GNG5140

Design Project User and Product Manual

Sustainable Food Storage – The Deep Roots Food Hub

Submitted by:

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Table 1: Acronyms

Acronym	Definition
DRFH	Deep Roots Food Hub
FCU	Fan Coil Unit – simple mechanical equipment providing treated air to a space via use of a blower fan and heating/cooling coil, typically using water as heat transfer fluid (hydronic), or refrigerant via a refrigeration circuit.
RH	Relative Humidity: a ratio, expressed in percent, of the amount of atmospheric moisture present relative to the amount that would be present if the air were saturated.
WCL	Wood chip layer
-	-

Table 2: Glossary

Term	Acronym	Definition
-	-	-

1 Introduction

This User and Product Manual (UPM) provides the information necessary for agricultural professionals and food distributors to continue the investigation into sustainable snow storage cooling methods for use at the DRFH root cellar, and for prototype documentation.

Deep Roots Food Hub is a volunteer organization dedicated to helping local agricultural professionals grow, store, and distribute produce, as well as providing local communities with access to affordable, healthy, locally-produced food. [1] In 2020, the DRFH team designed and built an off-grid root cellar to safely store root crops in a sustainable and locally accessible manner. GNG5140 Team A is tasked with designing and testing a new cooling system to maintain the cool temperatures required within the storage chamber portion of the root cellar. After discussions with DRFH personnel, the team opted to investigate the feasibility of harvesting and storing snow during winter months for use in cooling the storage chamber during the summertime. Research regarding existing snow storage cooling systems was completed in the initial stages of the project, and the team then focused on delivering a design solution for the snow storage area that maximizes usability throughout the summer months, and developed a numerical model capable of approximating the melt rate of snow within the storage area. The team moved forward with these project objectives with the following assumptions:

- The DRFH team has access to the necessary land to accommodate the cooling system and snow storage area near the root cellar.
- The DRFH team has the means to harvest snow during wintertime and transfer to the storage area.
- The DRFH team is capable of purchasing and installing additional solar panel assemblies to increase power availability at the root cellar.

The initial sections of this report outline the purpose of this project, and describe the functionality of the design solution, as well as the installation, operation and maintenance requirements. Detailed reviews of the design solution and prototyping testing methodology and results are included in Section 6 of this report. The team summarizes the work completed at this time regarding design work and prototyping, and makes recommendations for future actions and areas of potential improvement/validation for this solution. The intended audience for this document includes the following parties:

- The Deep Roots Food Hub organization and agricultural professionals who use the root cellar.
- University of Ottawa – Faculty of Engineering staff and course personnel, and students who may potentially build upon this work completed or take this document and its findings into consideration when collaborating with the DRFH in future.

2 Overview

The Deep Roots Food Hub organization aims to improve food security within the local Ottawa Valley communities and increase accessibility to safe, sustainable, nutritious food. Food security is defined by The World Bank as "the ability of all people, at all times, to have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life", [2] and is a vital metric in determining the quality of life and viability of a society or human settlement. While food security in the Ottawa Valley area, and Canada at large, is rated a higher level than many regions of the world including many developing nations where food security is a significant concern, it is recorded that in 2017, 1-in-15 Ottawa households reported experiencing food insecurity, and this figure rose to 1-in-7 Ottawa households in 2022. [3]

While improving food security may be commonly thought of as ensuring a population have access to enough food daily, it is important to consider the health and nutritional aspects of food security. Dr. Bruce of the DRFH has expressed to the team he has concerns regarding the nutritional value of much of the food consumed by Ottawa Valley residents, and wishes to continue educating the public on the benefits of a balanced diet that includes locally grown, unprocessed foods that are produced and distributed in a sustainable manner in an effort to keep humans healthy, and reduce the negative impacts of food production, distribution, and consumption upon the environment. With food security and environmental sustainability in mind, the Deep Roots Food Hub organization and its volunteers built and began operating an above-ground, off-grid community root cellar in West Carleton, on NCC land near the Federal Government's Communication Research Centre's campus. [1] Per the Deep Roots Food Hub website, "This community-funded facility 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." [4] An important aspect of the DRFH root cellar operation is the climate control within the vegetable storage chamber itself. To ensure the root crops can be safely stored for a useful duration, the chamber must be maintained at a temperature of approximately 2 to 4 °C, with a relative humidity (RH) of approximately 90 to 95%. [4]

Figure 1: The Deep Roots Food Hub community root cellar.

Since the construction of the root cellar, Dr. Bruce and the Deep Roots Food Hub organization have made use of a “ice block” cooling system to cool the storage chamber during summer months, with limited success. Frozen water containers are prepared and inserted into an insulated box structure with air inlet and outlet openings, to draw storage chamber air into the “ice cube” and cool it, before using fans to direct this cooled air back into the storage chamber to keep the indoor air temperature as close to the 2-4°C threshold as possible. This system is shown below, with images and information provided by the DRFH during student-client meetings. [1]

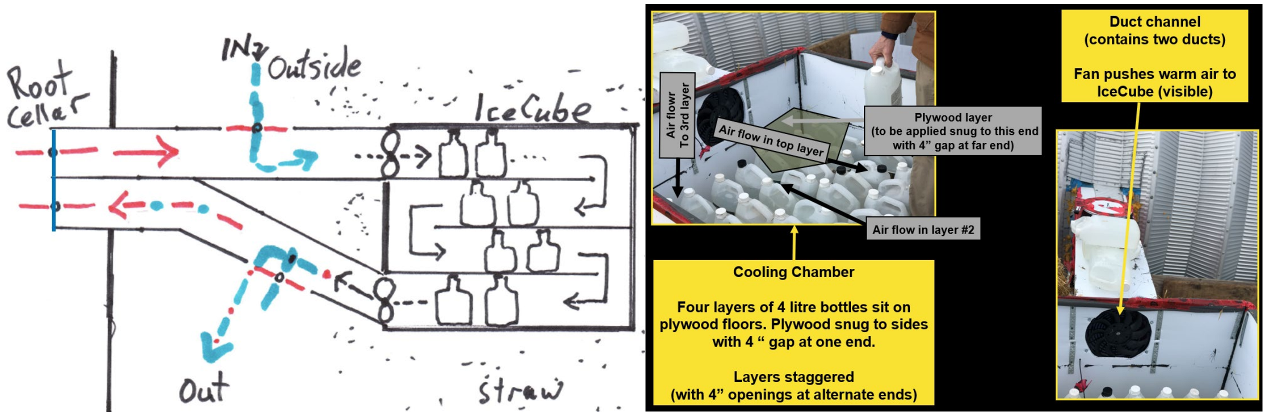


Figure 2: Existing cooling system for root cellar storage chamber.

With limited success in maintaining indoor temperatures during warm summer months, and difficulty preventing the frozen water containers from thawing rapidly and becoming much less effective in capturing thermal energy from the airstream, the DRFH team tasked Team A with designing a new cooling system for the off-grid root cellar. Dr. Bruce expressed interest in investigating and evaluating the feasibility of a snow-storage based cooling configuration in particular.

The fundamental, qualitative requirements of the new cooling system are listed below. Quantitative metrics for evaluating the design solution and prototype iterations are described in Section 6 of the report, along with a more detailed outline of the design process.

The root cellar cooling system must:

- Allow for operation off-grid (no requirement to integrate with municipal energy infrastructure).
- Provide cooling capacity to maintain storage chamber temperature for as long into the summer months as possible.
- Rely on locally harvested snow for use as cooling capacity.
- Not compromise the sustainability and environmental preservation goals of the DRFH root cellar operation.
- Allow for simple maintenance and operation to be performed by DRFH personnel and volunteers – reduce reliance on trained technicians by simplifying design.

The snow storage cooling system proposed by Team 'A' within this document makes use of locally accumulated snow to provide cooling capacity during the summer months. At the request of Dr. Bruce, co-chair of the 'Rural Healthy Living Coalition' and volunteer Board of Directors member of the Deep Roots Food Hub, the team investigated the feasibility of this snow-harvesting method to cool the root cellar storage chamber as an alternative to traditional heat pump / air conditioning unit installations that rely upon the energy grid, to explore the possibilities of improving the resiliency of systems to safely store and distribute food in areas that lack energy security. The use of snow as a natural resource instead of refrigerants reduces the root cellar's emissions and carbon footprint, and remains in-line with the DRFH organization's sustainability and environmental preservation goals.

While the initial construction costs and overall physical footprint of a snow storage cooling system is higher than a traditional HVAC/R approach, the team was directed to explore the sustainable alternatives to traditional refrigeration systems in an attempt to gain insight into the feasibility of alternative off-grid solutions that could prove viable in remote areas without energy infrastructure, or areas at risk of major power blackouts due to storm activity or poor energy security.

