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GNG 5140 Engineering Design

Project Deliverable E: Revised Prototype Analysis and Test Results

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 revision of the initial prototype. The team then tests revised designs to compare the performance against target specifications. Based on these results, the team listed out potential fixes to further improve the prototype. Unfinished tasks are also listed and shall be completed before final project report submission.

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List of Acronyms

Acronym	Definition
DRFH	Deep Roots Food Hub
HVAC	Heating, Ventilation, and Air Conditioning

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 will help us better understand the prototype's performance and flaws. This report will discuss in detail the further creation of the prototypes, the testing results against target specifications, and an updated project plan for the presentation and final report.

2 Global Solution Concept

2.1 Overview

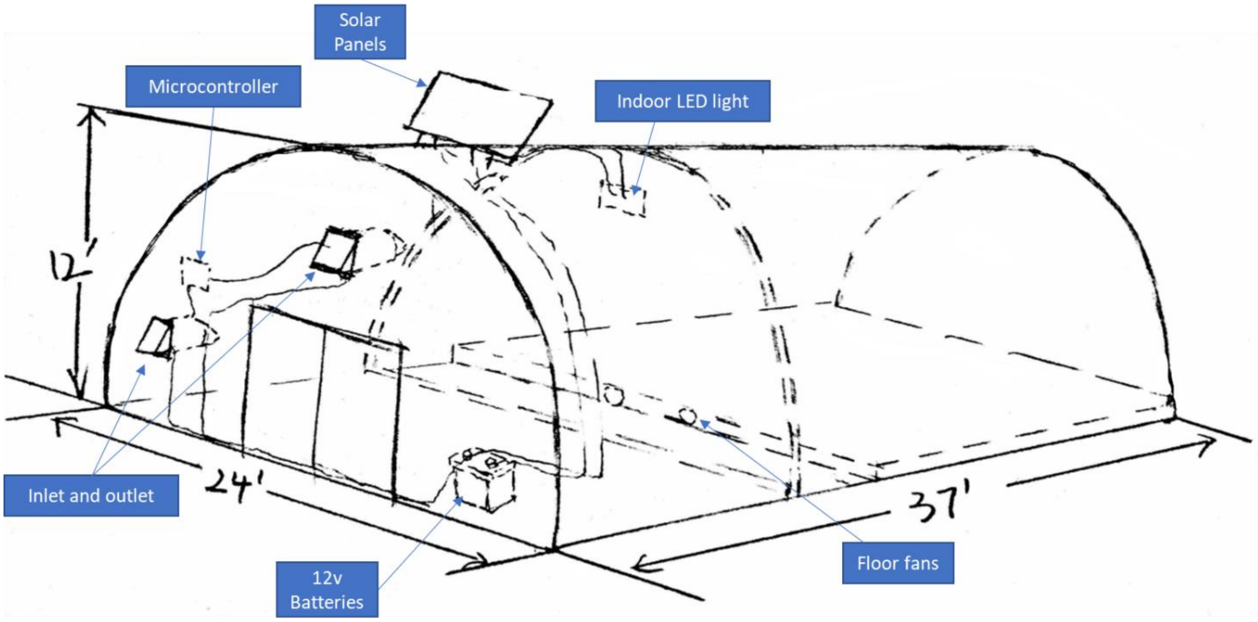


Figure 2. 3D view of the root cellar (detailed visuals of storage shelves, insulations, ice chamber are in section 3)

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 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, 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

The dimensions of the root cellar were calculated in Project Deliverable D and are summarized in Table 1. Because these numbers were retrieved from 3 sources, we assumed an average value for all three dimensions (width, length, and height). These values are summarized in Table 2.

Table 1. Dimensions of the root cellar according to three sources. Dimensions are listed in feet units as W, L, and H, which stand for width, length, and height. Some cells are empty because the value was not stated in the source(s).

Source	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)
DRFH website [3]	21	20		400	25	12		300				
Informative video speech [5]		24				12			37	24	12	10,656
Slides from informative video [6]						10			40	24	10	9,600

Table 2. Average 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)
21	22	11	**5,082**	25	11.4	11	**3,135**	38.5	24	11	**10,164**

From the dimensions in Table 2, 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 4-6). 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. Barry 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.

