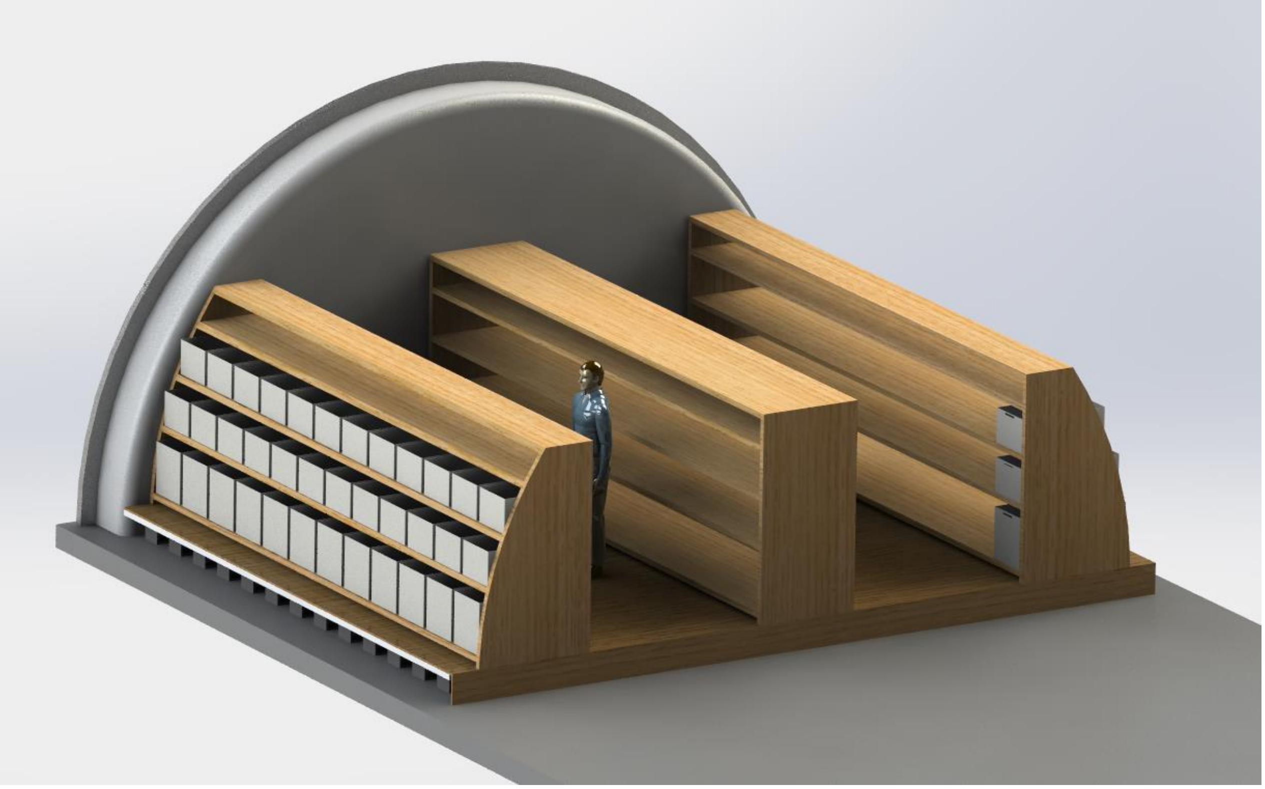


Figure 6. CAD model of the produce chamber after optimization

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

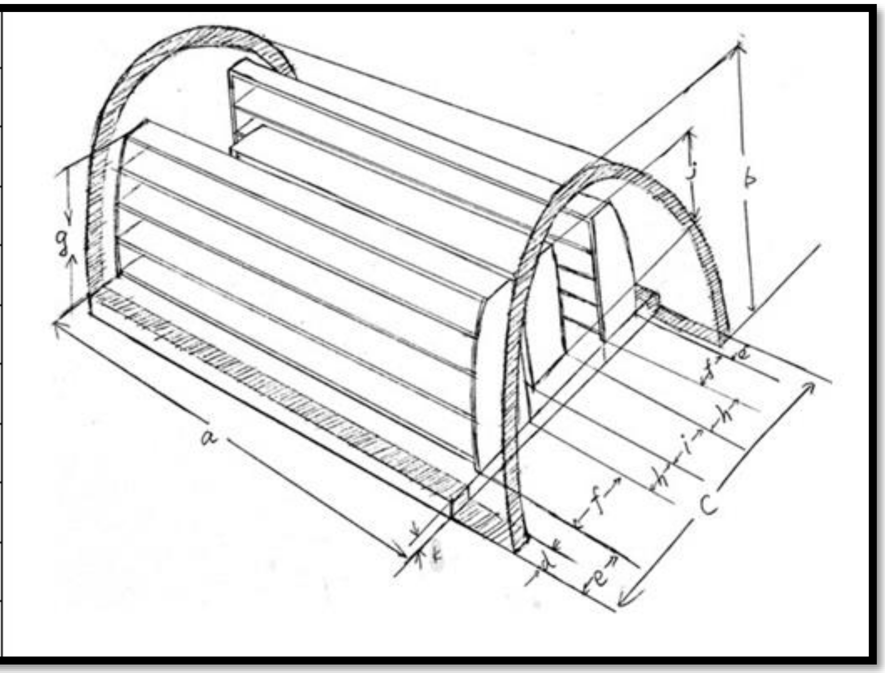


Figure 7. Placements of the racks in produce chamber and general dimensions

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’’