The design solution Team A developed is based on innovative sustainable cooling methods that have been researched and investigated by various universities and building science professionals located all across the northern hemisphere. The basic premise of the snow storage cooling system relies on harvesting a sufficient volume of snow during winter, packing this snow into an insulated cool space, and using the meltwater produced by the snow's gradual melt as a source of cooling in the summer.

The team reviewed scientific literature describing snow storage for cooling applications, including an open pond snow storage approach researched by Kjell Skogsberg of the Luleå University of Technology, which stores 60,000 m³ of snow for use in cooling the Sundsvall Hospital in Sweden [5], and a research paper outlining the preliminary design and numerical modelling of a snow storage cooling system for a poultry house in rural Quebec, completed by Victor Llonch of the École de Technologie Supérieure in Montreal [6].

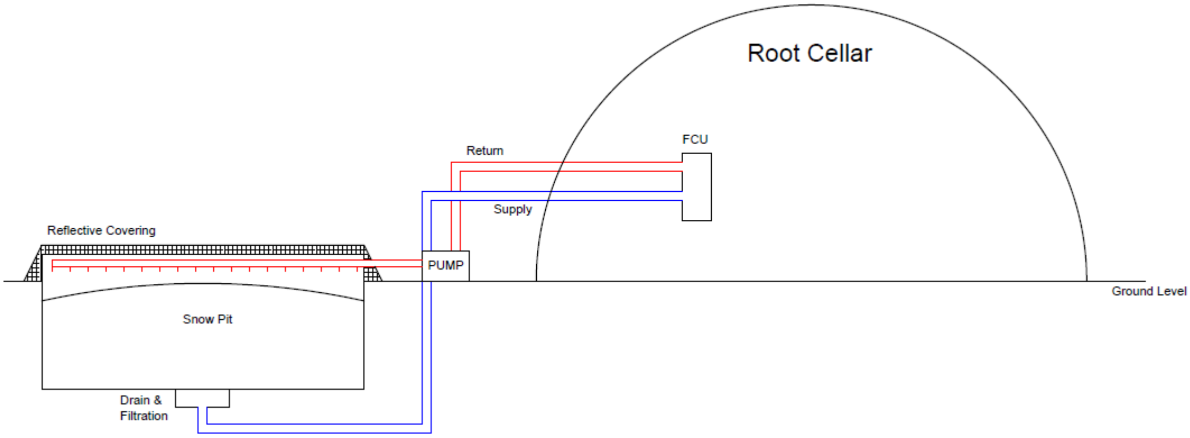


Figure 3: Schematic of design solution proposed by Team 'A'.

Snow must be harvested and packed into the pit area shown above during wintertime, where thermal insulation and solar/wind protective layers help reduce melt rate and maintain snow mass as the springtime leads to warmer ambient conditions. As the snow within the pit area begins to melt, this cool meltwater produced by snow melt (water temp. close to 0°C) is pumped above ground to a hydronic fan coil unit (FCU – free return, ducted supply) within the root cellar storage chamber to cool the space. Slightly warmed return water (shown in red) is pumped back to the snow pit area, to be distributed along the top layer of the snow pile to be cooled again and eventually pass to bottom of pit, completing the water loop. A more detailed review of the system layout, features, and function is included in Section 6 of this document.

For the purposes of prototyping and testing a design solution, the team focused on the snow storage portion of this design (shown below). The team completed multiple design iterations to arrive at a suitable solution for storing a significant volume of snow for long enough during the summertime to provide cooling to the storage chamber during storage timelines. The design iterations involved selecting and comparing pit dimensions, construction materials, wall thicknesses, and wall geometries to achieve sufficient insulation while attempting to keep installation and maintenance costs to a minimum, to provide a feasible design solution for the DRFH to continue to investigate and potentially implement.

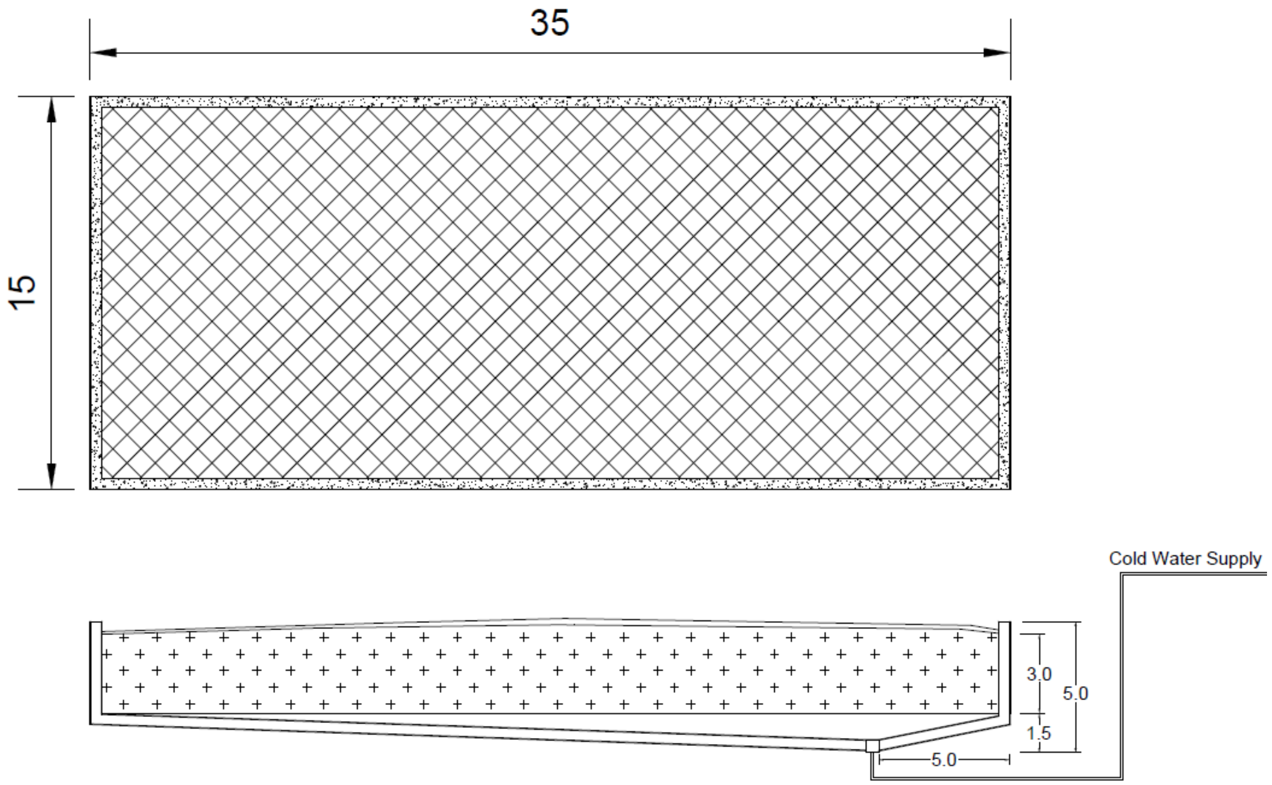


Figure 4: Schematic of snow storage area proposed by Team 'A'.

2.1 Cautions & Warnings

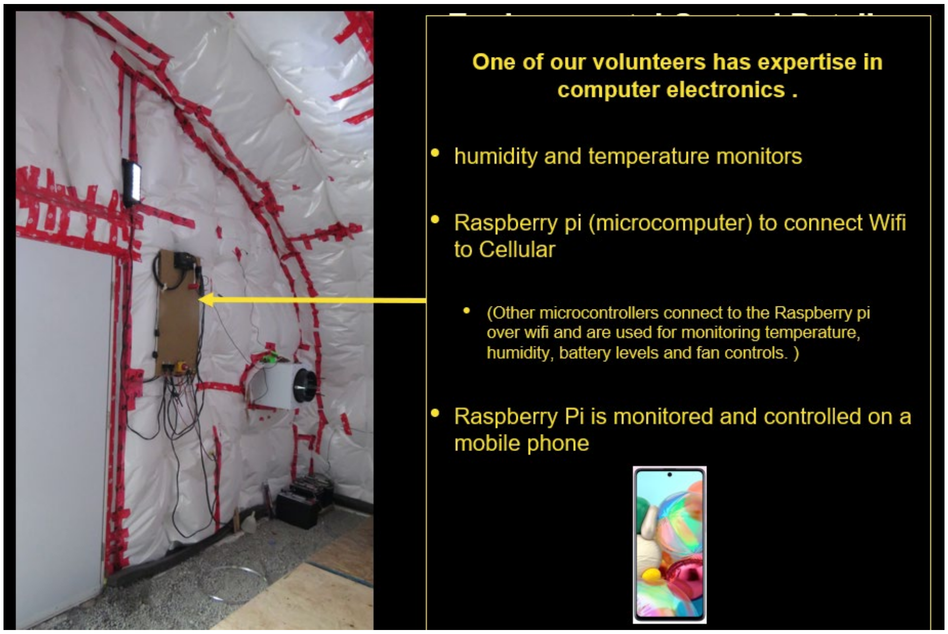
If the Deep Roots Food Hub continues to investigate the feasibility of a snow storage cooling system for use at the community root cellar facility, it is worth noting this document outlines a portion of preliminary research and investigation into the feasibility of storing snow for long enough into the summer months to prove useful, and the overall functionality of the system as described in this document is not validated by physical prototyping or advanced engineering evaluation, and there is much work to be completed before a full-scale trial system can be implemented and tested. Further work required is outlined in Section 7 of this document.