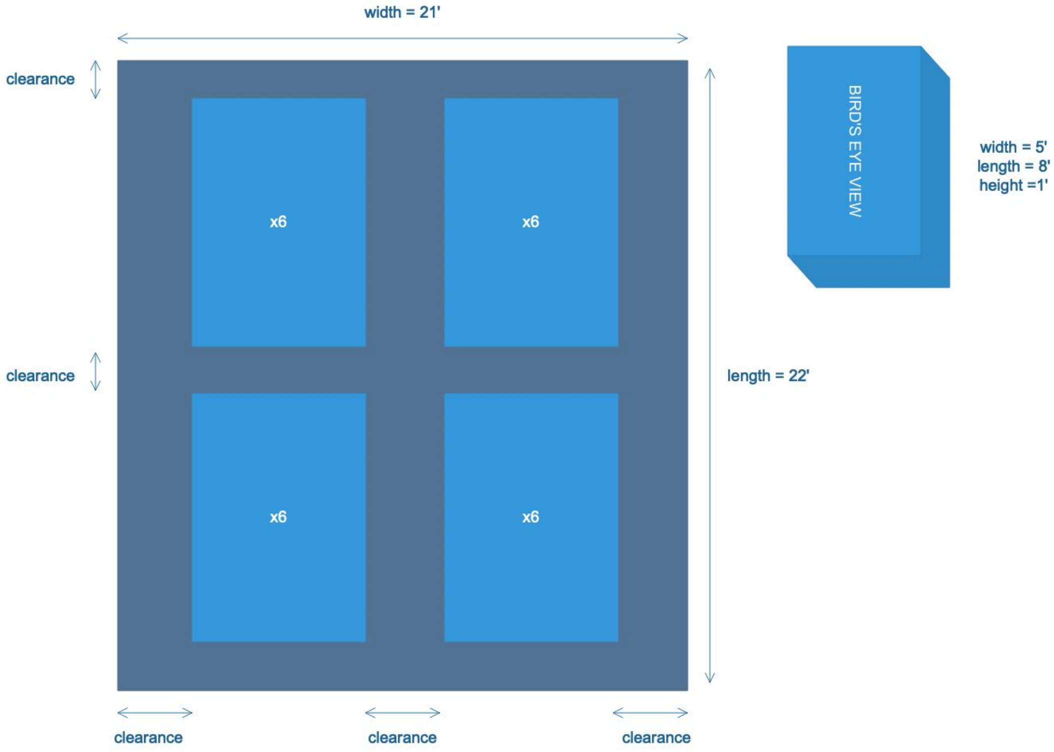


Figure 3. Bird's eye view of the produce chamber. The light blue boxes with 'x6' are 6 individual plywood boxes stacked. The dimensions of 1 plywood box are on the right of the diagram.

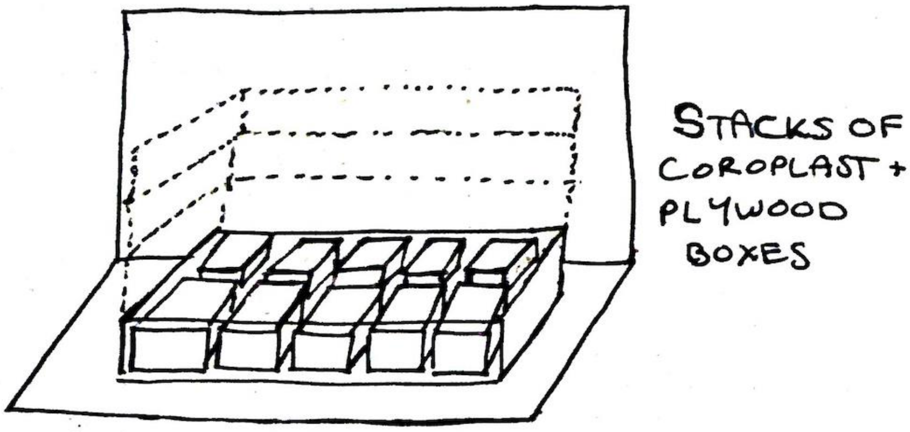


Figure 4. Sketch of the plywood box with space for coroplast boxes. The dashed lines represent the other plywood boxes that would be stacked.

