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A Modular Cryogenic Storage and Transportation Device

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Abstract

The project goal was to design a storage volume capable of maintaining extremely low temperatures for extended periods of time. The motivation was to support the advancement of space exploration by providing a platform with which to study the effects of extremely cold/cryogenic temperatures on electrical components. However, the Covid-19 pandemic exposed a critical need for extreme cold storage to facilitate the global vaccination effort, with specific vaccines needing to be stored at temperatures as low as -80℃ prior to injection. These two scenarios emphasized the need for a scalable storage transport device designed for testing of components needing extremely low temperatures. The project resulted in the development and design of a modular vessel capable of utilizing various cooling mediums ranging from liquid nitrogen to dry ice by switching out one of the modular components. This allowed for increased flexibility and versatility of the device to be used in various relevant applications while maintaining a standard level of control through sensors and other control components.

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1.0 Introduction

The onset of the Covid-19 pandemic in late 2019 set the world down a path unlike any other since the Spanish Influenza in the early 1900s. Covid spread quickly and uncontrollably, and only months later when vaccines became accessible did improvements come. However, underdeveloped countries without vaccine access are still battling this virus.

With multiple vaccines currently in the market, the issue of worldwide transportation is now moving to the forefront of the problem. There is a prominent lack of viable means of mass distribution of a Covid-19 vaccine in countries with poor infrastructure due to the vaccine's temperature constraints (Healthcare Global, 2021): storage at -70°C +/- 10°C (CDC, 2020). The low temperature requires a more substantial cooling system than the standard refrigeration systems that are utilized regularly for vaccine and organ transport. Achieving temperatures this low for a sustained period falls into the definition of cryogenic storage or more specifically, cryo-preservation (Pegg, 2007).

To address this need, the team designed a scalable and portable cryogenic storage unit. To guide the design process, the team conducted research on the current state of the cryogenic storage industry and applicable materials for these devices. Additionally, the team identified various elements necessary for the design to achieve core functionality as well as a handful of non-essential components that would be beneficial beyond critical device functionality.

2.0 Background

2.1 Fundamentals of Cryogenics

Cryogenics, or the production of and behavior of materials at very low temperatures, has proven to be a fruitful technological advancement. A material's chemical properties alter at lower temperatures as the molecules of the material slow down, allowing materials to act in completely different ways (Gaslab, 2019). In practice, it is generally accepted that cryogenic temperatures include any temperature below -150°C (NIST, 2002). This technology has progressed markedly since its conception in the late 1800s; what began with the liquefaction of gas has transformed into a billion-dollar industry (Foerg, 2002). Today, cryogenics covers a variety of uses including organ storage, in vitro fertilization, food preservation, rocket design, and many others. Cryotherapy, another form of cryogenic technology, has surged in popularity over the last several years due to its benefits in managing pain and boosting energy levels (Foerg, 2002). Cryogenics has advanced our modern lifestyle in ways we rarely consider.

Figure 1: Cryotherapy Chamber (Rocky Mountain Cryotherapy, 2018)

2.2 Manufacturers and Applications

Many companies recognize the benefits of cryogenics and work toward its progression. The Cryonics Institute, for example, focuses on “bringing state of the art cryogenic suspensions to the public” (Cryonics Institute, 2021). Their wish is someday to use cryonics to bring preserved people back to life. The Coriell Institute has pioneered biobanks used for storing and preserving cells and materials (Coriell, 2021). ThermoFisher is another popular company working on state of the art cryogenic preservation systems. Even NASA uses cryogenics to maintain low sensor temperatures in order to receive signals from outer space (NASA, 2020). Most cryogenic storage utilizes a true heat exchanger; in other words, it is not self-contained and requires constant monitoring. These factors need to be addressed for a truly portable design to be developed.

Cryogenic storage has been especially relevant as the need for a vaccine for the COVID-19 pandemic arose in 2020. Unlike other vaccines, the coronavirus vaccine functions best when stored at very low temperatures (Mecotec, 2020). The temperature requirement of the vaccine does not necessarily fall under the cryogenic definition, but in order for the system to be portable, extended duration cooling is difficult without a cryogenic cooling medium.

The coronavirus pandemic has affected nearly everyone, so the news of cold temperature vaccine storage inspired the team. Vaccine production and its need for state of the art cryogenic storage spearheaded our project.

2.3 Modern Cryogenics

Today’s competitive industries demand the latest and greatest in technology. Modern cryogenics have been on the rise to meet this need in sectors such as aerospace, tech, and even medicine (NIST, 2002). These advancements have come to include alarm systems, storage devices, and quality insulation to name a few.

2.3.1 Temperature

The usability of a device is dependent on its ability to maintain a consistent temperature in the storage volume. Regardless of the specific temperature, there must be a temperature sensor to continuously monitor the internal temperature and ensure that the requirement is met. Whether the requirement is -80°C for a vaccine or -150°C for cryogenic storage, a specialized sensor is necessary. Common thermometers cannot withstand the extreme temperatures that are utilized in this design, so a cryogenic grade thermocouple is needed (Omega Engineering Inc., 2018). Thermocouples, however, require a way to read the data they provide. This could be done in a few ways. First, a digital readout compatible with the thermocouple could be used. This has the benefit of being independent of the rest of the system. An alternative is a microcontroller such as an arduino or raspberry pi. The benefit of the microcontroller is the ability to interface the temperature readings with other processes in the system.

2.3.2 Cryogens

Arguably the most important aspect of the design is the cryogen itself. Given the storage requirement of -80°C (*203K*) (CDC, 2020), the cryogen must be held at that temperature or lower to achieve an equally cold temperature within the storage volume. So, the temperature of the cryogen must be at most -80°C. The second criteria to consider is the contact area within the unit. Optimal heat transfer from the storage volume to the cryogen requires the maximum amount of surface contact that is possible to achieve. Greater surface area is desirable because it improves the amount of conductive and convective heat transfer from the storage volume to the cryogen. Additionally, the use of liquid improves the amount of cryogen that can fit in the space, particularly if the space contains curved surfaces. By nature, a liquid cryogen would be optimal for these reasons. This means any solid cryogen such as dry ice is less desirable due to the inability to easily conform the shape to achieve greater contact.

Liquid cryogens are readily used in a variety of industries (NIST, 2002). Common Cryogens include liquid argon, oxygen, methane, and nitrogen (Princeton University, n.d.). Liquid Methane has one obvious limitation: it is flammable. The use of electrical sensors to operate the device means any flammable elements should be avoided. Liquid Oxygen has a slightly higher boiling point than Methane at about -183°C (*90K*) (Princeton), but it is not flammable. Instead, it is classified as an oxidizer. In order to accommodate this property, the materials of the containment shells in the device would need to be oxidation resistant such as stainless steel. Liquid Argon is an inert substance with a boiling point of -186°C (*87K*) (Princeton). The non-reactive nature of the substance is certainly useful, but the price of Argon is substantially higher than other similar substances (Pennsylvania State, n.d.). The high cost would limit the ability to procure large supplies. The last of the liquid cryogens is Liquid Nitrogen. This substance has a boiling point of -196°C (*77K*) (Princeton), lower than both the Argon and Oxygen. Like Argon, Nitrogen is also an inert substance by nature, but costs significantly less and is commonly available. The non-reactive nature and low cost are benefits that make it the best choice of liquid cryogen for our application. There is one significant challenge associated with Nitrogen, however. Figure 2 below shows the phase diagram for pure Nitrogen. The important element of this diagram is the location of the triple point. The critical point occurs at a temperature of -150°C (123K). Above this temperature, nitrogen occurs only as a gas.