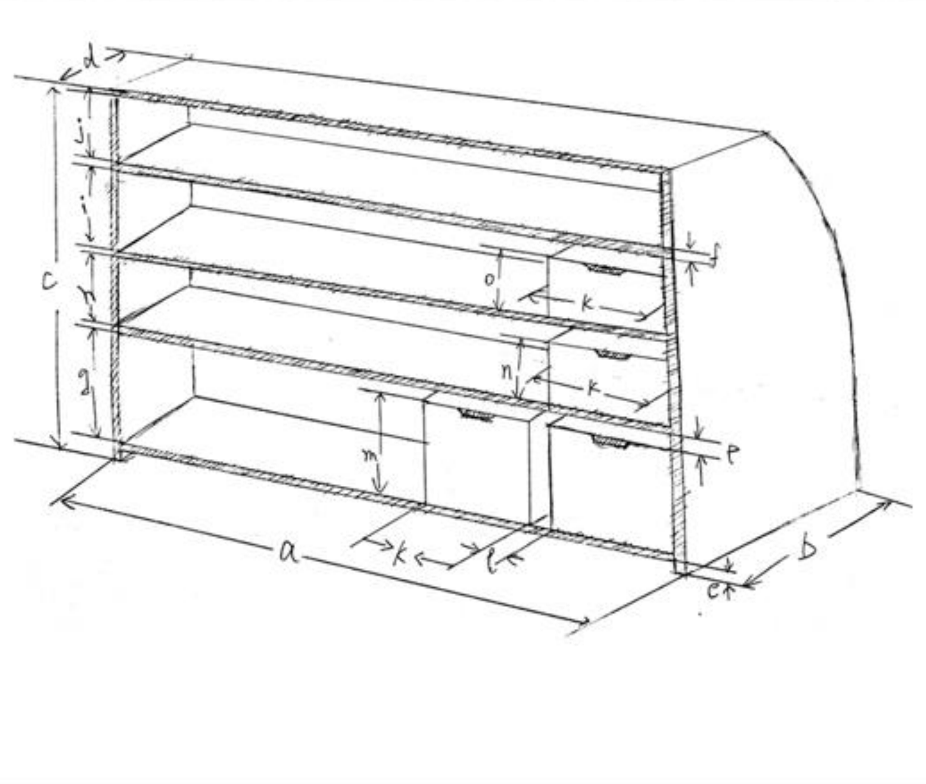


Figure 8. Side rack configuration

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

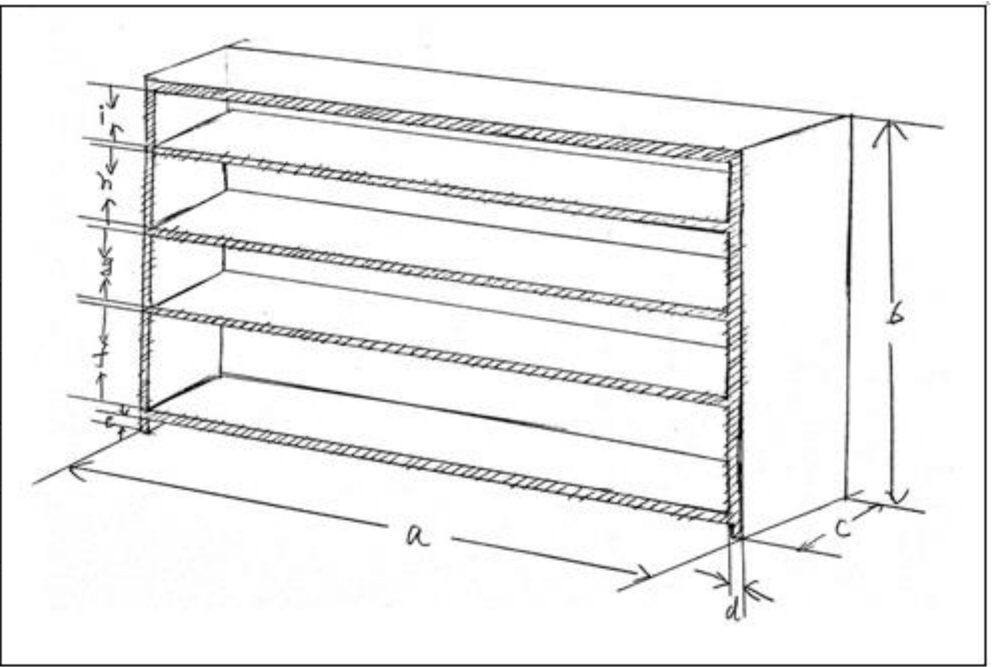


Figure 9. Middle rack configuration

2.3 Power systems

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.

2.3.1 Wind Energy

Figure 10. 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.

2.3.2 Additional Solar Panels

Figure 11. 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.