3 Getting started

3.1 Controls Set-up Considerations

The Deep Roots Food Hub community root cellar has a functional controls system in place that reads temperature and humidity conditions within the storage chamber, compare to outdoor ambient conditions, and execute automated decisions regarding the following actions to control the storage chamber:

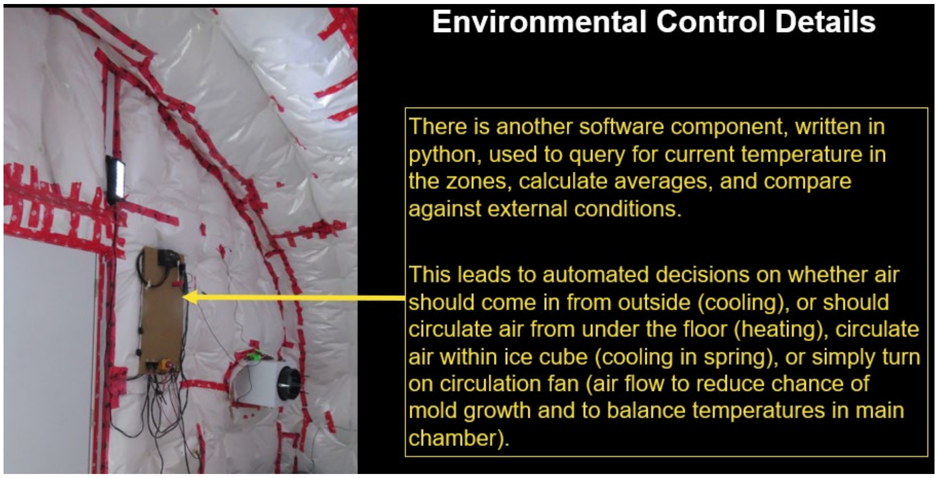
- Bring in supply air from outdoors (cooling during cool ambient conditions)
- Circulate air from under false floor (heating via geothermal radiation)
- Circulate air through cooling system ('ice cube' – cooling during spring & summer months)
- Circulate air within chamber (reduce mold growth and balance temperatures in chamber)



One of our volunteers has expertise in computer electronics .

- humidity and temperature monitors
- Raspberry pi (microcomputer) to connect Wifi to Cellular
  - (Other microcontrollers connect to the Raspberry pi over wifi and are used for monitoring temperature, humidity, battery levels and fan controls.)
- Raspberry Pi is monitored and controlled on a mobile phone

Figure 5: Controls information provided by Dr. Bruce of the DRFH



Environmental Control Details

There is another software component, written in python, used to query for current temperature in the zones, calculate averages, and compare against external conditions.

This leads to automated decisions on whether air should come in from outside (cooling), or should circulate air from under the floor (heating), circulate air within ice cube (cooling in spring), or simply turn on circulation fan (air flow to reduce chance of mold growth and to balance temperatures in main chamber).

Figure 6: Controls information provided by Dr. Bruce of the DRFH

This same controls strategy can be used for the replacement cooling system, with the modification that instead of a cooling signal calling the fans in the ‘ice cube’ assembly to power on, the cooling signal would call for the FCU fan motor, and hydronic pumps to power on instead, providing a flow of cool water for the hydronic coil in the FCU, and powering the fan to blow the cooled air into the storage chamber.

3.2 User Access Considerations

The users of this system can be divided into groups of users that interact with the community root cellar. These groups include the farmers and agricultural professionals that use the root cellar to store and retrieve their crops, and the Deep Roots Food Hub staff and volunteers who maintain the root cellar facility.

Farmers and individuals who use the community root cellar to store and retrieve crops must have access to the storage chamber, but likely should not have allowed access to the indoor fan coil unit supplying cooling to the space, or the piping/pump/snow storage equipment outside the cellar. Ideally, with the FCU placed in the storage chamber, perhaps in an elevated position, it will prevent any intentional or accidental tampering with the cooling system.

Deep Roots Food Hub volunteers and staff who are responsible for maintaining the root cellar facility must have access to the fan coil unit indoors, and the snow storage cooling system outside the cellar, in order to perform maintenance and checks of the system and determine if trained technicians must be hired to make repairs / address issues. By fencing off the snow storage pit for human and wildlife safety, instructing root cellar users to avoid the cooling equipment indoors and outdoors, the team believes the system can safely operate as needed and be accessible to the appropriate staff and technicians.

3.3 Exiting the System

The existing root cellar controls configuration allows for automated climate control within the storage chamber, with the option to track the indoor and outdoor temperature/humidity conditions in real-time, but without the requirement of user actions to cool/heat the storage chamber. If users enter the storage chamber, and begin storing / removing crops (likely increasing the indoor temperature due to increased activity and infiltration from doors opening), the controls schematic determines if power must be provided to enter cooling mode, and will act accordingly. When temperature setpoints are reached, the existing controls configuration powers down the fan motors. This same strategy will be used for the replacement cooling system, and therefore direct user actions to use / stop using the system will not be required past the initial installation and start-up. The option for controlling setpoints and other requirements will be the responsibility of DRFH personnel, as is the current situation at the root cellar.

4 Using the System

The following sub-sections provide detailed, step-by-step instructions on how to use the various functions or features of the snow storage cooling system.

4.1 Snow Storage Area

4.1.1 Snow Harvesting & Packing

The open pit schematic shown designed and built to store local snow is intended to be filled during the later months of winter, to store snow during spring and summer months.

The team intends for the DRFH and associated volunteer members and hired machinery operators to collect snow accumulation on the ground nearby the root cellar and bring this snow content to the insulated pit to be packed into a pile. At this time the team anticipates that the snow content can be moved and packed into the insulated pit, distributed approximately even along the surface area of the pit to maximize the volume of snow that can be deposited.

When the pit is filled, the snow pile must be covered with a 0.10-0.12m layer of wood chips to insulate and protect the top face of the snow pile. On top of the wood chip layer, sections of plastic lining must be placed across the surface area of the snow / wood chip pile, to reduce the effects of ambient air and rainfall on the snow pile melt rate. Atop the plastic lining, it is recommended that sections of an aluminet shade cloth or similar material be spread across the open face of the insulated pit to reduce the solar radiation transferring heat into the pit. To anchor the plastic lining and shade cloth layers, the team recommends driving u-channel stakes into the ground around the perimeter of the snow pit, at appropriate spacing intervals to attach the lining layers to these posts. Snow fencing can be spread between these perimeters posts as well to prevent humans and wildlife from entering the snow pit area.

By packing the snow into an insulated pit, the melt rate of the snow pile will be reduced as warm weather begins, to try and keep the snow volume from reducing rapidly before the end of the summertime. The produced meltwater from the snow pile melt will be redirected to the cooling unit within the storage chamber, and this process is described in the following sections.

4.1.2 Drainage System & Piping

The cold meltwater produced by snow pile melt will drain downwards to the bottom basin of the insulated pit, where a drain assembly collects the meltwater as it passes through a filter layer and enters the pipe routing that travels from underneath the snow pile, along the bottom of the pit to the perimeter and is directed upwards until reaching ground level, before being piped to the root cellar for use in the hydronic fan coil unit, which do not require user action as the controls configuration described in Section 3 will call for cooling mode to begin and water pumping / FCU powering will occur.

5 Troubleshooting & Support

5.1 Errors & Support

The main areas for potential errors/breakdowns include the piping/pump assemblies, and the fan coil unit within the storage chamber. The pipe routing and pump equipment are at risk of leaking if not properly sized and installed. It will be critical that further review of pipe and pump options is completed, and industry professionals are consulted to ensure the water loop portion of the design solution is built appropriately. By waiting until May/June to begin running the pumps, when cooling is required in the storage chamber, the potential for breakdowns and damage due to freezing is unlikely, as ground temperatures and ambient temperatures do not reach low enough to risk freezing the fluid in the hydronic loop. Suppliers of hydronic pumps typically provide warranty and technical support post-installation in the case of operating issues with their equipment, and the team deemed it reasonable at this time to assume that if a physical prototype was built and tested, with a properly installed water pump, if errors or breakdowns out of the DRFH personnel's control occurred, the pump supplier would likely be available to troubleshoot issues regarding their specific equipment. The fan coil unit used to cool the storage chamber will likely be supplied by an HVAC/R equipment manufacturer/supplier that is capable of reviewing the system requirements and providing recommendations for unit and coil sizing, and provide literature outlining the cooling capacity and hydronic coil operating parameters to ensure a suitable FCU is selected to operate safely within the overall snow storage cooling system. If issues occur with the operation of the FCU, the equipment supplier likely offers warranty and support similar to the pump suppliers, and can aid in repairing / reinstalling the FCU to avoid further issues.