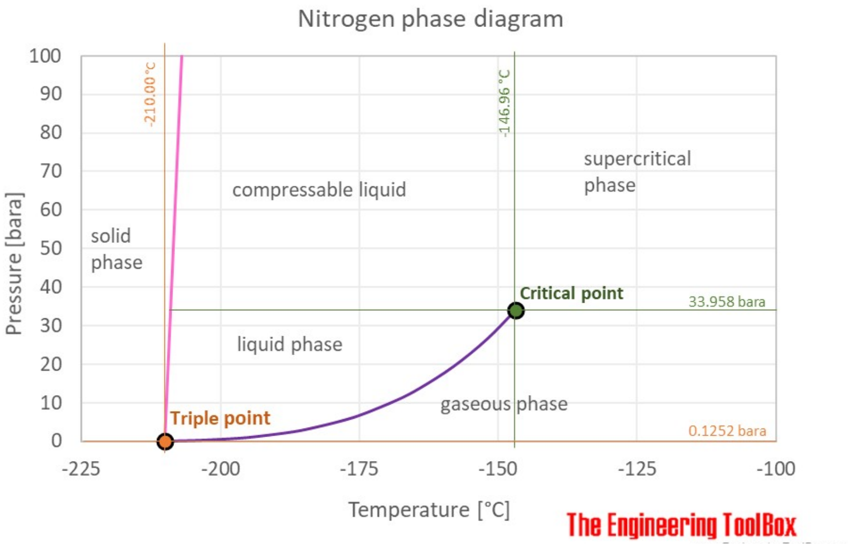


Figure 2:Pure Nitrogen Phase Diagram (Engineering toolbox, 2008)

The boiling point of the cryogenic fluid is related to the pressure it is held at, so the specific pressure range of the liquid nitrogen can be determined by the required steady state temperature of the system. That is to say that liquid nitrogen is added to the unit initially, at which point the air temperature of the internal storage volume equilibrates with the nitrogen. If the system is left alone, heat will penetrate the insulative layer and begin to heat the nitrogen. The nitrogen at this point is assumed to be at or near its boiling point, so the addition of heat will cause some of the nitrogen to vaporize, increasing the pressure. This would allow for control of the system temperature by altering the pressure of the nitrogen. The problem related to this is that the maximum temperature where nitrogen is a stable liquid is -150°C, well below the -80°C threshold required for the storage of the vaccine.

2.3.3 Pressure

In current cold storage and cryogenic storage technologies, there is a common element for pressure control in the form of a pressure relief valve. Many cryogenic storage solutions use a liquid cryogen for cooling, but when a liquid absorbs heat from its surroundings, it inevitably vaporizes. If there is a completely contained gas, concerns related to pressure buildup in the device then become apparent. To address this, some sort of relief or regulation valve will be implemented.

An emergency relief valve would function to prevent the pressure buildup associated with the vaporization of the cryogen from overstressing the device causing failure. This pressure relief valve would need to hold sufficient pressure to allow for proper temperature control but release well before pressure buildup becomes an issue. A different approach would be through a pressure regulator. This regulator could be controlled by the same microcontroller previously mentioned. The pressure regulator could control the flow of the cryogen to maintain a constant pressure within the cryogen chamber. The operating temperature of the system could then be controlled by changing the setting of the pressure regulator using the microcontroller. So using a single microcontroller and pressure regulator, the temperature and pressure could both be monitored and controlled continuously and automatically. For the purposes of this project, an upper pressure limit (the pressure at which the regulator or relief valve vents pressure) would be about 30 bar or 3 MPa. This limit allows for the boiling point of the cryogen to be controlled across a reasonable range such that the temperature can be regulated. Since the volume is controlled, increasing the pressure will increase the boiling point and temperature of the cryogen.

The extremely cold conditions in the device prevent the use of standard valves, however. Many valves use rubber or plastic components such as gaskets or O-rings, which under standard temperature conditions are completely acceptable. With cryogenic temperatures, these components would freeze and be very susceptible to fracturing and failure. To address this, a cryogenic grade regulator must be used.

2.3.4 Insulators

Silica aerogel is a lightweight solid derived from gel in which the liquid component of the gel has been replaced with gas. When the liquid is removed, what remains is a solid lattice with up to 99% porosity. This imparts the material with several unique properties such as being incredibly lightweight and insulative. Silica aerogel is known for having one of the lowest thermal conductivities of any material with a value of 0.005 W/m*K (Dorcheh, 2008), making it an excellent choice for insulating cryogenic containers. The material is also extremely lightweight with a density of roughly 1-2 kg/m^3 making it easily transportable and adding very little weight to the system as a whole.

The material is highly brittle and can, for the most part, only be obtained in sheets or blanket-like forms, making it more difficult to properly insulate the system with this material. The material is also relatively expensive compared to other options for insulation which makes it less suitable for this application especially in terms of mass-producing the system.

Perlite ($Al_2CaFe_2K_2MgNa_2O_{12}Si$) is a common ceramic material that is frequently used for a variety of applications. Larger grain perlite is often used in construction and horticulture as a filler and means to improve drainage and prevent erosion (Singh, 2020). More importantly, however, the thermal properties of this material are extremely useful for insulative applications. Perlite is particularly notable for its very low thermal conductivity which makes it an attractive option for cryogenic insulation. Small grain perlite, around 0.15 - 1.18 mm, is generally considered cryogenic-grade and is currently used in the industry (Perlite Institute, 2013).

Figure 3:Cryogenic grade perlite (Supreme Perlite, 2020)

In the case of a non-evacuated space and cryogenic temperatures, the thermal conductivity value ranges from about 0.025-0.029 W/m*K (Perlite Institute, 2013). If the space were partially evacuated, the effective thermal resistance would also be higher, perhaps dropping the thermal conductivity to a value closer to 0.02 W/m*K. Additionally, Perlite is inexpensive and readily available, making it ideal for this application, especially in large scale scenarios..

Since the selected insulation is a powdered solid, there will be countless pockets of air throughout the insulative layer. Reducing the amount of air between the grains of the insulation within the compartment would then improve the insulative properties of the layer. A reduction or removal of air between the particles in the volume would eliminate convection based heat transfer through the insulation into the storage volume, instead allowing only radiative and conductive heat transfer through the system. The overall rate of heat absorption into the system would subsequently be reduced from drawing some level of vacuum within the insulation and the effectiveness of the insulation would be improved.

2.3.5 Concentric Shells

A self-contained device is necessary, so naturally it requires a containment shell. The extremely low temperature requirements prevent the use of most plastics, so metals and ceramics are logical options due to their ability to withstand extreme temperatures. Ceramics are generally brittle by nature, so using a ceramic material as a containment unit creates a risk of the unit's containment shell breaking. Additionally, metals have better performance with pressurized contents.

The need to insulate the unit will require a set of concentric containers to prevent the cryogenic fluid and insulation from incorporating together. Therefore, the pressure experienced by each layer will be different. The cryogenic fluid pressure buildup must be controlled to prevent the containment from failing, so a pressure regulator will be inserted into the compartment to release excess gaseous cryogen and reduce the internal pressure. The shell material still must withstand the set regulator pressure with a reasonable factor of safety. An arbitrary safety factor of 2 would result in a maximum yield strength requirement of 6 MPa. This level of pressure is low when considering the strength of most metals. The most available choices for the shell material are Aluminum and Steel.

Aluminum 6061 has a yield strength of about 240 MPa and an ultimate tensile strength of 290 MPa (Engineering Toolbox, 2008). This comfortably meets the required ability to withstand the expected pressures. AISI 302 Stainless Steel has a defined yield strength of 502 MPa (Engineering Toolbox, 2003), substantially higher than that of aluminum. The ultimate tensile strength is 860 MPa (Engineering Toolbox, 2003), also significantly larger than the value of aluminum.