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. Exact numbers cannot be determined because the team has not measured the precise dimensions of the produce chamber and the antechamber, the values will be available in the final report. For storage size testing, estimated dimensions from the client were used.

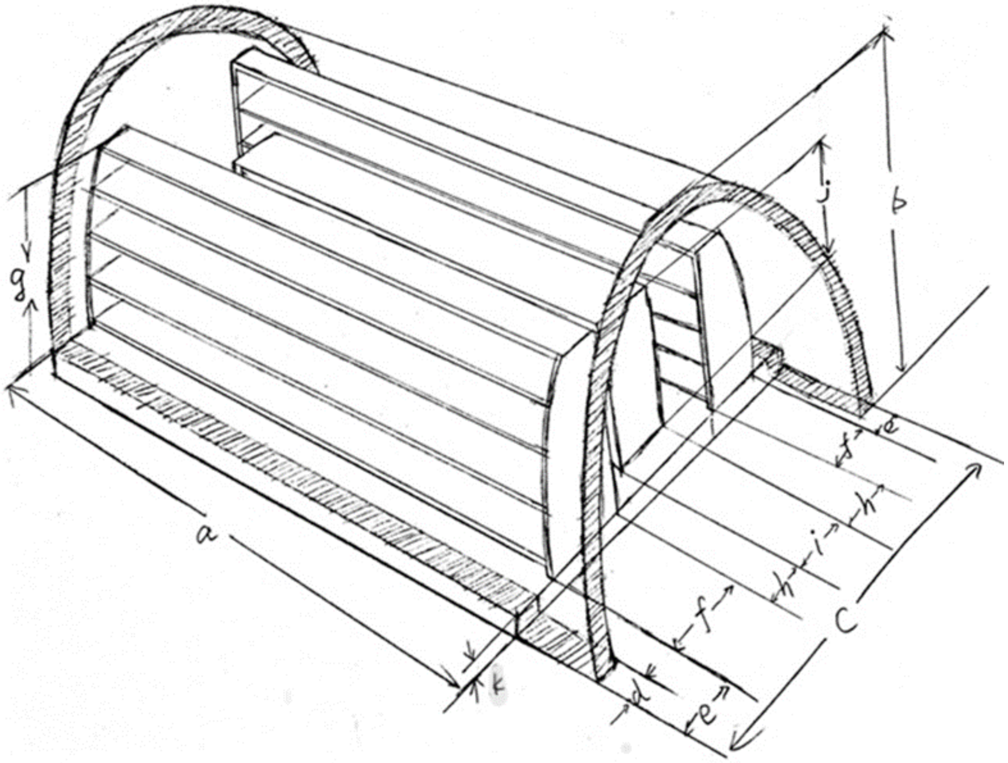