5.2 Maintenance

In the instance that the DRFH moves forward with the construction and testing of a functional prototype system in place at the community root cellar, the following maintenance activities are recommended.

- Consider the pump and FCU manufacturers recommended frequency for scheduling regular maintenance of this equipment.
    - Ensure entire system is shut down before performing maintenance
- Observe the system while running and examine for any leaks / unusual noise, or vibrations.
- Mechanical inspection of the following components of the prototype:
    - Mounting points – ensure components are securely fastened
    - Inspect and repair any damaged seals/hoses/O-rings between piping joints, equipment connections, etc.
    - Inspect and clean filters for pump and FCU equipment
    - Inspect electrical connections for pump and FCU equipment and controls configurations
    - Inspect motor vents and windings for pump and FCU equipment

6 Product Documentation

This report section outlines the design process and evaluation of the final design iteration of the snow storage enclosure. Quantitative analysis and prototype testing methodology and results are described in Section 6.3.

The team finalized the snow storage space design after modelling snow melt rate, meltwater production rate, and total snow storage time-series results for varying construction materials and pit dimensions. Design solution metrics used to evaluate numerical model results are outlined in Section 6.3.

6.1 Snow Storage Area

6.1.1 Design Solution

Due to the smaller scale of Team A’s design solution (with regards to snow pile volume) and complexity in calculating heat transfer into the pit geometry, the team’s design solution takes the shape of a simple rectangle, with the snow pile sitting atop a perforated steel grate to allow meltwater to travel downwards into a sloped basin and filter/drain assembly.

The snow pile is packed into the insulated pit and rests atop a perforated steel grate to allow melt water to travel downwards. The meltwater collects at the bottom basin of the insulated pit and is filtered and directed through a drain into a piping and pump system responsible for channeling the cold melt water upwards, above ground, where the cold supply meltwater is sent into the storage chamber to travel through the cooling coil of the FCU, treating the airflow through the FCU. A second piping path returns the meltwater to the insulated pit and diffusors (not shown) distribute the return meltwater evenly across the top face of the pit, to eventually travel through the wood chips layer and the snow pile before reaching the drain basin again, completing the water loop.

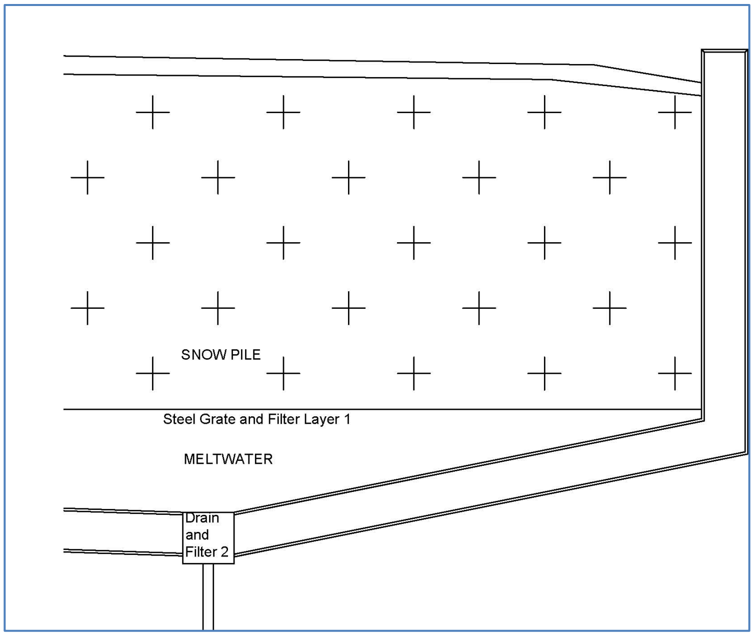


Figure 7: General schematic of basin drain of snow storage pit.

Shown below is a closer look at the dimensions of the wall thickness and wood chip layer of the insulated storage pit. The team optimized the material thicknesses used via iterations of numerical model testing in an effort to reduce the heat transfer into the pit, to increase the time duration that significant volumes of snow can be stored during Ottawa spring/summer months. Results for the final iteration of design and testing are outlined in Section 6.3 of this report.

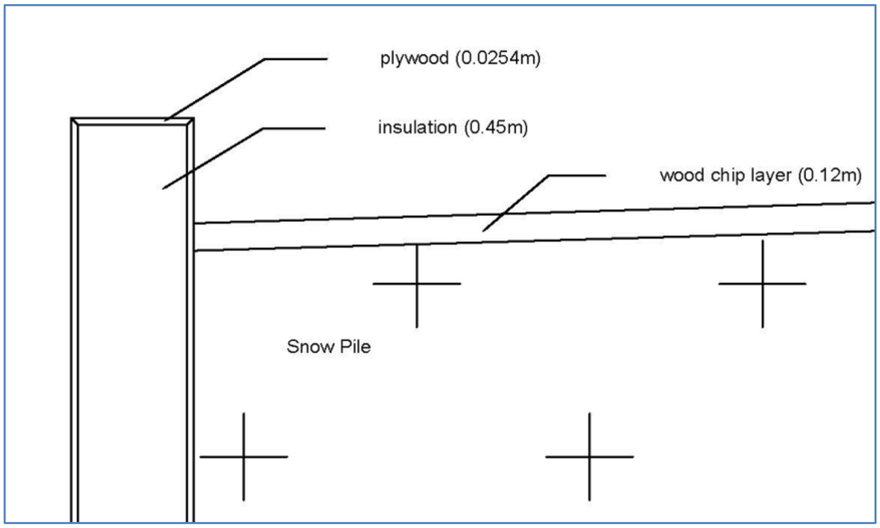


Figure 8: General schematic of wall layer materials and geometry of snow storage pit.

Figure 9: Example of wood chip layer (WCL) for use as insulating layer for snow pile.

The team completed numerical model testing of different design dimensions for various construction materials, and opted to build the insulated storage space using plywood inner and outer layers, with a layer of plastic between the earth's soil and the outer plywood, as well as a plastic layer between the snow pile and inner plywood, and fibreglass insulation to reduce heat transfer. The final design includes a 0.12m layer of wood chips covering the snow pile, to reduce the melt rate by decreasing the heat flux into the snow pile due to warm and sunny ambient conditions. The wood chips became a necessary addition to the design when the pit dimensions increased significantly to house the appropriate volume of snow, and the team realized the construction and installation of a movable lid (or series of lids) to cover and uncover the pit would not be convenient for use, or even feasible without the use of heavy machinery.

The team included a reflective covering for the top face of the pit, to reduce the rate of heat flux into the snow pile due to solar radiation. The team selected an aluminet shade cloth material to spread across the storage pit area, to address the solar radiation issues, and a plastic liner atop the shade cloth to reduce degradation of the fabric due to the elements. Fastening these materials across the top face of the storage pit, above the return water redistribution piping and the woodchip / snow pile will reduce the water introduced to the snow pile space due to rain, maintain the cleanliness of the snow pile, and reduce the heat transfer into the snow pile due to solar radiation.

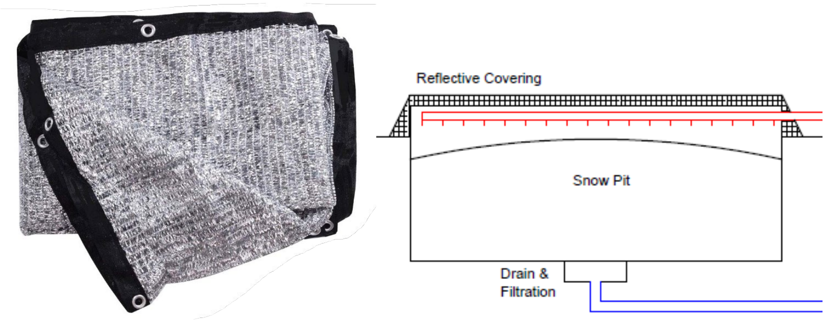


Figure 10: Example of suitable shade layer to reduce solar radiation impact on snow pile.

A final consideration for the design of the snow storage space is safety and usability. The intended users of this system are the Deep Roots Food Hub staff, volunteers, and agriculture professionals in general, and they must have access to the snow pile. However, it is unsafe to leave a large open pit in the ground, even if it is mostly filled with packed snow and woodchips. It presents a hazard to humans and animals traversing across the field, as well as a very dangerous obstacle for vehicles and farming equipment travelling across the field near the DRFH root cellar.