2.3.6 Humidity

Anytime an object or space is cooled from a high temperature to a low temperature, humidity concerns must be considered. The cooling of air with high relative humidity will inevitably lead to some condensation forming. In this application, any humidity in the storage compartment's air will likely condense into liquid water droplets due to the extreme cold. This has the potential to pool at the bottom of the storage volume or form on the internal surface of the compartment. For cold storage vials, this would not be a problem since the vials are sealed. However, any electrical components or sensors in the storage volume could experience issues. Additionally, the formation of water could cause problems in other applications such as the testing of electrical components and systems in extreme cold conditions. Some means to monitor and address the humidity and condensation build-up must then be an integral aspect of the unit. A humidity sensor implemented within the storage volume will continuously monitor the relative humidity of the volume and orange indicating silica gel absorption packs would line the internal surface of the storage space. The packs could be easily replaced and any condensation buildup and ambient humidity would be absorbed. Timing the absorption pack replacement would be equally simple as the packs indicate when saturated via a change in color from orange to green (Engineering Toolbox, 2003).

2.4 Design Objectives and Requirements

Before our group could model the initial design of the system, several requirements needed to be laid out for the design. The first requirement our group believed needed to be met was portability. If this system is to be used for delivery of vaccines to remote regions it needs to be easily transported without need for special equipment. This would limit the design to something small enough a single person could carry. The next requirement our group decided upon was the amount of time it could remain cold. If the system warmed up in transit all doses of vaccine would be rendered useless. For this our group set a time of at least 24 hours of continuous cold storage needed for viability. These requirements change when the system is used for scientific testing as it would no longer need portability or a timer as it would most likely remain stationary and connected to a continuous cryogen supply. This leaves the only requirement for scientific application as to hold temperature internally and have a large enough storage volume for testing of small components. Both of these results can be achieved as a byproduct of fulfilling the requirements needed for vaccine transport and can thus be ignored.

3.0 Methodology

3.1 Engineering design process

When designing a system to fit a need, a comprehensive process should be followed to assure all goals are met and the final system will be able to accomplish any of the tasks it was designed for. When creating this cryogenic storage device, the generic engineering design process (Teach Engineering, 2020) was used for constructing the model.

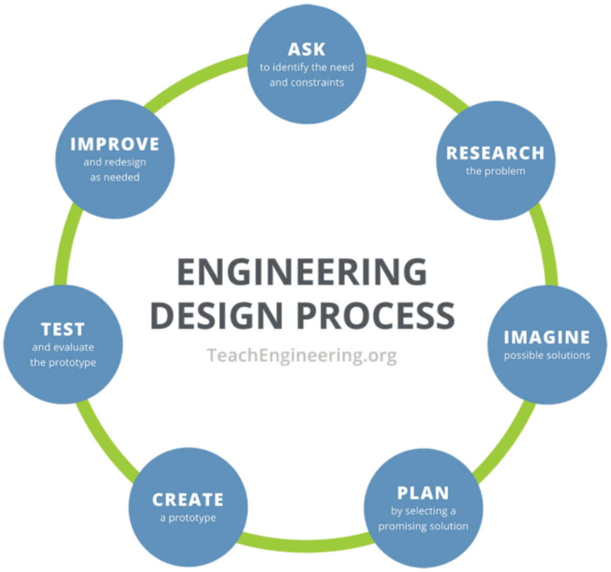


Figure 4: General Schematic of Engineering Design Process (Teach Engineering, 2020)

The process began the same way as many design procedures by first outlining the need the system was intended to fill. This included any constraints the design must take into consideration. For this device, the need that the Covid-19 pandemic placed on extreme cold and cryogenic storage vessels was identified. Properly defining energy transfer constraints as well as size constraints was also a critical element of the design process. After the need was identified, the second step of the process was to research the issue and associated information. In this step it was crucial to properly understand the problem as well as determine if a solution to the problem already existed. This step involved researching methods that other cryogenic storage vessels use to regulate temperature and pressure as well as these existing tank sizes and specific uses. Once research was complete, the third step was to develop several possible solutions based on the knowledge obtained to that point. These solutions were considered with close attention paid to all constraints, the research conducted, and the problem itself to determine which solution best addressed the problem. Once all the members of the team collectively came to a decision on the best solution, a preliminary prototype was iteratively designed with the intention of constructing the final version.

3.2 Our design

The first step in designing a cryogenic storage tank was setting out requirements the final model would need to fulfill. For this project's design, an insulation that could sufficiently reduce convective and conductive heat transfer, a storage location for the cryogen (as well as a way to refill and monitor its pressure), and a location for storage of vaccines were determined to be the most important design requirements. From these requirements, it was decided a relatively small cylindrical system would be practical as it made the process of nesting these layers simpler. The additional benefit was that cylindrical containers were a more suitable shape for pressurization. Stainless steel would be used as the main structural material due to its high durability to the cold as well as being easily obtained and manufactured to the required shapes. The insulation would be constructed using granulated perlite due to its incredibly low thermal conductivity and low cost. Once these basic details were decided upon, the initial iteration could be modeled.

3.2.1 Modelling iterations

To model the design prior to prototyping, the SolidWorks CAD program was utilized. The initial iteration was designed with three separate chambers separated by stainless steel cylindrical shells. The outermost chamber was designed to be filled with perlite insulation, the intermediate chamber was designed as the storage for the cryogenic fluid that will maintain extreme cold temperatures, and the innermost chamber is the storage volume. A lid was also modeled for the system made from a stainless steel shell with perlite insulation inside the main body of the lid. This initial design was simple and mainly used to show the concepts of insulating the storage volume with perlite. Once this first iteration was finished, it was brought to our advisor for comments.