Figure 4. Placements of the shelves in produce chamber

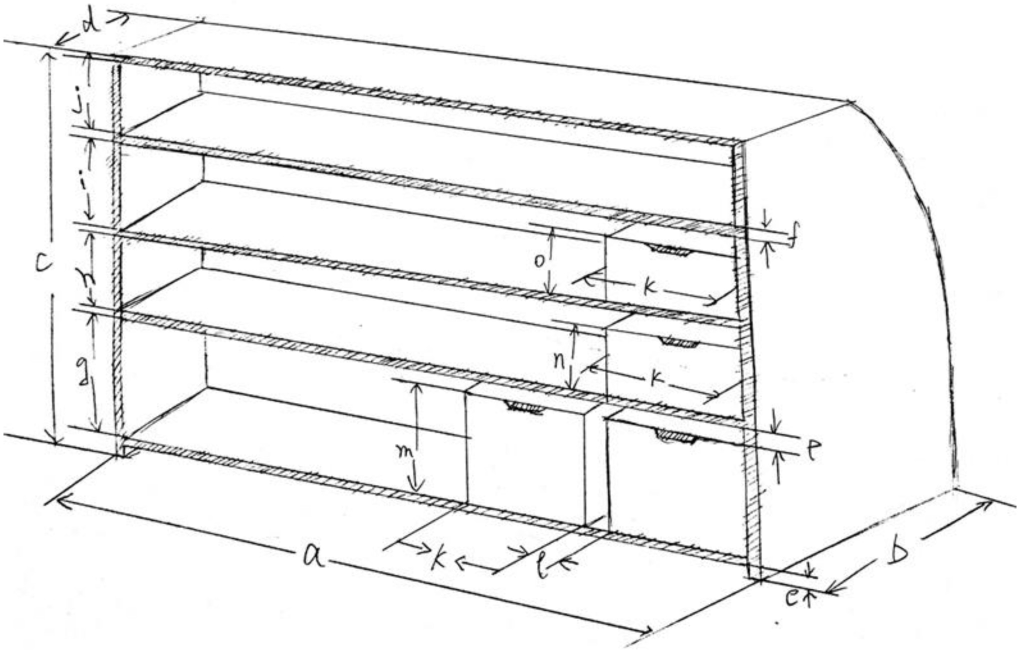


Figure 5. Side shelf configuration

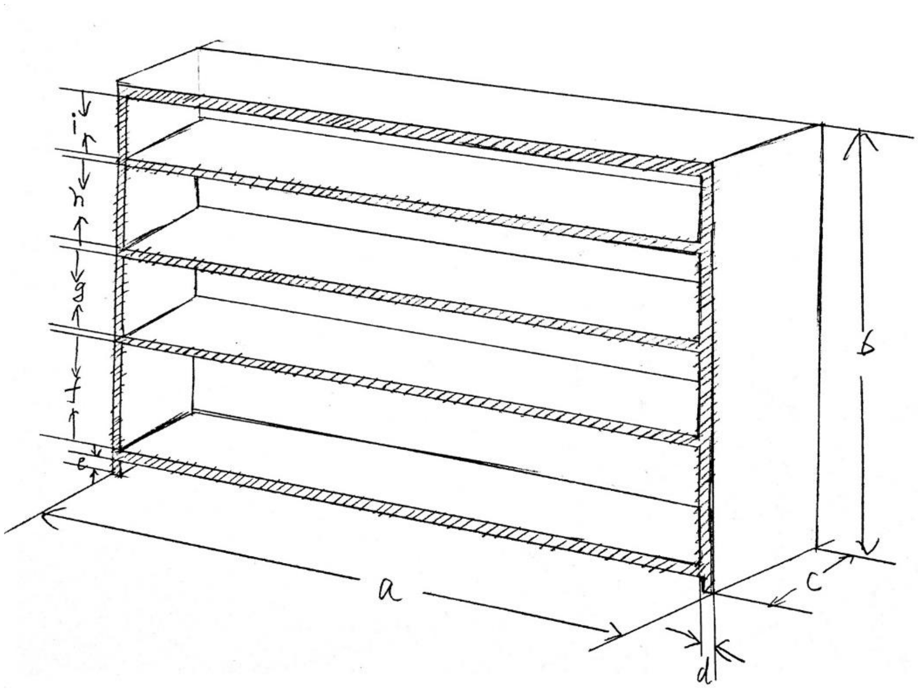


Figure 6. Middle shelf configuration

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 7. 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 8. 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