To address the safety issues associated with the in-ground snow storage pit, the team will implement the use of snow fencing around the perimeter. Typical applications of snow fencing for safety purposes involves driving stakes / posts into the ground around the perimeter of the space, and in this instance, running highly visible snow fencing between posts to create an easily seen barrier between the perimeter of the pit and the surrounding ground will greatly reduce the risk of an animal or human interacting with the snow storage pit. If wildlife or human activities present a more prominent threat to the pit structure, or themselves, a more permanent and sophisticated approach may be required.

Figure 11: Example image of snow fencing to enclose perimeter of snow storage area.

6.1.2 BOM (Bill of Materials)

A bill of materials for the construction and operation of the snow storage area is shown below.

Table 3: Bill of Materials I

Item	QTY
½" Plywood Grade D	825 m^2
Fibreglass Insulation	370 m^3
Plastic Liner	825 m^2
Wood chips / mulch (top layer on snow pile)	60-70 m^3
Aluminet Shade Cloth	525 m^2
Steel grating (bottom platform for snow pile)	525 m^2
Drain Basin filter	1
Snow Fencing	100 m
U-channel posts	TBD
Timber (deadmans, retaining wall assemblies)	TBD

6.1.3 Equipment list

Due to the large-scale nature of this design solution, the team has not completed a physical prototype to perform testing, and the team has not assembled a comprehensive build plan for the snow storage area. A preliminary list of the equipment needed to build a physical prototype of the snow storage space design solution proposed in this document is shown below.

- Excavator
- Hand tools (shovels, drills, hammers)
    - For use in building plywood/insulation composite walls to line pit.
- Pipefitting tools
    - For use in assembling drain and piping to create path for meltwater to be pumped above ground

6.1.4 Instructions

Due to the large-scale nature of this design solution, the team has not completed a physical prototype to perform testing, and the team has not assembled a comprehensive build plan for the snow storage area.

6.2 Hydronic Loop & Cooling Unit

6.2.1 BOM (Bill of Materials)

Further investigation into the piping, pump, and FCU requirements is needed, but the team has prepared the following general overview of the system at this time.

Table 4: Bill of Materials II

Item	**QTY**
Basin Drain Filter	1
Piping (3/4")	TBD
Hydronic Pump (system at ~ 5GPM)	2
2-2.5 ton FCU	1
Supply ducting to overhead air diffusers	TBD
Return water diffusers	TBD

6.3 Testing & Validation

6.3.1 Testing Scope

As discussed in the previous report sections, the team's prototyping and testing of proposed design solution was limited to the design and simulation-based testing of the insulated snow storage pit (outlined in orange dash below). An overview of the design and implementation of Filtration, Piping, Pump, Fan Coil Unit portions of the design solution is briefly described in Section 6.2, but testing and design iterations will not be included in the prototyping efforts for this project. Please note the below schematic is a generic description of the team's solution and geometry/dimensions are not entirely accurate to the team's intent.

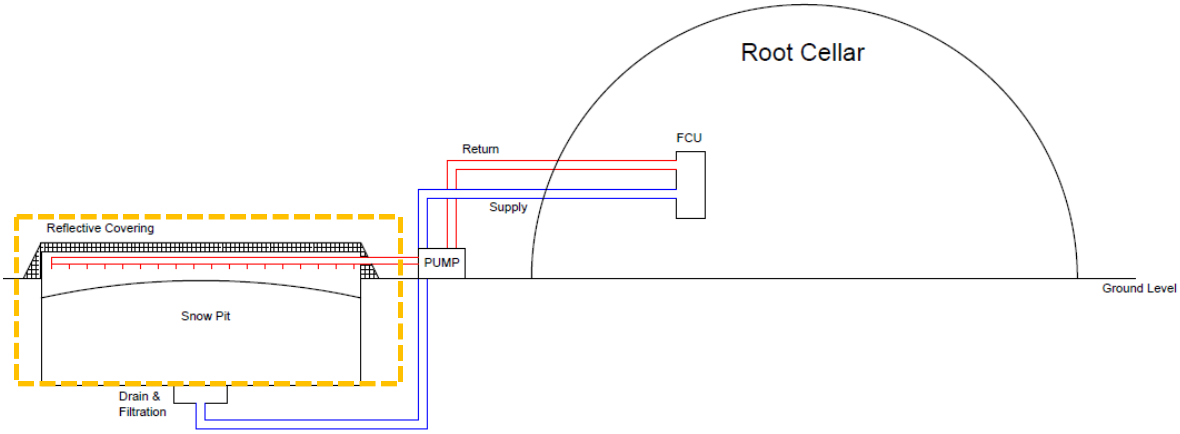


Figure 12: Schematic of design solution - snow storage area highlighted.

6.3.2 Design & Performance Metrics

The team developed updated solution metrics and design requirements after adjusting the project and prototyping scope for the purposes of GNG5140 project. The solution metrics are shown below in Table 1.

Table 5: Design Solution Metrics

Design Metric	**Goal**
Pit Dimensions (Outer)	minimized
Mass of Snow/Ice Stored	300 - 500 tonnes
Total Meltwater Produced	~ 100,000 L
Meltwater available by June 1st	~ 30,000 L
Snow Pile t_critical	150 Days

The pit dimensions shall be minimized while still meeting the other snow mass / meltwater / melt rate objectives. Minimizing the pit size (length x width dimensions, height has been kept constant for simplicity) reduces the economic costs of construction and maintenance, as well as reducing the impact of the system on the environment and minimizing impact to human activities near the root cellar.

The mass of packed snow/ice stored in the insulated pit shall be between 300 – 500 tonnes. This range of values was determined by approximating the yield of meltwater produced by given volume of packed snow, and approximating the required flow of meltwater during the months of June – September (the operating months of the cooling system, as no produce is typically stored during April – May). By approximating the heat transfer into the root cellar storage chamber and reviewing the time-series data of storage chamber temperatures during weather fluctuations, the team has determined it would be suitable for a 2 - 2.5-ton fan coil unit to be responsible for cooling the space. This cooling capacity in a hydronic FCU typically requires approximately 3.6GPM of supply flow of cool water, and reviewing the storage chamber temperature data provided by the DRFH to determine the expected operating time of the FCU to cool the space during peak warm ambient conditions, the team has estimated using basic flow calculations that storing enough snow to ensure the system is producing between 25,000L - 30,000L of meltwater by June 1st (cooling requirement begins) would allow for approximately 4-6 days of cooling before any new meltwater (produced by snow pile melt, and returned meltwater passing through wood chips and snow pile to re-enter filtration layer) would be required. The team has determined at this time that this is a suitable design goal to aim for.

The team has collaborated with the Deep Roots Food Hub personnel to approximate an operating period where cooling is required for the storage chamber. This period is approximately June 1st – September 1st. This requires snow to be safely stored from April 1st (assuming harvesting takes place over February, March, and significant snow melt does not occur until April 1st) until September 1st, which is 153 days. The team has set a goal of 150 days for snow storage before mass reaches 0 tonnes of snow, deemed the critical point that sufficient cooling capacity can no longer be provided.

6.3.3 Testing Methodology

Due to the unique application of thermal modelling for snow pile melt rate within an insulated enclosure, the team needed to develop a custom numerical modelling approach to account for environmental factors driving snow melt during warm ambient conditions typical of an Ottawa area summer. Preliminary modelling using Autodesk Revit and other commercially available software applications did not yield useful results due to the long-term time duration of a required simulation, and the highly unique structure function and thermal energy transfer environment being investigated in this document. The team instead developed a MATLAB model responsible for calculating the heat transfer into the insulated snow pit, with the final iteration of this testing approach improving upon the previous model iterations by adding the effects of solar radiation upon the top face of the snow pile. The MATLAB code now imports Ottawa climate data for soil temperatures, ambient temperatures, and solar radiation at an hourly rate. In order to capture the heat transfer rates over time in this dynamic environment, the team needed to develop a loop within the MATLAB code to iterate through these calculations at an hourly rate, using hourly climate data for the Ottawa region which was available online. The team opted to use climate data for Ottawa from April 1st – September 1st, 2022, the previous summer, retrieved from a website combining data courtesy of Environment and Climate Change Canada.

The team attempted to improve the accuracy of the MATLAB numerical model in the final stages of the GNG5140 project by factoring in the impact of redistributing warm return water from the FCU, spread across the top face of the snow pile, to eventually permeate the wood chip layer and interact with the snow pile, rejoining the snow system until melting rates bring this cooled water downwards through the snow pile to the drain basin again. This slightly warmed water (10°C - 15°C) being added to the snow pile system will likely cause the entire pile to melt at a higher rate, and the team implemented a function to increase the melt rate due to heat flux into the space by 25%, which was an estimate of the overall effect of introducing warm water to the snow, after time reaches June 1st (when cooling operations will commence for the summer).