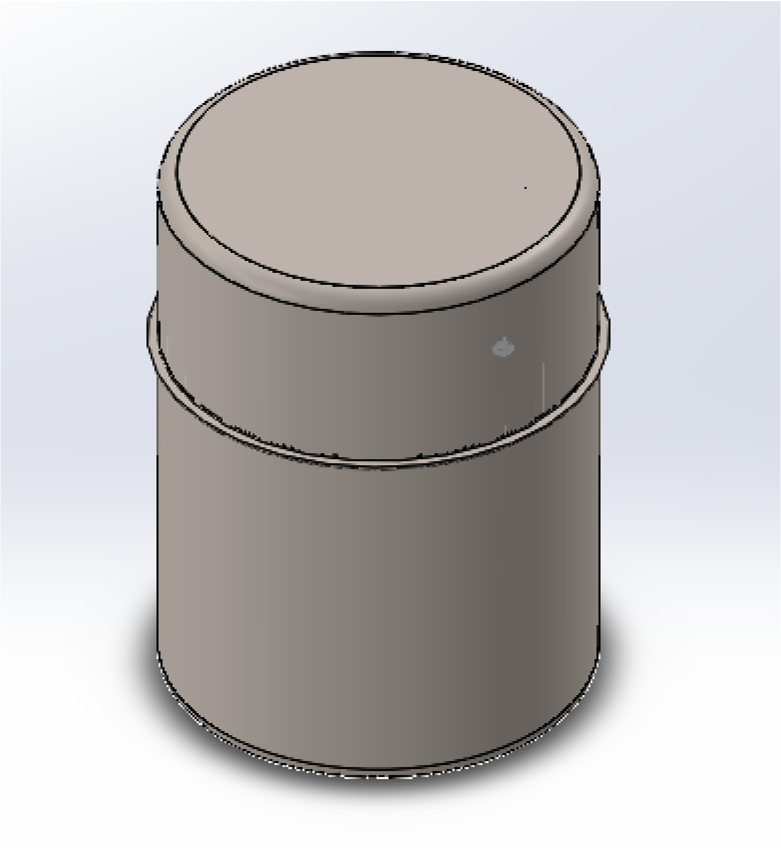


Figure 5: First Iteration CAD Model

The second iteration of the design started due to the idea of making the internal temperatures of storage change drastically. To do this, initially discussion considered changing the internal pressure of the cryogen chamber to adjust the storage temperature. However, it was quickly realized that the internal pressure of the chamber would have to reach dangerous levels to be able to adequately shift the temperature from true cryogenic temperatures of less than -150℃ to vaccine storage temperatures of closer to -80℃. To solve this issue, an idea of making the cryogen chamber modular by designing the chamber to be removable from the system was devised. To do this, an additional stainless steel shell was modelled on the inner layer of insulation allowing the cryogen module to slide in and out of the insulation module when the lid is removed. This allows for a cryogenic liquid module for temperatures below -150℃ as well as an extreme cold solid module that can be filled with dry ice for vaccine storage. This iteration also saw the inclusion of basic instrumentation and mechanical components such as pressure regulators, latches, handles, and gaskets. With this the second iteration, seen below, was completed and submitted for comments to our advisor.

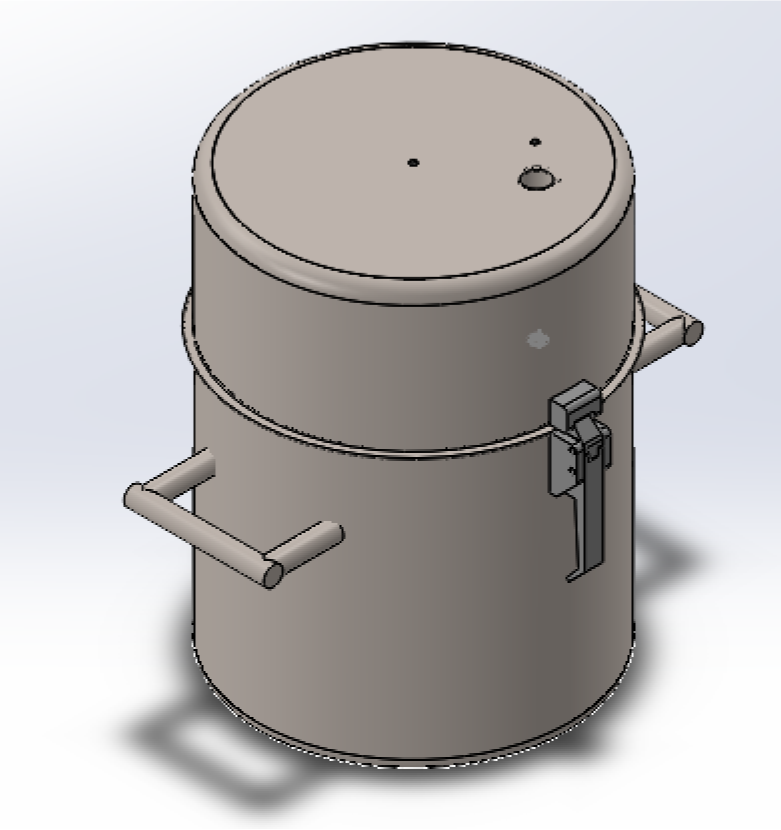


Figure 6: Second Iteration CAD Model

Based on comments received after the second iteration, the model was revised again with several more complex instruments being added on to the model. Our group at this point started researching various systems for both monitoring and controlling the pressure and temperature in the system. The consensus that was arrived at was that a Raspberry Pi Touch model would be best as it would be able to run off a small power source such as a battery for an extended time as well as being its own interface and display without need for external monitors or accessories to interface with the sensors used. The pressure regulator as well as the thermocouple can both easily interface with the Raspberry Pi and with some slight code this can be used to slightly adjust temperature through pressure regulation of the cryogen chamber. An image of this final iteration can be seen below.