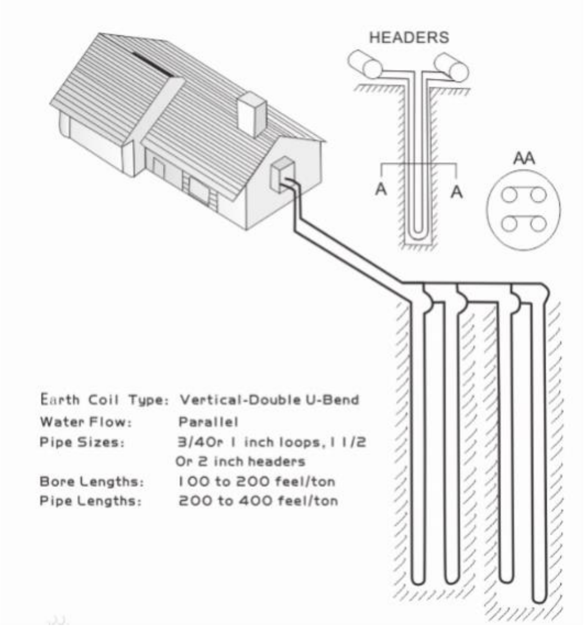


Figure 8. Geothermal heating network

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

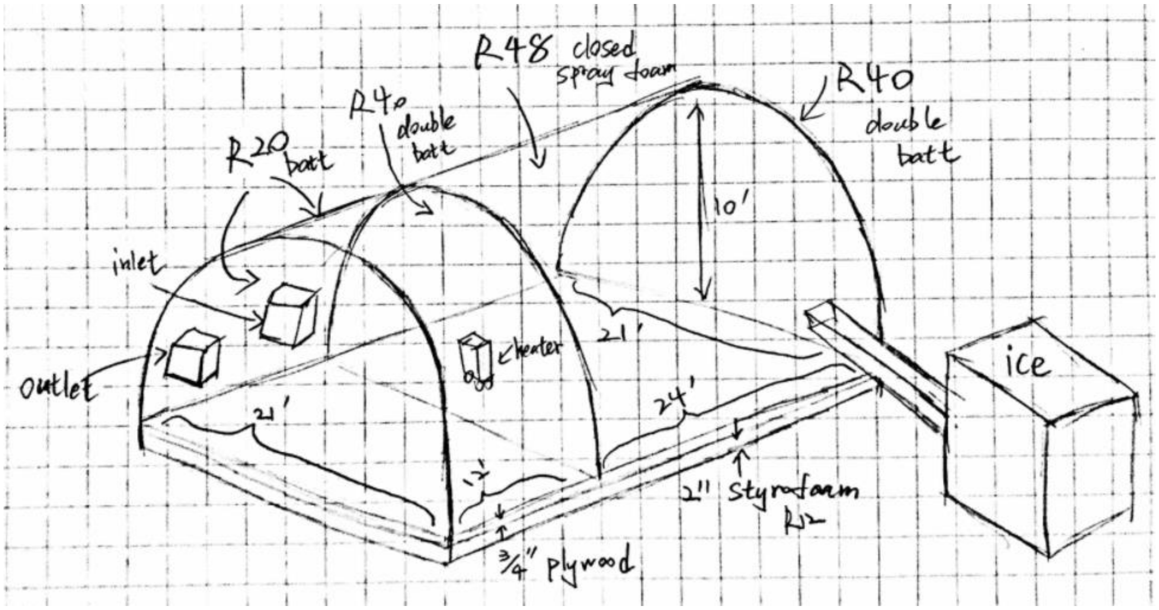


Figure 9. Detailed view of the HVAC system.

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.

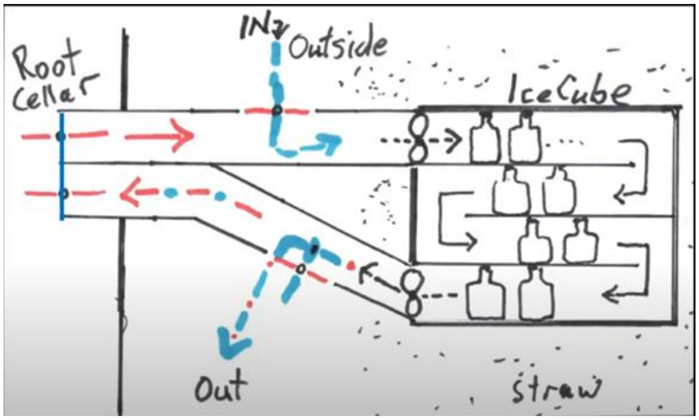


Figure 10. Schematic of the ice chamber.

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.