2.3.3 Ground Source

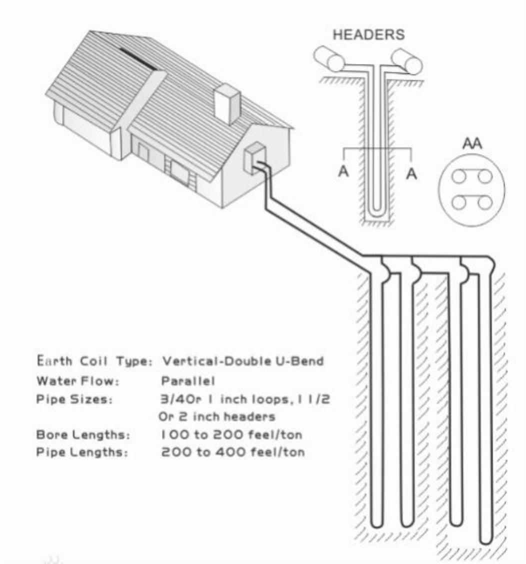

HEADERS
A
A
AA
Earth Coil Type: Vertical-Double U-Bend
Water Flow: Parallel
Pipe Sizes: 3/4Or 1 inch loops, 1 1/2 Or 2 inch headers
Bore Lengths: 100 to 200 feel/ton
Pipe Lengths: 200 to 400 feel/ton

Figure 12. 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.

2.4 Heating and Cooling Efficiency of Current System

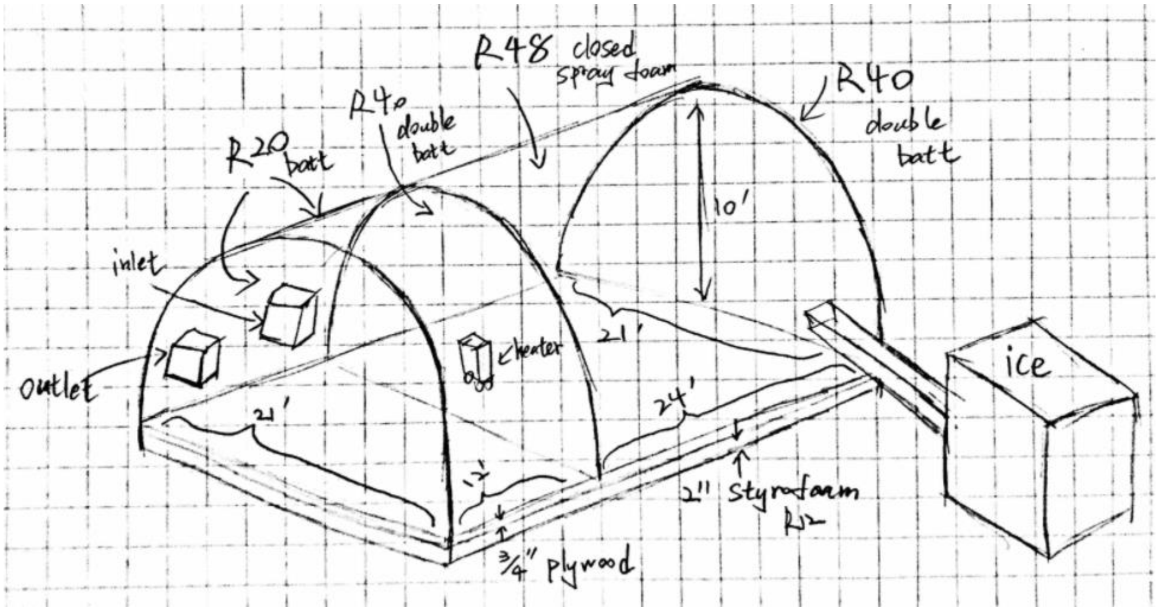


Figure 13. Detailed view of the HVAC system.

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.

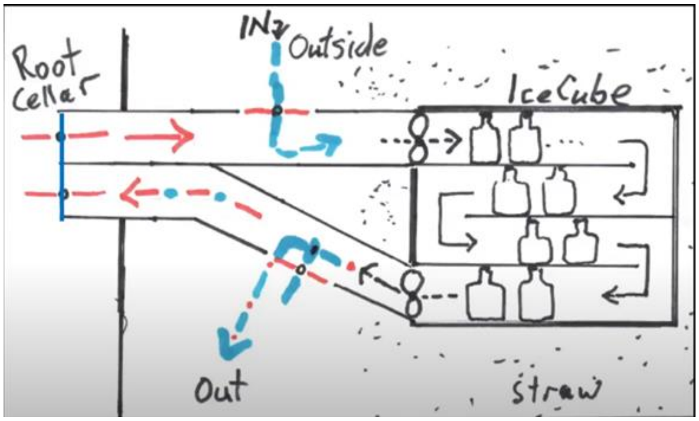


Figure 14. Schematic of the ice chamber.

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.