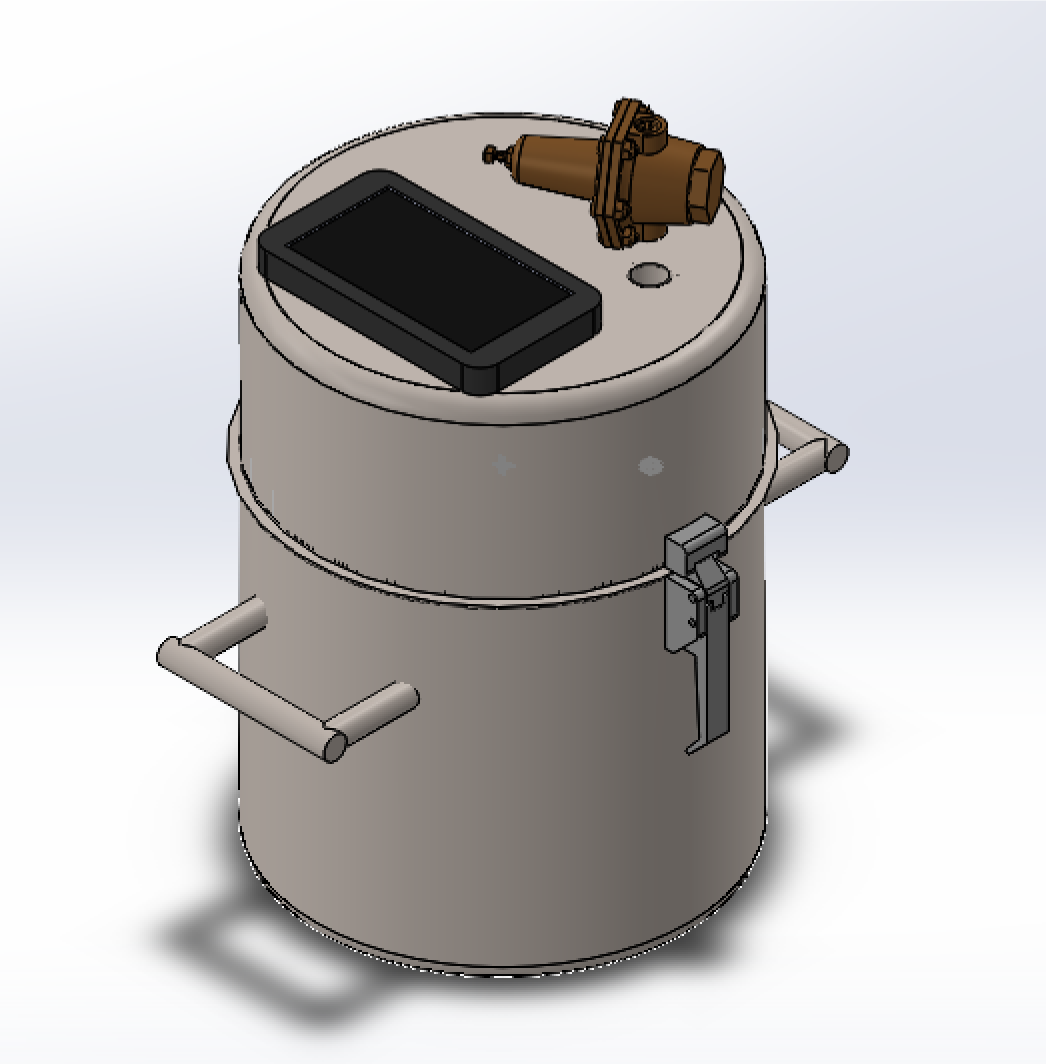


Figure 7: Final Iteration CAD Model

3.2.1.1 Modularity

Modularity became an important part of this design in the second iteration. It was found to be a comprehensive solution to the need for a variable temperature cryogenic storage vessel. To account for a wide array of temperatures, two separate cryogen modules were modelled, one designated for using cryogenic fluids and one for extreme cold solids. This was deemed the optimal amount of modules for the current scope of this project as the cryogenic fluids module will be able to hold the majority of cryogens, such as liquid helium, liquid nitrogen, or liquid argon. This will allow the fluids module to sustain temperatures as low as -268℃ by utilizing liquid Helium (Cryogenic Fluids, 2011). While this module could theoretically sustain temperatures of roughly -80℃ by utilizing pressurized liquid ethylene, the cryogenic fluid with the highest boiling point, it was deemed too much of a safety risk due to the flammability of ethylene. All other cryogenic fluids would also be a safety risk if gotten to the temperature due to the high pressure needed to achieve -80℃ with any other choice. To circumvent this issue we looked towards other materials that would be able to achieve the desired temperature for vaccine storage. It was decided that dry ice would make an optimal material for the task as it sublimates directly from solid to gas at -80℃. To accommodate this a module for containing solids was modelled. The module was designed to be filled with pelletized dry ice through several small openings in the chamber to allow total filling of the cryogen chamber. Images of each of these models can be seen in the figures below. While these two were the modules chosen for the current project, the concept of modularity allows the creation of more designs with different purposes down the line.

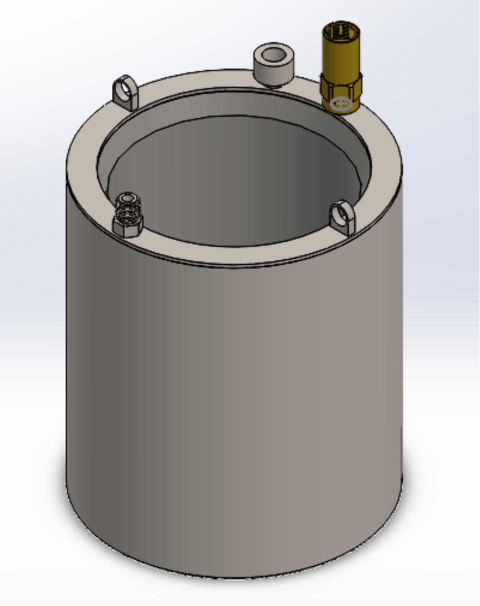


Figure 8: Liquid Nitrogen Cryogenic Module

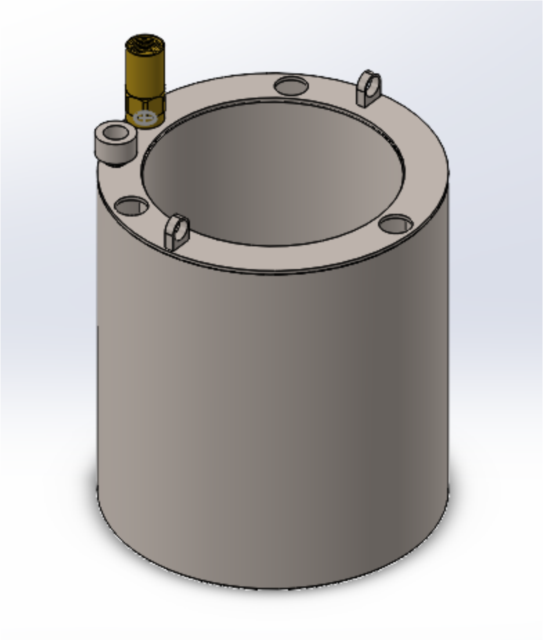


Figure 9: Dry Ice Cryogenic Module

Once the modules were created, the next step was to determine how to properly run any instrumentation throughout the device. As the modules must be able to slide in and out of the insulation chamber, no instrumentation could be run through the insulation. This leaves the lid of the assembly as the only viable option. A pressure relief valve was modelled on each module and a corresponding hole was cut through the lid to allow pressure to always be able to vent from the chamber in case of emergency. A pressure regulator, that was modelled as to be located on the upper surface of the lid, was connected to the fluid chamber with a friction fit pipe fitting as the regulator itself will only be changing the pressure by several psi for any liquids. With this all current problems created by the module system were solved and a plan of how any further instrumentation needed later could be integrated into the design was developed.

3.2.2 Prototype

Due to the circumstances of the COVID-19 pandemic, it was impossible to assemble a physical prototype however, we had gathered the materials and developed the steps someone could use to build a prototype with the materials chosen. The prototype we initially intended to model was not intended to be an exact replica of the model created in the design portion, but rather a proof of concept on the ability of the system to maintain its internal temperature for an extended duration. This explains any deviations between prototyping steps and the model shown in the previous section.

3.2.2.1 Bill of Materials

Before our group could begin a prototype, a bill of materials needed to be created to ensure we were in budget. Due to the very custom nature of the CAD model the prototype was based upon, many of the materials that had to be bought retail did not fit the exact dimensions. Three stainless steel vessels in varying sizes were bought to be used as outer shells for the different chambers. In the final bill, these vessels became one of the most expensive parts as they had to be bought retail. Custom made, mass produced containers would bring the end expense of these vessels down considerably. The thermocouple is a type-T and is designed for cryogenic temperatures to accurately measure temperature changes in the storage volume. The pressure regulator was chosen for it’s extremely low operating temperatures. The Raspberry PI was to be used as a readout for temperature in the storage volume and pressure in the cryogen chamber. The perlite chosen was a fine grain cryogenic grade perlite with extremely low thermal conductivity to insulate the cryogen and storage volume.

Prototype	Unit Quantity	Unit Size	Company	Unit Cost	Net Cost
Small SS Container	1	6.5” x 5.25”	Webstaurant Store	$5.89	$5.89
Large Stainless Steel Container	1	13" x 12.25"	Restaurant supply	$115.60	$115.60
Medium SS Container	1	9" x 7.6"	Cole Palmer	$165.00	$165.00
Thermocouple	1	1	DigiKey	$105.43	$105.43
Raspberry Pi Touch	1		Raspberry Pi	$70	$70
Chamber Inserts	3	3D Print	WPI	$18.24	$54.72
Pressure Valve	1	1/4" Inlet	McMaster	$393.11	$393.11
Dry Ice	8.43	lbs	WPI	$7.5	$63.20
Perlite	1	25 Lbs	Amazon	$85	$85.00
				Total	$1057.95

3.2.2.2 Vaccine Tray Insert

In order for this design to be a viable means of transporting vaccines, it needed to ensure that the vaccines would not break within the design. Since the space needed to remain modular, 3D-printable inserts designed to fit the diameter of the storage volume were modelled. These were modeled in solidworks after the initial system design was completed. The trays were designed with two things in mind, safety of vials and maximum storage. To accomplish these goals, it was decided that these inserts should be stackable to utilize the entire storage volume, and have pre-sized holes to perfectly fit each vial with no chance of movement. Research was done into the size of each vial and circular holes were cut into the model slightly larger than the dimensions found through initial research to account for material shrinkage due to cooling. After finding an optimal pattern for these holes, a design was found that allows twenty doses per tray and up to five stackable trays in the storage volume totalling one hundred doses in each system. This can be an optimal solution as several plastics, such as polycarbonate (Hetchel, 2014), can operate at these temperatures as there is no mechanical load on them outside of the weight of vaccines. These plastics are also cheap and easily manufactured to specification. An image of the tray can be seen in the figure below.