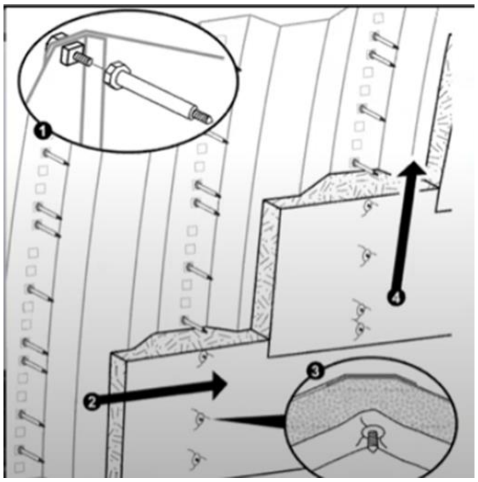


Figure 11. Wall insulation installation.

Due to the size of insulation materials, the actual usable area is less than the outside dimensions:

Estimated produce chamber usable area dimension: 24’x 21’x 10’

Estimated antechamber usable area dimension: 12’x 21’x 10’

2.4.1 Insulation Material Update

To 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. However, the material and installation cost would be >$20000 if the client decided to buy brand named ones like Panasonic.

2.4.2 IceCube Chamber Improvement

The IceCube chamber is well insulated, so no new insulation method is proposed here. A revised calculation was made because the client updated some parameters on temperature range and chamber size, the updated results can be found in the prototype testing section. The ice chamber can still 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^oC, the dampers can be opened again to allow airflow once the internal temperature drops to 3.8-3.5 ^oC. 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)

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

According to the design, the distance from the first drawer to the ground is 23 inches, the distance from the second drawer to the ground is 40 inches, the distance from the third drawer to the ground is 57 inches, and the distance from the fourth drawer to the ground is 70 inches. So the team can get the distance from the handle to the wall of each drawer as the width when calculating the volume.

1.The width of the first layer is 36*(1-23/95) =27.3 inch
The width of the second layer is 36*(1-40/95) =20.8 inch
The width of the third layer is 36*(1-57/95) =14.4 inch
The width of the fourth layer is 36*(1-70/95) =9.5 inch
2.The volume of the first layer is 18*16*27.3*14=110073.6 inch^3
The volume of the second layer is 12*16*14*20.8=55910.4 inch^3
The volume of the third layer is 12*16*14*14.4=38707.2inch^3
The volume of the forth layer is 252*9.5*9=21546 inch^3
3.The volume of the middle drawer is (6*12-6*2)*3*12*15*12=388800 inch^3
4.The sum of the volume is (110073.6+55910.4+38707.2+21546)*2+388800=841274.4 inch^3=486.85ft^3

The weight of produce: The weight of vegetables in 1 sq.ft area * The total area

The area of middle drawer is 3*12*15*12=6480inch^2
The area of the first layer is 16*27.3*14=6115.2inch^2
The area of the second layer is 16*14*20.8=4659.2inch^2
The area of the third layer is 16*14*14.4=3225.6inch^2
The area of the forth layer is 252*9.5=2394inch^2
The total area is (6115.2+4659.2+3225.6+2394)82+6480=39268inch^2=273ft^2
Taking the example of potatoes, the average weight of vegetables in 1 square feet area is 10kg.

So the weight of produce is 2730kg.