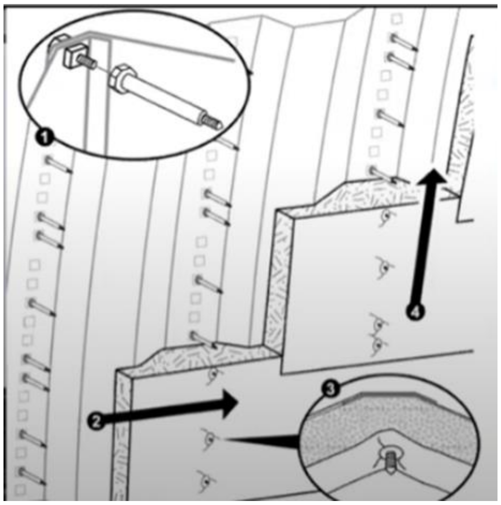


Figure 15. Wall insulation installation.

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 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.

3 Revised Prototype and Test Results

3.1 Test Result (Storage)

- **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**

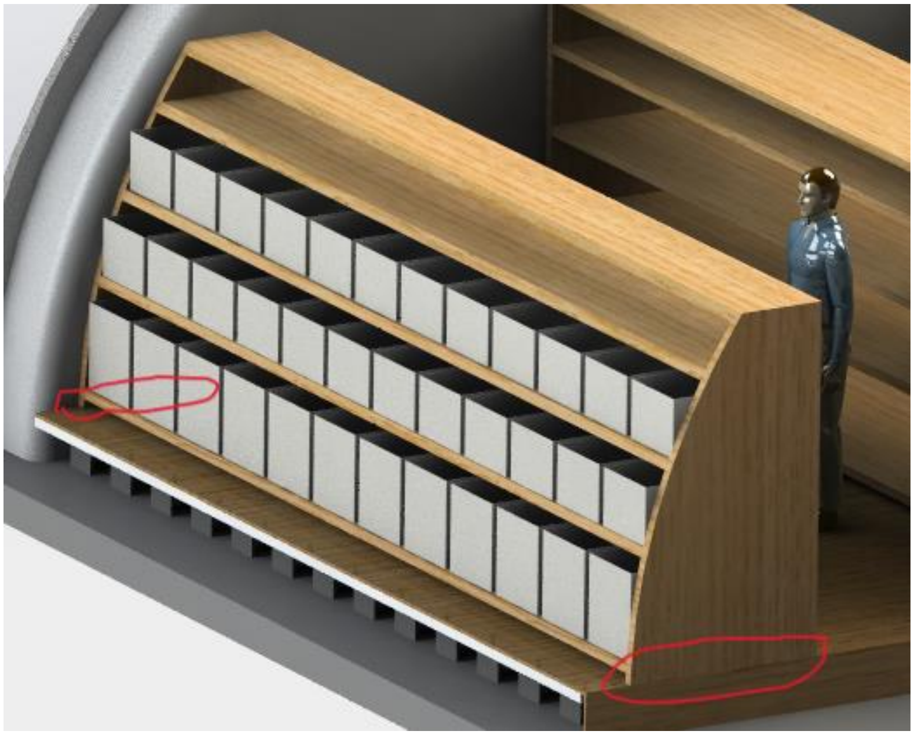
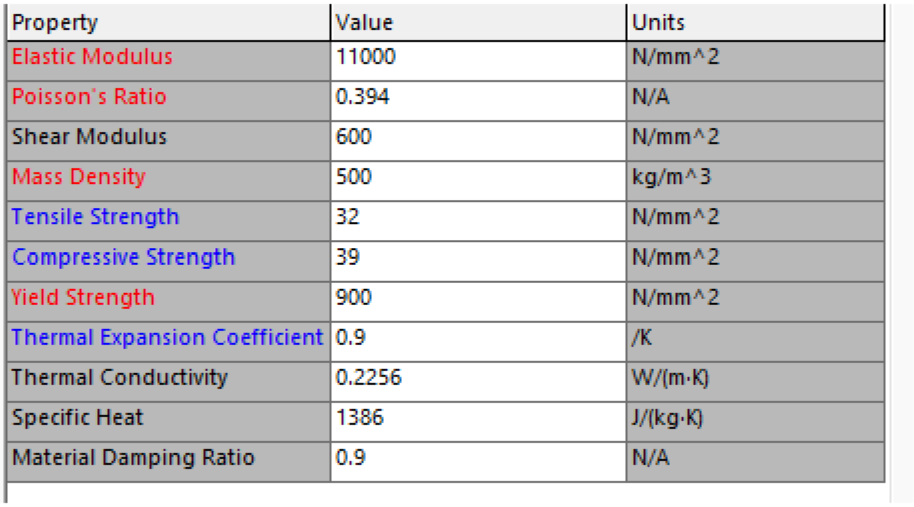


Figure 16. Side rack selected for testing (red line circles the standing areas)

The stress test was carried out by using SolidWorks. 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 17. 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.