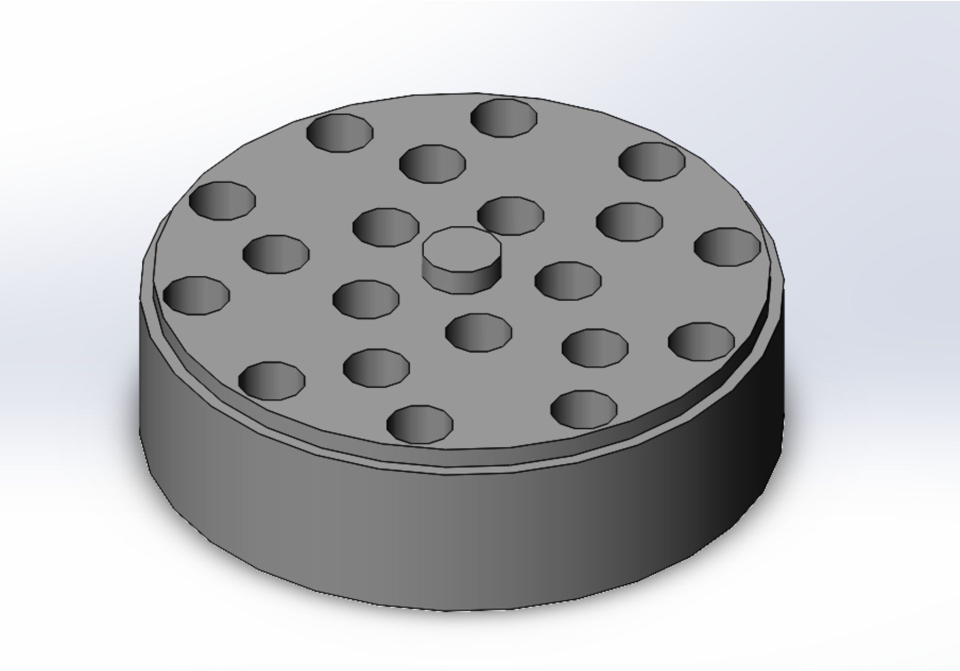


Figure 10: Vaccine Tray for Storage Volume

3.3 Calculation Methods

Before ordering the parts required to build the prototype, several tests and analyses were conducted to verify our assumptions. Several methods were used to gather data necessary for these analyses including, Basic 1-dimensional heat transfer calculations and thermal simulations.

3.3.1 Heat Transfer Calculations

To determine results for the duration of cooling as well as heat absorbed by the cryogen, a Google Sheets spreadsheet was used to perform 1-dimensional heat transfer calculations. This allowed for easy changes to each variable without having to change any equations. The calculations were used based on the following known heat transfer properties and formulas for hollow cylindrical materials:

$$R_{thermal,\,cond} = \frac{1}{2\Pi Lk} \times ln(\frac{r_{out}}{r_{in}})$$

$$R_{thermal,\,conv} = \frac{1}{2\Pi rLh}$$

where: $R_{thermal}$ is the effective thermal resistance of a system

L is the characteristic length of the system (height of the device in this case)

k is the thermal conductivity of the material

r_{out} is the outer radius of the system

r_{in} is the inner radius of the system

h is the convection coefficient of the surround fluid (air at room temperature)

$$R_{thermal,\,total} = R_{thermal,\,cond} + R_{thermal,\,conv}$$

$$q = \frac{\Delta T}{R_{thermal,\,total}}$$

The limitations related to this simplified method of heat transfer analysis are discussed in the Theoretical Scenario located in Section 4 of this paper.

3.3.2 CAD Simulations

The thermal simulations were run using the Solidworks Thermal simulation software and due to the nature of the experiment, necessitated a transient simulation rather than steady-state as the desired data was to view how temperature changed over time. To accomplish this, the original Solidworks assembly needed to be simplified to allow for an efficient simulation. This simplified model was modeled as a single part, using separate solid bodies in the part to represent the four integral units of the system for heat exchange, insulation, cryogen, storage volume, and the lid. Each of these solid bodies was assigned a material according to researched values for thermal conductivity and heat capacity. The lid and insulation were both assigned perlite as a material with a thermal conductivity of 0.025 W/(m*K) and specific heat of 387 J/(kg*K). The main cryogen used in the simulation was dry ice and thus the material assigned to this solid body was dry ice, a custom material with a thermal conductivity of .0096 W/(m*K) and specific heat of 849 J/(kg*K). This could easily be edited to separate cryogens such as liquid nitrogen by making a custom material in the software and adding researched values for thermal conductivity and specific heat. Finally, the storage volume was assigned air as its material as the group wished to see how the empty storage volume temperature changed with time rather than filled as many different loads could be used in the storage volume depending on the use. Solidworks lists the thermal conductivity and specific heat for air as 0.027 W/(m*K) and 1000 J/(kg*K) respectively. Once the materials were assigned to each solid body, the thermal loads and parameters of the simulation could be established.

A Solidworks thermal simulation requires several things in order to accurately display data for a transient simulation. Firstly, it requires the parameters of the simulation be set, which for a transient simulation are the total time and time step. For the total time of the simulation, three hours was chosen as Solidworks is limited in its ability to accurately simulate the energy used to sublimate dry ice or how pressure can change the internal temperature of the cryogen chamber. This meant the simulation would deviate more heavily from the actual data as the total time was increased. This ended with a decision to utilize simulations from earlier times as the data could be deemed more reliable. All results from solidworks simulations can be found in the appendices.

3.4 Design Specifications

For the model, all dimensions associated with the shells in the system can be seen in the figure and table below.