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=20m

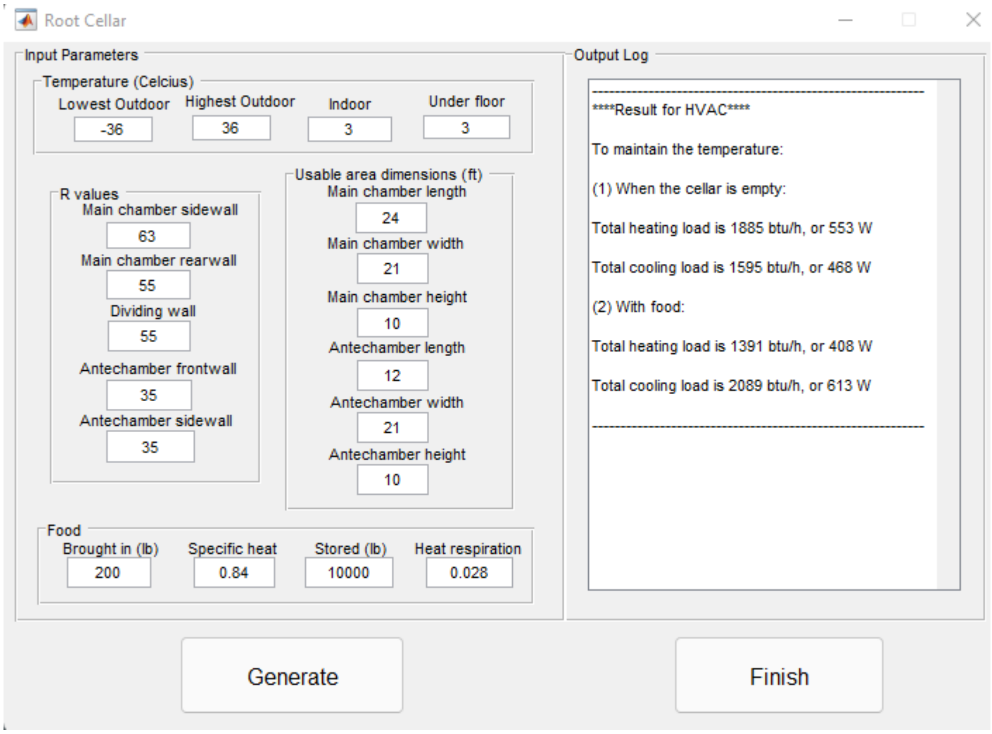
Ground source heat pumps tend to be expensive to install and require more space because deep digging is necessary to obtain stable subsurface temperatures. In Canada, most of the shaft depths are 50~100m, and the team chose a shaft depth H of 50m. A word of caution: 20 meters is less than 50 meters,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

3.3 Test result (HAVC)

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 12. 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^oC (or $32\ ^oF$) 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.

3.4 Results comparison

Table 3. 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.
3	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.
4	Storage Capacity	Tons	>150,000	The calculated weight is about 2740 kg, it is way lower than what our client anticipated. We could see the actual value to be higher since the shelf's dimensions are not final.

6	Cost	Canadian ($)	<20000	It would be a little bit difficult to keep the total cost under 20000, the estimated insulation cost is already near that amount.
7	Total storage area after shelves being installed	Ft^2	>20	This requires a precise measurement of the produce chamber, so the value is not available in this report.
8	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.

3.5 Remaining Tasks

- Produce chamber and antechamber dimension measuring

The team will meet with client at root cellar on Mar 23, 2022, to get dimensions of the root cellar spaces, mainly antechamber and produce chamber. Once the dimensions have been obtained, the dimensions for the storage ensemble can be deduced (those will be included in the final report). Therefore, the storage calculation results will be updated.

- CAD representation of the root cellar

A CAD drawing of the root cellar will be completed before the presentation day.

4 Updated Project Plan

The picture below is the updated plan for our project presentation and design day.