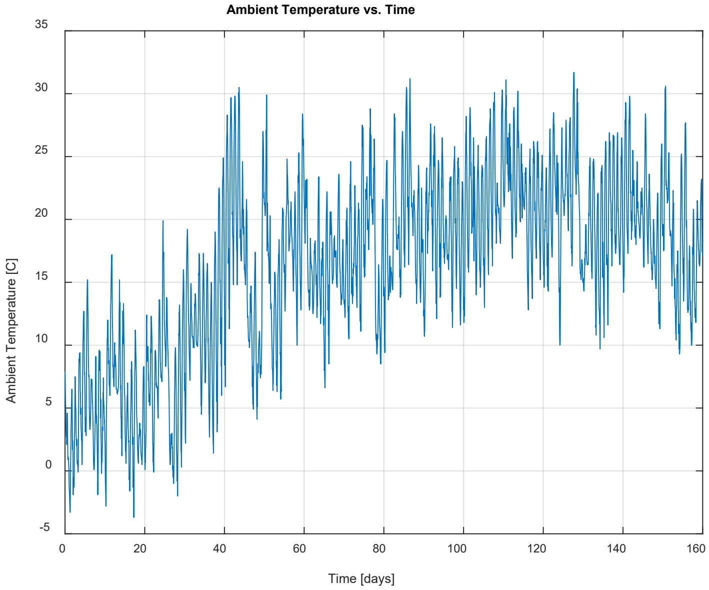


Figure 13: Ambient Temperature data (Ottawa - Summer 2022).

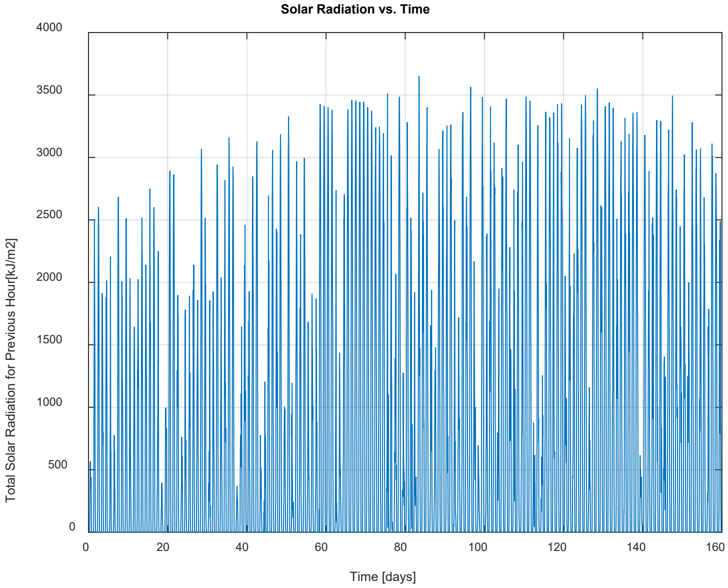


Figure 14: Ambient Solar Radiation data (Ottawa - Summer 2022).

The results of final prototype testing are included in Section 6.4 of this report, and the MATLAB code is included in Appendix II.

The following paragraphs describe the function of each portion of code within the MATLAB numerical model developed by Team ‘A’.

Pit & Snow Pile Parameters:

This section defines the thickness of each construction material used, the inner and outer dimensions of the snow storage pit, and the geometric and thermal parameters of the snow pile itself.

```
% Pit Parameters
t_ply = 0.0254;             % Thickness of plywood (m)
t_ins = 0.45;               % Thickness of insulation (m)
t_wood = 0.12;

Lout = 35;                  % Outer Length of Pit (m)
Wout = 15;                  % Outer Width of Pit (m)
Hout = 4.5;                 % Outer Height of Pit (m)

L = Lout-4*t_ply-2*t_ins;   % Inner Length of Pit (m)
W = Wout-4*t_ply-2*t_ins;   % Inner Width of Pit (m)
H = Hout - 1 - 4*t_ply-2*t_ins;  % Inner Height of Pit (m)

% Snow Pile parameters
h0 = 3.0;                   % Initial height of snow pile (m)
SA = L*W;                   % Surface area of snow pile (m^2)
A_G = (2*W*H)+(2*L*H)+(L*W); % Surface Area of snow pile against wall
rho = 250;                  % Density of snow (kg/m^3)
C = 2090;                   % Specific heat of snow (J/kg.C)
k = 1.8;                    % Thermal conductivity of packed snow (W/m.C)

tonnes_snow0 = L*W*h0*rho/1000;
```

Ambient Constants and Time Parameters:

This section of code defines the thermal conductivity constants for ambient air and air inside the snow storage enclosure, and defines time range and time step values for the thermal equation loop used to calculate melt rate iteratively over simulation time period.

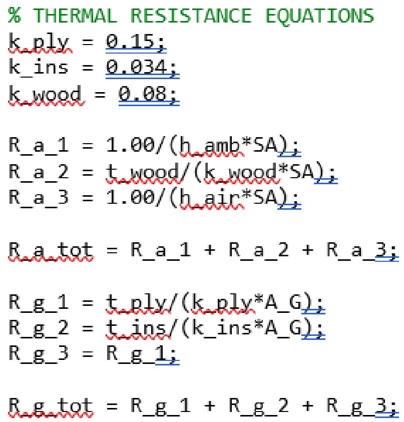
```
% Ambient Parameters
h_air = 2.0;                % Convection constant for cool air inside pit
h_amb = 5.5;                % Convection constant for warm ambient air

% Time parameters
t0 = 0;                     % Initial time (s)
tf = 160*24*3600;           % Final time (s)
dt = 3600;                  % Time step (s)

% Calculate snow pile mass and initial temperature
m = rho * SA * h0;
T0 = 0;                     % Initial temperature of snow pile (C)
```

Thermal Resistance Equations

This section defines the thermal conductivity constants for each construction material used, and calculates the approximate thermal resistance of each layer of construction material (wood layers, insulation layer, protective layers) for surfaces in contact with the earth (R_g) and ambient air (R_a).



```
% THERMAL RESISTANCE EQUATIONS
k_ply = 0.15;
k_ins = 0.034;
k_wood = 0.08;

R_a_1 = 1.00/(h_amb*SA);
R_a_2 = t_wood/(k_wood*SA);
R_a_3 = 1.00/(h_air*SA);

R_a_tot = R_a_1 + R_a_2 + R_a_3;

R_g_1 = t_ply/(k_ply*A_G);
R_g_2 = t_ins/(k_ins*A_G);
R_g_3 = R_g_1;

R_g_tot = R_g_1 + R_g_2 + R_g_3;
```

Initializing Arrays and Main Calculation Loop

This section of code defines the time array used to simulate through a period of approximately 5 months, at an hourly rate to allow the main calculation loop to iteratively calculate melt rate and snow pile characteristics each hour, using the previous hour's results as a starting point. Heat flux into the snow pile area is calculated using the general equation:

Q [heat flux] = Temperature Gradient / Thermal Resistance

Included in the main calculation loop are calculated values for heat transfer into snow pile due to:

1. Radiation from the earth, through the walls and bottom surface of the pit.
2. Radiation from the sun, through the protective liners/wood chip layer on top of snow pile.
3. Convection from the upper layers of the snow pit interacting with the warm ambient air.

The total heat flux into the snow pile is calculated as the sum of the above heat transfer methods, and this Qtotal value is used, along with the thermal coefficients for snow pile, to determine the thermal gradient between the surface of the snow pile receiving warm energy from the surroundings, and the center of the snow pile. This gradient is evaluated and if resulting temperatures are above melting (0°C), the change in snow mass and snow pile height for that hour due to heat transfer into the pit is calculated using the surface area of the snow pile and the density of packed snow. Meltwater production rate is calculated using the change in mass of snow and the relationship between packed snow and resulting water content.

```
% Initialize arrays
t = t0:dt:tf;
h = zeros(1,length(t));
T = zeros(1,length(t));
Ts = Tsoil(:,1);
Tamb = Tambient(:,1);
Solar = SolarRad(:,1);

% Set initial values
h(1) = h0;
T(1) = T0;

Q_air(1) =  (7.9-T0)/R_a_tot;
Q_ground(1) = (0.1-T0)/R_g_tot;
Qsolar(1) = 0;
Qtot(1) = Q_air(1) + Q_ground(1);
tonnes_snow(1) = tonnes_snow0;


% Calculate melt rate and snow pile mass/height over time
for i = 2:length(t)

    % Calculate heat flux due to Earth
    Q_air = (Tambient(i)-T(i))/R_a_tot;
    Q_ground = 0.2*(Ts(i)-T(i))/R_g_tot;
    Qsolar = SolarRad(i)*0.8*0.7*SA/1000;
    Qtot = Q_air + Qsolar + Q_ground;

    % Calculate temperature gradient
    dTdx = 0.005*(Qtot/k) / (rho*C);

    % Calculate change in height and mass due to melting
    if t(i)<1440
        cool = 1;
    else
        cool = 1.25;
    end

    dh = (- 0.005 * SA * dt * dTdx * cool)/ rho;
    dm = - dh * SA * rho;

    % Update height, mass, and temperature

    h(i) = (h(i-1) + dh); %2881 outputs
    if h(i) < 0
        h(i) = 0;
    end

    m(i) = m(i-1) + dm;
    T(i) = T(i-1) + 0.25*Qtot*t(i)/(m(i)*C);

    tonnes_snow(i) =  L*W*h(i)*rho/1000;

    meltwater(i) = 1000/4 * (tonnes_snow0-tonnes_snow(i));
    if meltwater(i) < 0
        meltwater(i) = 0;
    end

end
```