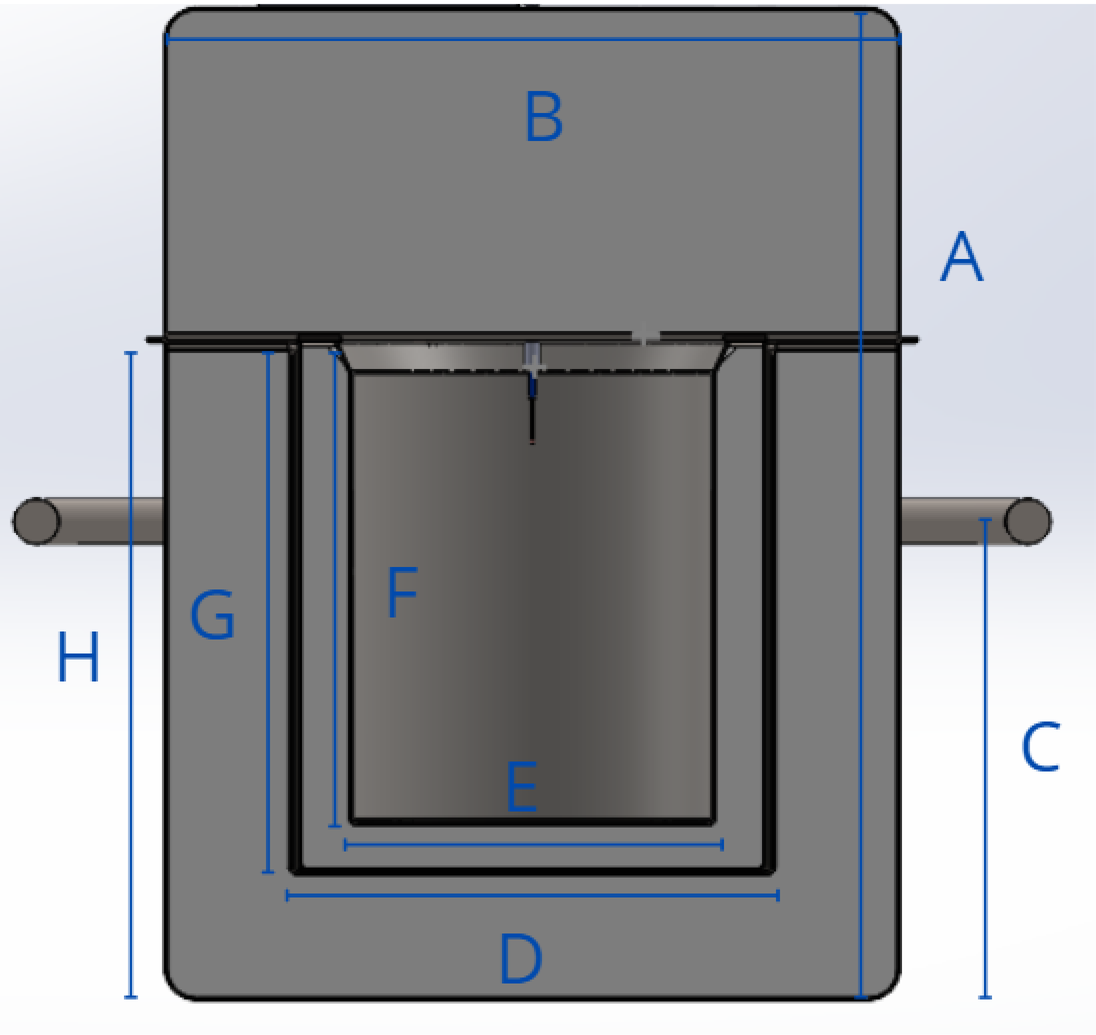


Figure 11: Dimension Labels

Dimension Label	Corresponding Part	Value (in)
A	Total height of system	16.50
B	Total diameter of system	12.25
C	Distance from base to handles	8.20
D	Diameter of cryogen module	7.8

E	Diameter of storage volume	6
F	Height of storage volume	7.95
G	Height of cryogen module	8.85
H	Height of insulation module	10.90

These dimensions show the main dimensions associated with the shells, the missing dimension for this is the shell thickness which for all is equal to .05”. The insulation is layered throughout the entire lid aside from the holes designated for the thermocouple, and pressure relief systems, as well as a 2” layer on the inside of the insulation module along the sides and base. With these dimensions the base system could be easily constructed. Holes and designated locations for instrumentation are dependent on the exact instrumentation used in the assembly and should change based on the usage of the system.

4.0 Results

4.1 Operational Data

The following section details the specific outcomes of our design process related to the theoretical calculations and parameters of the Cryogenic Storage Device.

4.1.1 Theoretical Scenario

For the preliminary heat transfer calculations of the design, we utilized a simplified model and temporarily neglected end effects of the device. We subsequently treated the cylindrical sealed system as a standard, multi-layered pipe such that the heat transfer calculations could be simplified. There were a number of assumptions involved to allow the calculations to be performed. These assumptions included:

- No heat absorption from the interior of the device. In other words, the storage volume and cryogen compartment are assumed to already be in equilibrium at the temperature of the cryogen. In the case of Liquid Nitrogen, this is assumed to be the boiling point of Nitrogen at atmospheric pressure equal to 77K. In the case of Dry Ice (Solid State Carbon Dioxide), the temperature is assumed to be 193K.
- Perfect conductive and convective heat transfer with no additional losses due to external factors.
- No radiative heat transfer, since in atmosphere, radiative heat transfer is much less significant compared to conductive and convective heat transfer. No compartments of the device are planned to be vacuum environments, reducing the impact of this emission.

- Ignoring the top and bottom of the device. The top and bottom surfaces of the device would naturally absorb heat from the surrounding environment, but for the purposes of this calculation, they are ignored and an additional multiplier is added to any heat absorption values instead.

4.1.2 Sample Calculation

The previously discussed functions were added to a spreadsheet where the parameters could be altered yielding instant results. Below is a general sample of the results from these calculations. Of note, these calculations were performed with an assumed length of the device of one meter. The calculations above 0.75 m in thickness are then irrelevant. If the thickness of the insulation is increased beyond, then the characteristic length switches. The overall diameter of the device becomes more important since more heat is absorbed through the top and bottom of the device than the sides.

Another important aspect to note is that the heat absorption and evaporation asymptotically approach a value of about 40-50W and 1 kg/hr, respectively. These exact values would change with different parameters, but that there is a decreasing benefit to increasing the thickness beyond a certain point is critical when it comes to optimizing the design. The amount of benefit from increasing the insulation thickness diminishes to a level that is negligible.

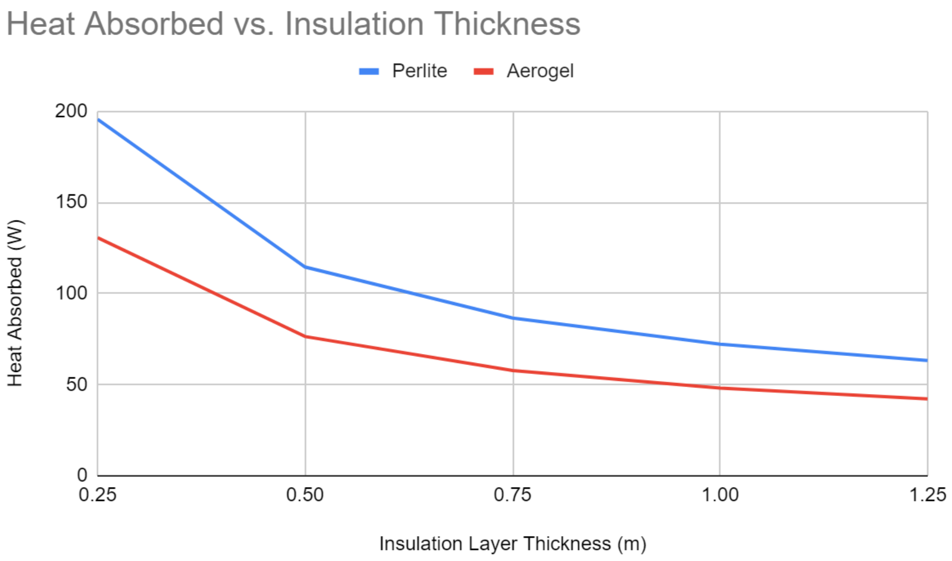


Figure 12: Graph of heat energy absorbed at different insulation thicknesses; each line corresponds with a specific insulation material.

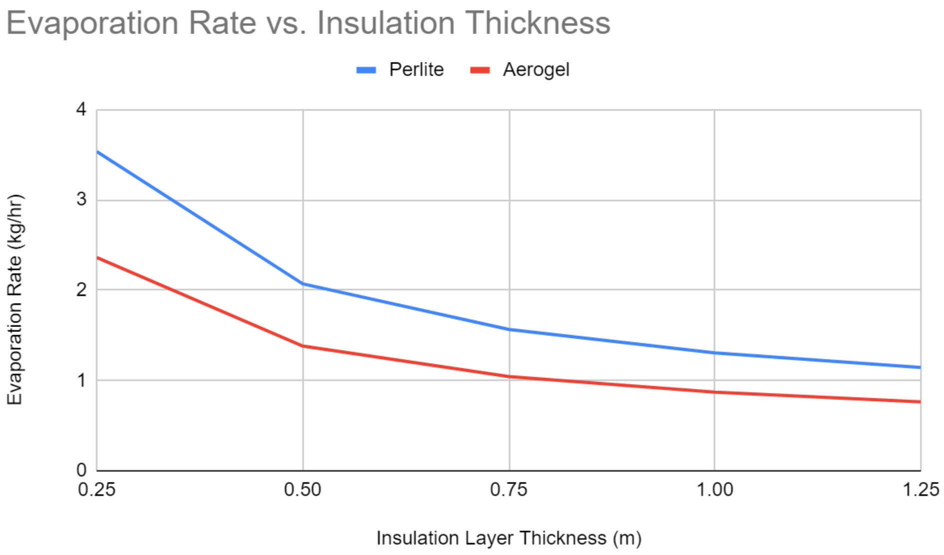


Figure 13: Graph of the expected evaporation rate of liquid nitrogen at different insulation layer thicknesses; each line corresponds to a specific insulation material.