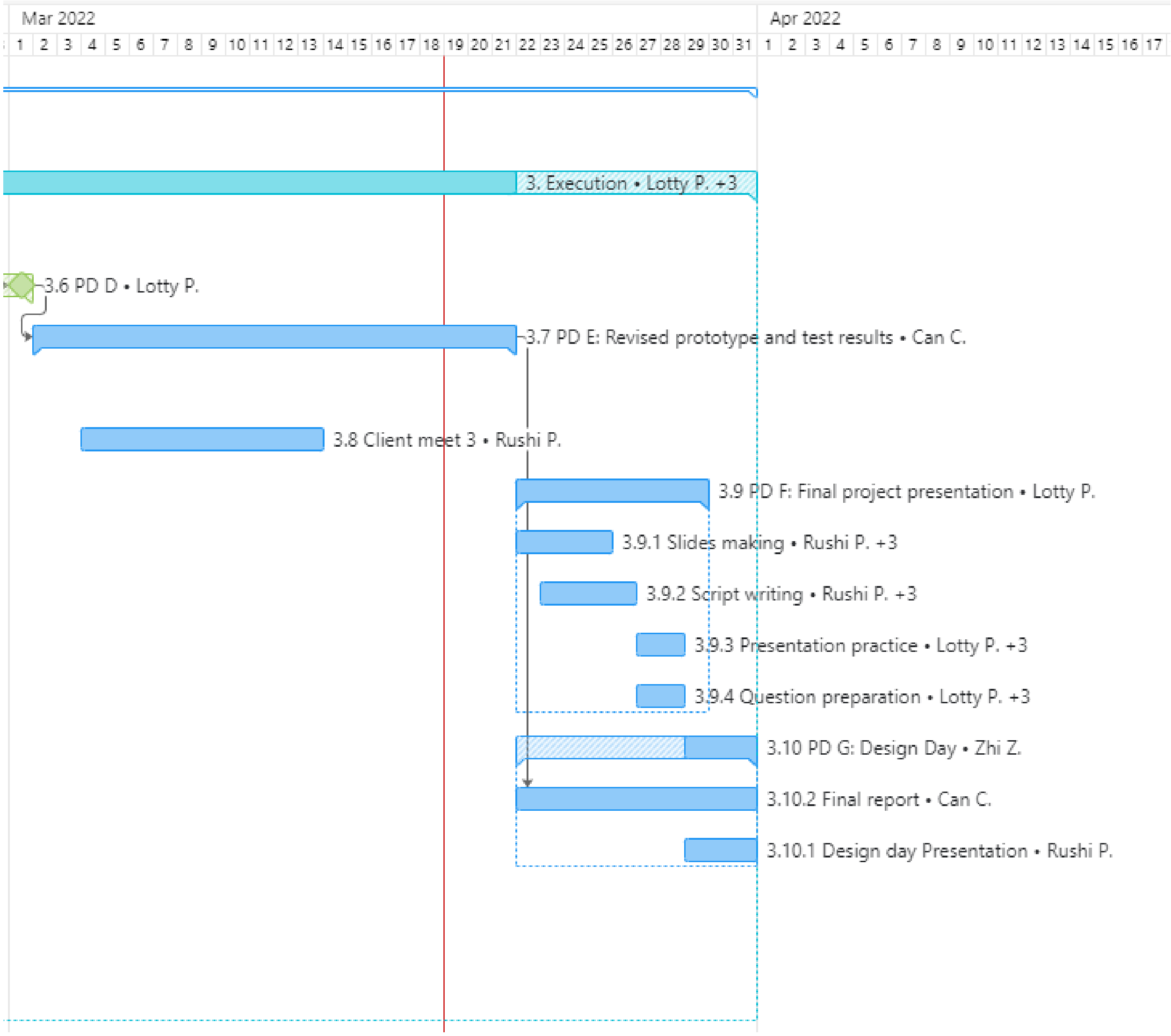

Figure 13. Updated project plan

5 Conclusions and Recommendations for Future Work

For this project, the team optimized the way food is stored in the cellar and created a drawing. For the energy system, the team has three recommendations, adding the calculation of ground-source heat pumps to the previously proposed wind and solar. For the convective heat transfer system, the team made some assumptions and improvements to the insulation material. Finally, the team examined the feasibility of improved food storage and HVAC systems.

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Appendix A

Table A.1. Specific heat and respiration for food

		Respiration (Btu/lb/hour)	
Commodity	**Specific Heat (Btu/lb/°F)**	**Cool**	**Warm**
Apples, summer	0.87	0.018	0.340
Apples, fall	0.87	0.012	0.240
Asparagus	0.94	0.245	2.523
Beans, butter	0.73	0.123	0.716
Beans, string	0.91	0.161	0.885
Beets, topped	0.90	0.028	0.092
Blueberries	0.86	0.028	0.748
Brambles	0.87	0.092	0.711
Broccoli	0.92	0.092	1.376
Cabbage	0.94	0.023	0.257
Cantaloupes	0.94	0.025	0.305
Cucumbers	0.97	0.119	0.170
Grapes	0.86	0.014	0.179
Green onions	0.91	0.096	0.704
Leafy greens	0.90	0.100	1.034
Okra	0.92	0.257	1.583
Peaches	0.91	0.023	0.466
Peas, garden	0.79	0.177	1.651
Peas, field	0.73	0.160	1.554
Peppers	0.94	0.046	0.252
Potatoes	0.84	0.028	0.055
Squash	0.95	0.161	0.751
Strawberries	0.92	0.069	0.872
Sweet corn	0.79	0.186	1.644