6.3.4 Test Results & Interpretations

The final design iteration for the insulated snow storage solution was evaluated using the above-mentioned MATLAB numerical model to determine the melt rate, and volume of snow remaining over time, for the snow pile during the months of April – September. The goal of the team is to develop a design solution that allows for a gradual melt rate to produce sufficient meltwater during the summer months, while maintaining snow volume for as long as possible to ensure cooling capacity can be provided to the root cellar for the majority or all of the warm season, to maintain storage chamber temperatures and preserve the shelf life of the produce stored there. The team objectives are summarized below, with some goals having been re-adjusted during the semester to account for changes to project scope after discussions with Dr. Bruce of the Deep Roots Food Hub and Professor Bruce of the University of Ottawa.

Table 6: Design Metrics and Test Results

Design Metric	**Goal**	**Result**	**Result**
Pit Dimensions (Outer)	minimized	**35 m x 15 m**	n/a
Mass of Snow/Ice Stored	300 ~ 500 tonnes	**356.8 tonnes**	pass
Total Meltwater Produced	85,000 ~ 100,000 L	**89,235 L**	pass
Meltwater available by June 1st	25,000 ~ 30,000 L	**25,081.6 L**	pass
Snow Pile t_critical	~150 Days	**145 days**	TBD

Shown below are figures with time-series simulation results plotted to visualize snow storage performance during summer months.

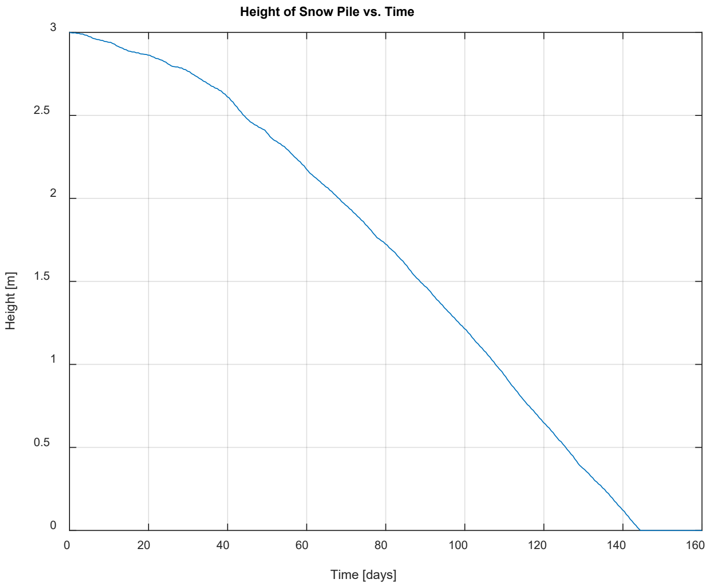


Figure 15: Time-series data of Snow Pile Height during simulation.

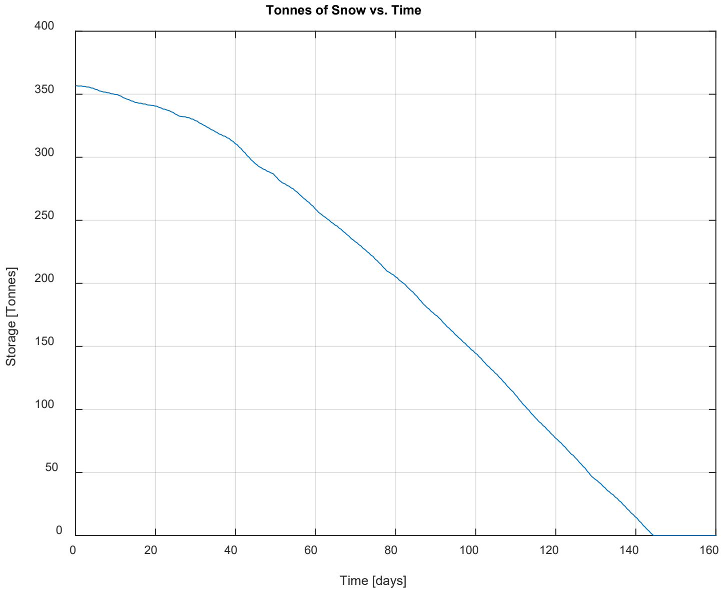


Figure 16:Time-series data of Snow Pile Mass during simulation.

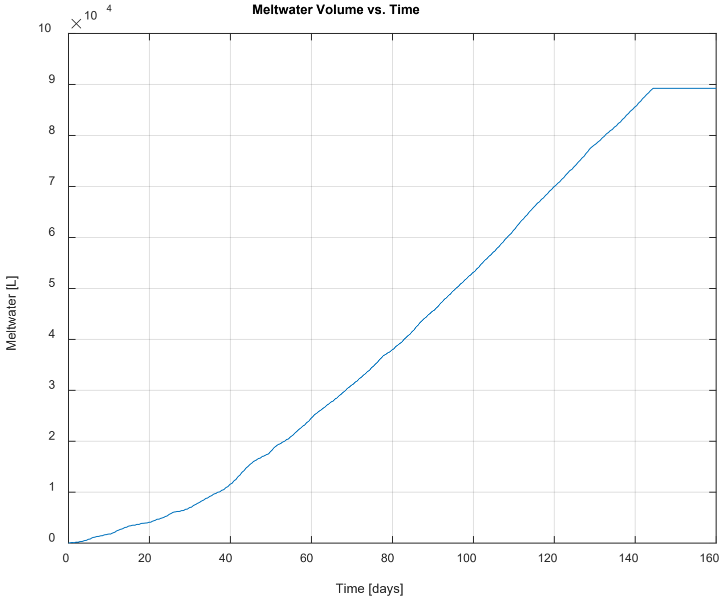


Figure 17: Time-series data of Meltwater Production during simulation.

As shown in the above plots providing visual representations of the resulting snow pile mass, height, and meltwater produced for the simulation period, it is difficult to control snow melting on a large-scale during summer months. As ambient and soil temperatures begin to increase significantly around early May (~40 days into simulation), the snow pile melt rate increases. At approximately June 1st (60 days into simulation), cooling demand begins for the storage chamber, meaning the redistributed warm water returning from the FCU will be spread atop the snow pile / wood chip layer, and this warm water causes melt rates to increase again and remain higher until total snow pile melt occurs around day 145, as seen in Figure 17. The trends visible in the above plots indicate the main driving factor of snow pile rate is the warm water redistributed to the snow pile, and the heat transferring into the insulated space via radiation and convection, due to the warm ambient air above ground. This analysis allowed the team to focus design changes on the "problem areas" of the solution, namely this top face interacting with the elements, which inspired the team decisions to increase the wood chip layer thickness, and introduce additional material layers above the water piping to reduce solar radiation and heat transfer.

The meltwater production rate and total meltwater values correspond to the team's design requirements, indicating the volume of snow may be sufficient with respect to meltwater production, and therefore increasing the snow volume stored to achieve longer storage duration would likely not negatively affect the meltwater aspects of the design solution, merely increasing the availability of meltwater which will likely prove beneficial in allowing the hydronic cooling equipment to function for longer periods.

7 Conclusions & Recommendations for Future Work

Team ‘A’ was faced with a unique design problem and a large portion of this project involved continuous research into the applications of snow storage for large-scale cooling purposes, and much effort went into developing a method of evaluating a given snow storage solution and producing measurable results. While the results of this project are less tangible than other projects this semester, and not as immediately available for implementation, the team has proposed a theoretical solution for snow storage and attempted to build a numerical model to predict the performance of said solution with as much accuracy and real-world usability as possible at this time. An outline of lessons learned, and possible missteps made throughout the project timeline are shown below.

- Prototype testing / evaluation can be a challenging process. It likely would have been beneficial to focus prototyping efforts on an alternative portion of the design solution that could be more easily modelled using software / more easily physically modelled for prototype iterations.

- Likely misstep was a lack of continued communication with the Deep Roots Food Hub past the beginning stages of design work. Further direction from users may have been available regarding the team’s solution if team members hade made commitments to reaching out at planned intervals throughout the project.