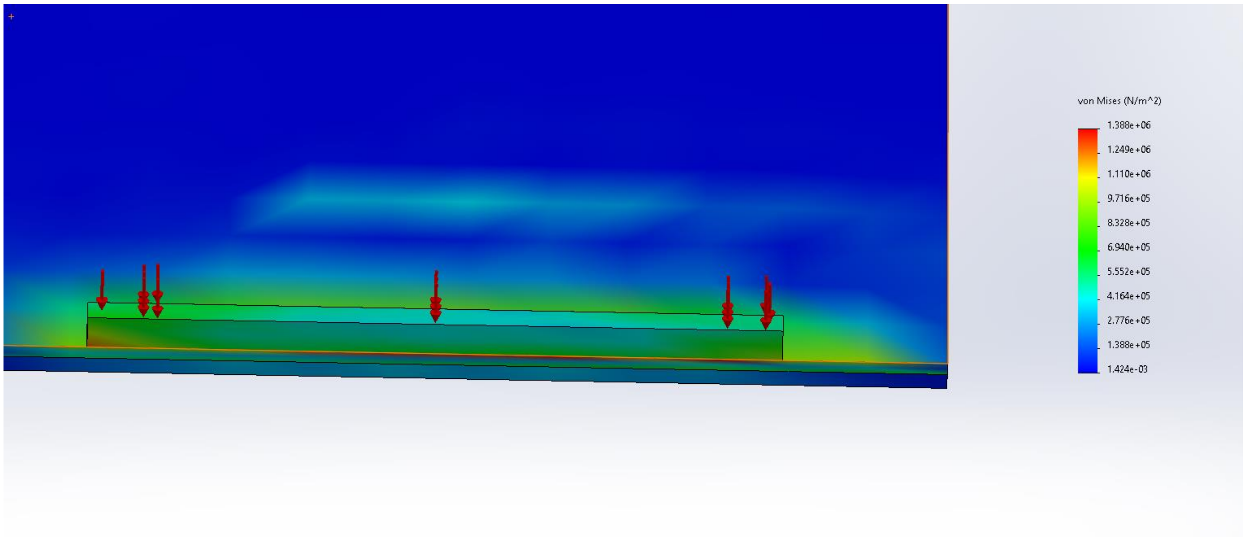


Figure 18. von Mises stress distribution graph by SolidWorks

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.

3.2 Test result (Power system)

- **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)

$L=670/35=20$m

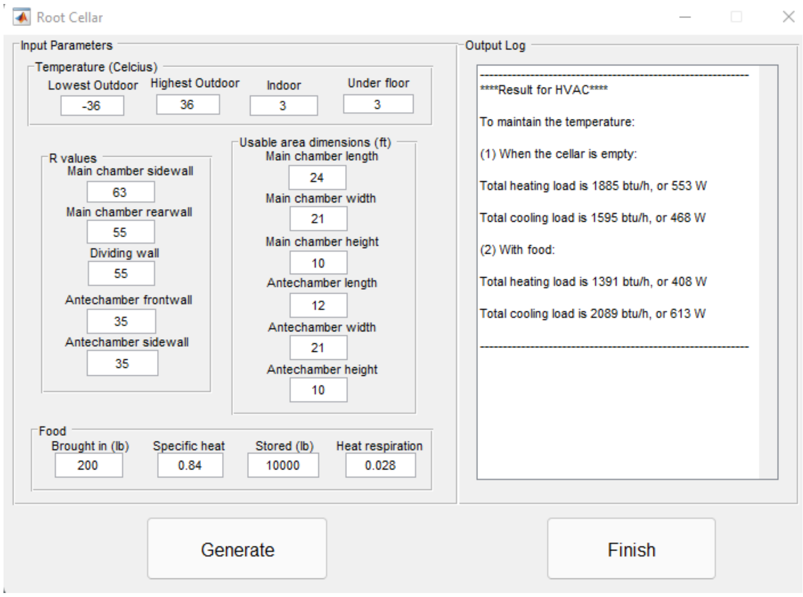
Ground source heat pumps tend to be expensive to install and require more space because deep digging is necessary to obtain stable subsurface temperatures. In Canada, most of the shaft depths are 50~100m, and the team chose a shaft depth H of 50m. A word of caution: 20 meters is less than 50 meters,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

3.3 Test result (HVAC)

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 was also revised with updated dimension values from 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 tool developed for heating and cooling calculations for the root cellar, the hand calculation steps can be found in Deliverable D.



Temperature (Celcius)
Lowest Outdoor: -36
Highest Outdoor: 36
Indoor: 3
Under floor: 3

R values
Main chamber sidewall: 63
Main chamber rearwall: 55
Dividing wall: 55
Antechamber frontwall: 35
Antechamber sidewall: 35

Usable area dimensions (ft)
Main chamber length: 24
Main chamber width: 21
Main chamber height: 10
Antechamber length: 12
Antechamber width: 21
Antechamber height: 10

Food
Brought in (lb): 200
Specific heat: 0.84
Stored (lb): 10000
Heat respiration: 0.028

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****Result for HVAC****

To maintain the temperature:

(1) When the cellar is empty:

Total heating load is 1885 btu/h, or 553 W

Total cooling load is 1595 btu/h, or 468 W

(2) With food:

Total heating load is 1391 btu/h, or 408 W

Total cooling load is 2089 btu/h, or 613 W

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Figure 19. Root cellar heating and cooling loads

- Ice chamber

This section is the revised calculation for the IceCube chamber with updated parameters. 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^{o}C (or 42.8^{o}F), evening temperature is at -2^{o}C
- the produce chamber air enters the duct at 5^{o}C, 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^{o}C (41.9°F), and it leaves the ice chamber at 3^{o}C (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 ^{o}C).