The most productive avenues for future work exist within two spheres of investigation. Firstly, further work is required to design and validate a working solution for the piping, pump, and fan coil unit portions of the design solution. While the team focussed on the snow storage area to allow for completion of a prototype design and quantitative analysis of performance through simulation, the construction of a snow storage area will be useless without the properly designed and validated ‘other half’ of the cooling system. While some of the design work may be possible through engineering review and relatively simple calculations regarding pipe size, pump size, fan coil unit selection, and overall power requirements for the system, the team is unable to make definitive recommendations for these aspects of the solution without further collaboration with the Deep Roots Food Hub, and collaboration with experienced plumbing and HVAC/R industry professionals to ensure a full-scale system would function as intended. It is quite likely that through further collaboration the team would make tweaks to the design solution to accommodate for unseen circumstances, and a large allocation of time and resources would be required before a working prototype could be physically built and tested.

Regarding the snow storage area itself, further work is required to improve upon the design solution. It would be beneficial to improve the numerical model responsible for evaluating performance to ensure prototyping results closely match real-world system performance. It is possible, and even likely, that through more sophisticated modelling and review of the snow storage area, pit dimensions and construction materials could be further optimized to maximize snow storage duration and reduce construction and operation costs when implementing a physical prototype in place. The team, with more time, would focus on the feasibility of using concrete to form the boundary surfaces of the pit, as this would allow for much simpler construction. The team initially found the construction costs due to concrete material costs to be higher than deemed appropriate, so the team decided to design and test a plywood-insulation structure to determine if performance and costs could be optimized with this approach. The team believes that, if given more time the design solution could be improved with the use of concrete, offsetting the higher material costs with the reduced labor and maintenance of installing plywood panels and insulation for such a large space. Thermal conductivity through the concrete layer would have to be modelled and evaluated, but the team deems it likely that a thickness value that minimizes cost and performs as well or better than the current design solution is available.

8 Bibliography

[1] Dr. Barry Bruce, *Off-Grid Root Cellar,* ON: Deep Roots Food Hub, 2020.

[2] The World Bank Group, "What is Food Security?," The World Bank Group - IBRD, [Online]. Available: https://www.worldbank.org/en/topic/agriculture/brief/food-security-update/what-is-food-security#:~:text=Based%20on%20the%201996%20World,an%20active%20and%20healthy%20life. [Accessed March 2023].

[3] M. Carr, "Carr: City of Ottawa has a special role in ending food insecurity," Ottawa Citizen, 10 January 2023. [Online]. Available: https://ottawacitizen.com/opinion/carr-city-of-ottawa-has-a-special-role-in-ending-food-insecurity#:~:text=Food%20insecurity%20in%20Ottawa%20has,rose%20to%20one%20in%207. [Accessed April 2023].

[4] Deep Roots Food Hub, "Deep Roots' Root Cellar," Deep Roots Food Hub, 2020. [Online]. Available: https://www.deeprootsfoodhub.ca/community-root-cellar.html. [Accessed April 2023].

[5] K. Skogsberg, "Seasonal Snow Storage for Cooling Applications," Luleå University of Technology, Luleå, 2001.

[6] V. Llonch, "Preliminary Design of a Snow Storage Cooling System for a Poultry House Placed in Quebec," ECOLE DE TECHNOLOGIE SUPÉRIEURE - UNIVERSITÉ DU QUÉBEC, Montreal, 2019.

APPENDICES

9 APPENDIX I: Design Files

MakeRepo Project: LINK

(https://makerepo.com/Fadial88/1645.snow-storage-group-)

Table 7. Referenced Documents

Document Name	Document Location and/or URL	Issuance Date
CADD Plans	MakeRepo LINK	April 2023
MATLAB File	MakeRepo LINK	April 2023
Weather Data	MakeRepo LINK	April 2023

10 APPENDIX II: MATLAB Code for Snow Pile Modelling

```
% Pit Parameters
t_ply = 0.0254;              % Thickness of plywood (m)
t_ins = 0.45;                % Thickness of insulation (m)
t_wood = 0.12;

Lout = 35;                   % Outer Length of Pit (m)
Wout = 15;                   % Outer Width of Pit (m)
Hout = 4.5;                  % Outer Height of Pit (m)

L = Lout-4*t_ply-2*t_ins;    % Inner Length of Pit (m)
W = Wout-4*t_ply-2*t_ins;    % Inner Width of Pit (m)
H = Hout - 1 - 4*t_ply-2*t_ins;  % Inner Height of Pit (m)

% Snow Pile parameters
h0 = 3.0;                    % Initial height of snow pile (m)
SA = L*W;                    % Surface area of snow pile (m^2)
A_G = (2*W*H)+(2*L*H)+(L*W); % Surface Area of snow pile against wall
rho = 250;                   % Density of snow (kg/m^3)
C = 2090;                    % Specific heat of snow (J/kg.C)
k = 1.8;                     % Thermal conductivity of packed snow (W/m.C)

tonnes_snow0 = L*W*h0*rho/1000;

% Ambient Parameters
h_air = 2.0;                 % Convection constant for cool air inside pit
h_amb = 5.5;                 % Convection constant for warm ambient air

% Time parameters
t0 = 0;                      % Initial time (s)
tf = 160*24*3600;            % Final time (s)
dt = 3600;                   % Time step (s)

% Calculate snow pile mass and initial temperature
m = rho * SA * h0;
T0 = 0;                      % Initial temperature of snow pile (C)

% THERMAL RESISTANCE EQUATIONS
k_ply = 0.15;
k_ins = 0.034;
k_wood = 0.08;

R_a_1 = 1.00/(h_amb*SA);
R_a_2 = t_wood/(k_wood*SA);
R_a_3 = 1.00/(h_air*SA);

R_a_tot = R_a_1 + R_a_2 + R_a_3;

R_g_1 = t_ply/(k_ply*A_G);
```

```
R_g_2 = t_ins/(k_ins*A_G);
R_g_3 = R_g_1;

R_g_tot = R_g_1 + R_g_2 + R_g_3;

% Initialize arrays
t = t0:dt:tf;
h = zeros(1,length(t));
T = zeros(1,length(t));
Ts = Tsoil(:,1);
Tamb = Tambient(:,1);
Solar = SolarRad(:,1);

% Set initial values
h(1) = h0;
T(1) = T0;

Q_air(1) =  (7.9-T0)/R_a_tot;
Q_ground(1) = (0.1-T0)/R_g_tot;
Qsolar(1) = 0;
Qtot(1) = Q_air(1) + Q_ground(1);
tonnes_snow(1) = tonnes_snow0;

% Calculate melt rate and snow pile mass/height over time
for i = 2:length(t)

    % Calculate heat flux due to Earth
    Q_air = (Tambient(i)-T(i))/R_a_tot;
    Q_ground = 0.2*(Ts(i)-T(i))/R_g_tot;
    Qsolar = SolarRad(i)*0.8*0.7*SA/1000;
    Qtot = Q_air + Qsolar + Q_ground;

    % Calculate temperature gradient
    dTdx = 0.005*(Qtot/k) / (rho*C);

    % Calculate change in height and mass due to melting
    if t(i)<1440
        cool = 1;
    else
        cool = 1.25;
    end

    dh = (- 0.005 * SA * dt * dTdx * cool)/ rho;
    dm = - dh * SA * rho;

    % Update height, mass, and temperature

    h(i) = (h(i-1) + dh); %2881 outputs
    if h(i) < 0
        h(i) = 0;
    end
```

```
    m(i) = m(i-1) + dm;
    T(i) = T(i-1) + 0.25*Qtot*t(i)/(m(i)*C);

    tonnes_snow(i) =  L*W*h(i)*rho/1000;

    meltwater(i) = 1000/4 * (tonnes_snow0-tonnes_snow(i));
    if meltwater(i) < 0
        meltwater(i) = 0;
    end

end

% Plot results
figure;
plot(t/(3600*24),h);
title('Height of Snow Pile vs. Time');
xlabel('Time [days]');
ylabel('Height [m]');
grid on;

figure;
plot(t/(3600*24),tonnes_snow);
title('Tonnes of Snow vs. Time');
xlabel('Time [days]');
ylabel('Storage [Tonnes]');
grid on;


figure;
plot(t/(3600*24),Tamb);
title('Ambient Temperature vs. Time');
xlabel('Time [days]');
ylabel('Ambient Temperature [C]');
grid on;

figure;
plot(t/(3600*24),SolarRad);
title('Solar Radiation vs. Time');
xlabel('Time [days]');
ylabel('Total Solar Radiation for Previous Hour[kJ/m2]');
grid on;

figure;
plot(t/(3600*24),meltwater);
ylim([0 100000])
title('Meltwater Volume vs. Time');
xlabel('Time [days]');
ylabel('Meltwater [L]');
grid on;
```