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 ^{o}C) * (5.5 - 3 ^{o}C) = 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.

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

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

Surface without straw bale

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

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

The total heat transfer with the outside is:

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

- 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°C, and at the same time the produce chamber is kept at below 4°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 °C during daytime for April, the air mix enters at 8 °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 °C during daytime for May, the air mix enters at 14 °C, it would produce a total heat transfer of 8396W, the time it takes to melt the ice is 10 hours.

3.4 Results comparison

Table 2. Results comparison.

#	Metrics	Unit	Expected Value	Tested Value and Comments
1	Temperature	Celsius (°C)	2-4	The HVAC testing shows that the chamber can easily maintain between 2-4 during extreme cold winter days, but it would be very difficult for summer.
2	Power Generation	Watts (W)	>500	The wind panels and solar panels can generate more than 500W in the worst-case scenario. So, it will be sufficient to supply the power for fans and controllers.
3	Storage Capacity	kg	>50,000	The calculated weight is about 17820 kg, it is lower than our client's prediction, but this could also be caused by the inclusion of the whole antechamber as storage space. Therefore, our storage method is still very efficient.
4	Cost	Canadian ($)	<20,000	The plywood racks and coroplast boxes are cheap to make, they cost less than $1000. However, $20000 may not be enough if the client wants to apply the new insulation materials.
5	Total storage area after shelves being installed	ft^2	>20	The total storage area is over 190 ft^2. We also managed to leave enough space for walking.
6	Maximum power usage	Watts (W)	<500	The maximum power usage is close to 500W as it is shown in the HVAC testing section that the heating will be >400W for extreme cold winter days, so this assumption is relatively safe for now.

4 Scalability of the Prototype

The team learned more about the client's scalability goals when we visited the root cellar and met with the client in-person. At that time, someone from The Ottawa Food Bank (TOFB) was also there to learn about a potential partnership with DRFH. The man from TOFB mentioned that during the non-Winter months (3 out of 4 seasons), their fridge is stocked with about 166,000 lb of produce, with about 30% being potatoes and 35-40% root crops. The turnover is very fast and is all gone in about 2 weeks' time. In the Winter, they must rely on grocery stores to buy crops, mainly potatoes and onions. The latter is the same case for local farmers and most of the population in Ottawa. The local food markets are closed during the Winter months and people rely on imported crops from the grocery stores. The client wants to buy the farmers' produce and store it during the Winter months. However, if the storage we designed is implemented, the root cellar could store 17,820 kg or 39,300 lb. If we go with the turnover rate of TOFB, this will only feed the community for 3.3 days. That is the motivation to scale-up the root cellar: to store more produce and feed the community for a longer period during the Winter months.

If the curved root cellar is scaled-up, our storage design can be easily modified to be scaled-up as well. If the root cellar is scaled-up on the width, then there may be enough clearance to add a second middle rack, which would have a big impact on the amount of produce stored. Due to user experience and to continue having a functional design, the height of the racks is likely to be limited to 6' tall even if the root cellar ceiling is increased. If the client pursues the scaling-up of the root cellar, then we can give him access to the SolidWorks 3D CAD file containing our design; this way, he can easily change the dimensions of the root cellar and the curved racks to fit the new space.

Another thing to consider is the additional power and energy that will be required in order to keep the inside of the root cellar in the right conditions (humidity, temperature, air circulation). Our team had calculated that ground source heating and cooling may become feasible once the root cellar is expanded/scaled-up in the future. So, even though the ground source (geothermal energy) may be "overkill" for the current root cellar, it may more feasible and cost-efficient in the long-term when implemented in a scaled-up cellar.

5 Quality of the Prototype

Table 3. User needs and their status

#	Need	Completion

1	The root cellar can store a large variety of crops, vegetables, and fruits.	Yes
2	The root cellar has large power sources.	Yes
3	The root cellar stays off-grid.	Yes
4	The root cellar needs an eco-friendly backup power.	Yes
5	The root cellar needs an efficient heat source.	Yes
6	Making a mathematical model for heat distribution in each chamber.	Yes
7	A mathematical proof of the heat gains from the gravel floor during winter and summer.	Yes
8	The root cellar has good heat insulation	Yes
9	The root cellar can maintain a consistent temperature.	Yes
10	A better method to store snow or ice.	Yes
11	The generator can be turned on autonomously without direct human manipulation.	Discarded
12	The root cellar needs a stable wireless control system.	Discarded
13	The control system can use weather forecast to make decisions.	Discarded

The quality of our prototype can be measured by using perceived quality and engineering quality. The perceived quality is what the user sees as the quality of the prototype, it can be acquired by checking how many of the user needs and project requirements have been met. The table above is from deliverable B, it shows that we have met most needs the client asked for except the last three, and those were discarded because the client agreed with excluding the control system from the project. The engineering quality is the quality based on mathematical model and scientific evidence, and it is already shown in the result comparison section where we compared the prototype performance with target specifications. Overall, we achieved a satisfying quality for our prototype.

However, by applying the definition of quality used in the class, which is the extent to which the efficient product of the prototype meets the requirements that the user needs, we identified several issues happened during the prototype development that could be improved by using methods like kaizen, six sigma, and house of quality.

- Kaizen

The basic idea of Kaizen is to improve the productivity, effectiveness, and safety by having everyone involves in the project to identify gaps and inefficiencies. Although Kaizen was originally developed to improve manufacturing processes, we can gain benefits of this approach on a team level by reducing organizational waste. The wastes could have been reduced in the design process are discussed below.

- Overproduction: during prototype development, there were some over production on the storage solutions and HVAC tool design as those were not directly demanded by the client, time and resources spent on each could be less if we had a thorough discussion with the client before starting working.
- Inventory: In the beginning stage of the design, we were told that the control system of the cellar had disconnection issue. A brief inspection of the online logging system shown us that the control system was well maintained, and further inspection on it would add no value to the design. However, we stopped analyzing the control system only during the middle of the semester after having a discussion with the client. There would be more time to work on other aspects of the design if we decided to drop the control system earlier.
- Waiting: Some tests we did like storage size, plywood stress, and HVAC all rely on the precise dimensions of the cellar, and the numbers were measured in the ending phase of our prototype development, team members were left to wait for a prolonged time. This issue is related to project planning, we could have planned a visit to the cellar in the beginning of the semester, and that would leave less uncertainty for the design.
- Motion: During the prototype design, there were some unnecessary movements of roles for designing subsystems. This could have been resolved by better understanding each person’s discipline instead of assigning roles randomly.
- Rework: The team reworked on the calculations for HVAC, storage, and power system several times during the design. It was partially due to the constant changes in the root cellar by the client. Fixed parameters should have been predefined in the early design stage.

- Six sigma

Six sigma is developed to improve manufacturing process by reducing defects, but it can also be used as an approach to increase the overall project success rates through structured methodologies. Two methodologies exist, and they are DMAIC (Define Measure Analyze Improve Control) and DFSS (Design for Six Sigma), the former is used to improve business process, which is not applicable in our case, while the latter is a data-driven quality strategy for designing a product. Therefore, we can use the DFSS as a guideline to improve our design.

The definition stage of DFSS involves market research and quality metrics checking which were completed in early phase of our design, but it also asks for developing a failure mode and effects analysis which was not realized by us. The second stage is measurement, we completed it by quantifying client needs and measuring existing prototype performance. The third stage is the analysis phase, it includes statical analysis to find functional relationships between quality parameters and input variables to allow designer to make fact-based decisions, we could have built such relationships for our design. The last two stages are design and verification, they involve designing and testing the prototype against target objectives. Due to the scale of our design, a physical implementation is difficult for the members, but we could have designed a small version of the root cellar for testing.

- House of quality

House of quality is an approach to prioritize and reorder design specifications so the designers can focus on satisfying the most important user needs. In the early stage of our design, we did build customer needs and target specification tables as our design guidelines. However, according to house of quality, another table should have been built to relate the specifications and needs to show how each of them affects others, and a roof matrix could be made to determine the strength of the relationship between the specifications. With this approach, we could have planned our time and effort more efficiently by concentrating on the subsystems that matter the most instead of dividing the whole system equally then discarding some parts after working on it.

6 Sustainability of the Prototype

- **Sustainability aspects of current root cellar design**

In 2015, all United Nations members agreed to the shared blueprint for peace for people and the planet for the 2030 Agenda for Sustainable Development. The root cellar project came about from the realization that agriculture and food availability will be an issue in the upcoming years. There are 17 sustainable goals in total, and the storage and maintenance of produce in a root cellar meets the following ten United Nations sustainability goals.

Table 4. UN Sustainability Goals

UN Sustainability Goal	How our design meets the goal
1 NO POVERTY	• By providing a storage space for farmers to keep their produce for longer so they can sell it • Farmers can generate and store their own produce, so they don't have to spend money in grocery stores
2 ZERO HUNGER	• By providing produce that would have otherwise gone bad (extending the lifetime of produce) • Increased storage space to store more produce, which in turn will feed more people when in need
3 GOOD HEALTH AND WELL-BEING	• Providing storage space, and providing the appropriate temperature and humidity to store healthy vegetables • Promoting an agricultural lifestyle and sourcing food from the Earth

	• Promotes not being wasteful of food by providing the means to store it for longer
8 DECENT WORK AND ECONOMIC GROWTH	• Economic growth when farmers and the community come together to support their crops and produce
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	• New infrastructure (root cellar) on farmland. There’s a lot of farmlands in Ontario and this prototype may show how feasible it is to incorporate it elsewhere
11 SUSTAINABLE CITIES AND COMMUNITIES	• Creating a self-sustaining and sustainable community by providing the right space to store their produce
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	• Promotes responsible consumption of produce and limits the wastefulness that comes with not being able to store crops

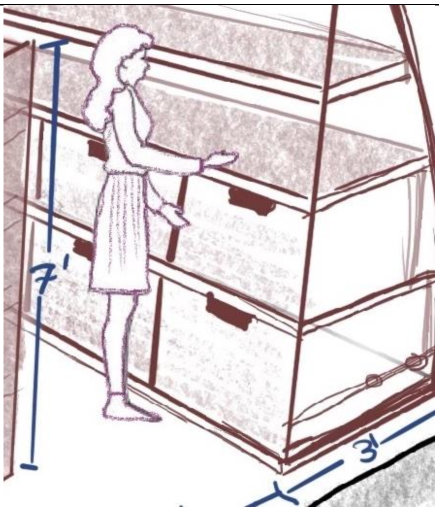
13 CLIMATE ACTION	• The power sources (solar-powered batteries, wind energy, ground heat) are renewable and do not generate harmful gases • The storage space is also designed to be made of renewable materials
15 LIFE ON LAND	• Life can be sustained longer on land thanks to having housing for food that is grown by farmers • Keeps the land alive and fertile when it is being tend to (some farmlands become barren when people move away from them and stop farming in them)
17 PARTNERSHIPS FOR THE GOALS	• The storage space generates partnerships with local farmers and community members interested in sustainability and food security

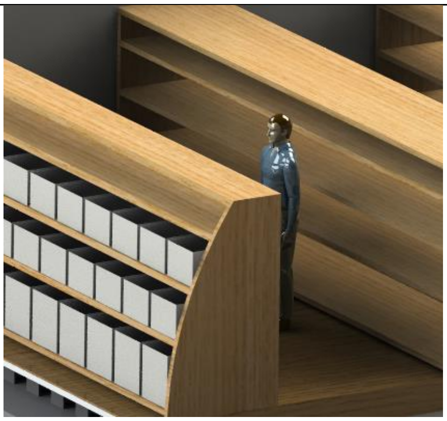
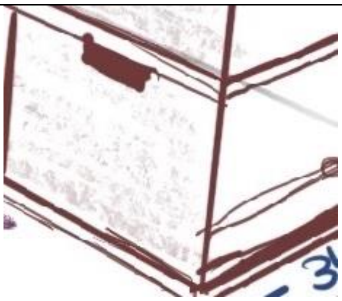
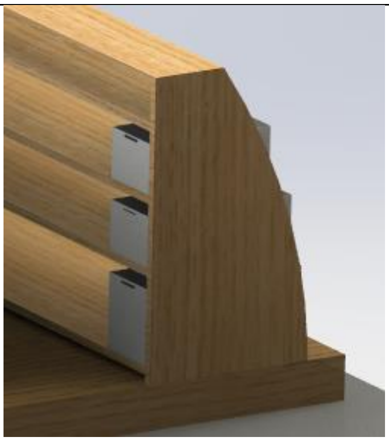
- **Improving economic, social and environmental sustainability**

The cellar can be extended economically to achieve sustainable development. By expanding the cellar to two or three times its original size, the amount of food that can be stored will also increase. This allows farmers to store more food here, prolongs the shelf life of food, and reduces food waste. More food can be sold by farmers, promoting sustainable economic development. Farmers can use the funds to sell fruits and vegetables to build regional infrastructure, and they can also use the money to invest in education, realizing the sustainable development of society. In addition to this, the diffused cellar will be able to use a geothermal heating system. The geothermal heating system only needs to invest in the initial construction cost, and the cost of the later enclosure is less. Therefore, the longer the use time, the more economical returns, which can be applied to the development of the cellar. In terms of environmental sustainability, the effect of geothermal heating systems is also significant. Geothermal heating systems use geothermal wells as cooling or heat sources, and underground heat exchangers buried in the ground form a loop to exchange heat with the earth. The cellar will not rely on the engine to generate heat, thus reducing greenhouse gas emissions and achieving environmental sustainability. To reduce environmental impacts, cellars can make the following efforts: 1. Use cheaper energy sources such as solar, wind or geothermal energy. 2. Reduce the use of fossil energy to reduce greenhouse gas emissions. 3. The wall uses clean and environmentally friendly thermal insulation materials.

7 Usability of the Prototype

Table 5. List of Usability

#	Usability Feature	Explanation	Image
1	Drawers	Drawers in the last 2 rows of the storage so that it is easy to access vegetables	

2	Walking Space	We have kept about 4 feet on space on both side of middle rack for easy walking	
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.	
4	Airflow	½ feet of space at the back of racks for easy air flow.	
5	Handle	A cut out in plywood of the drawers for easily opening drawers.	
6	Shape	Curved Spaced rack design to maximize space.	

Improving usability of the design by:

a. By adding smooth drawer trolleys that remains smooth even when fully packed.
b. Adding ladder in the design for easy accessibility of short-heighted people.
c. Movable design for adjusting the air flow.
d. Labels for easy searchability
e. More innovative storage space to increase the capacity

8 Conclusions and Recommendations for Future Work

For this project, the team optimized the way food is stored in the cellar and analyzed the construction methodology by performing stress test. For the power system, the team has three recommendations, namely wind, solar, and geothermal power. For the convective heat transfer system, the team made some assumptions and improvements to the insulation material. Finally, the team examined the prototype in terms of its scalability, sustainability, quality, and usability. Future improvements can be made by using the above four sections as guidelines. Overall, the final prototype has satisfied the client’s requirement.

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