4.1.3 Design Scale

The primary application for this design is for the small-scale transportation and short-term storage of Covid-19 vaccines. However, the design could be scaled up to allow for larger storage volumes. Scaling up has some challenges, primarily associated with the difficulties related to limiting the heat absorption. Any change in the height or diameter of the device has an exponential effect on the amount of heat absorbed from the ambient surroundings. As an example, increasing the length or height by a factor of two would increase the amount of exterior surface area and the amount of insulation by the same factor. This is due to the linear proportionality of these properties:

$Surface\ Area\ of\ a\ Cylinder\colon\ A = \pi d L$

Note: This neglects the top and bottom surfaces for simplicity

Here, d is the exterior diameter of the device and L is the length or height of the device. Similarly, the amount of insulation in the device is described by:

$Volume\colon V = (\pi D^2 L - \pi d^2 L)/4$

where D is the outer diameter of the insulation layer and r is the inner diameter of the layer. In both cases, the relationship between L and the relevant physical properties is strictly linear. However, changing the diameter of the storage volume has an amplified effect on the amount of insulation required to fill the cavity in the device.

To frame this problem in a more abstract way, scaling the device up to make it larger will generally require more materials. If the device is larger, it will absorb more heat from the surroundings and this will require more cryogen. This is generally demonstrated by figure 14 below.

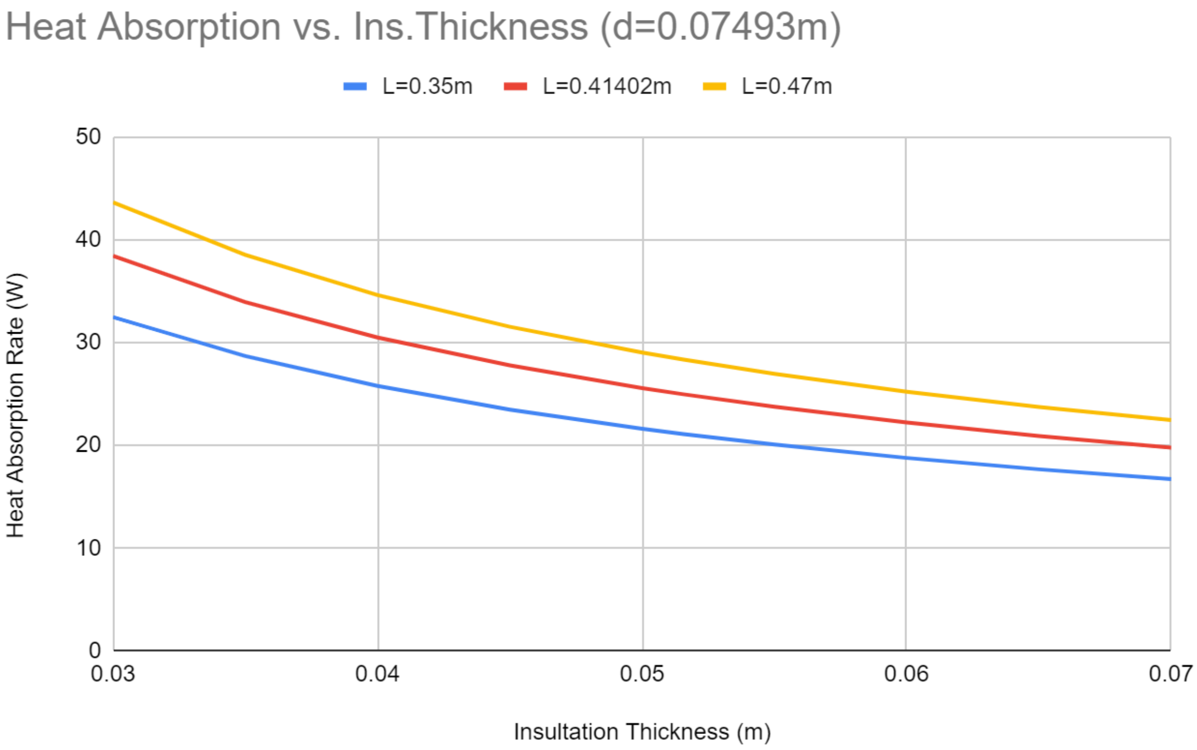
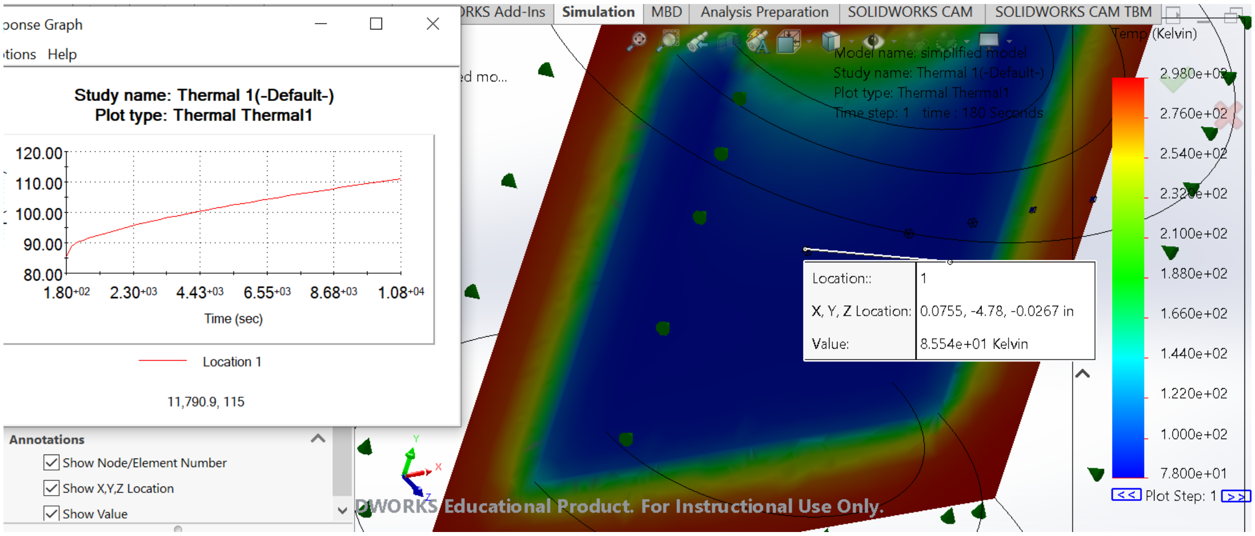


Figure 14: Heat Absorption vs. Insulation Layer Thickness at different theoretical lengths of the device.

4.1.4 Simulation Results

Figure 15 is one of the results of the simulation showing thermal response showing temperature over time at center of storage volume using liquid nitrogen for cooling. Figure 16 shows the thermal response over time at the exterior surface of the system. Both of these graphs are using liquid nitrogen as the cryogen and recorded after three hours time. These are the most relevant temperature graphs of the system as the interior of the storage volume determines the duration of storage for materials and the exterior surfaces determine the level of safety equipment needed when handling the device. While these are the two most relevant graphs to the project, several more showing thermal response over time at different locations along the cross-section of the system can be found in the appendices of the report.



Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1

11,790.9, 115

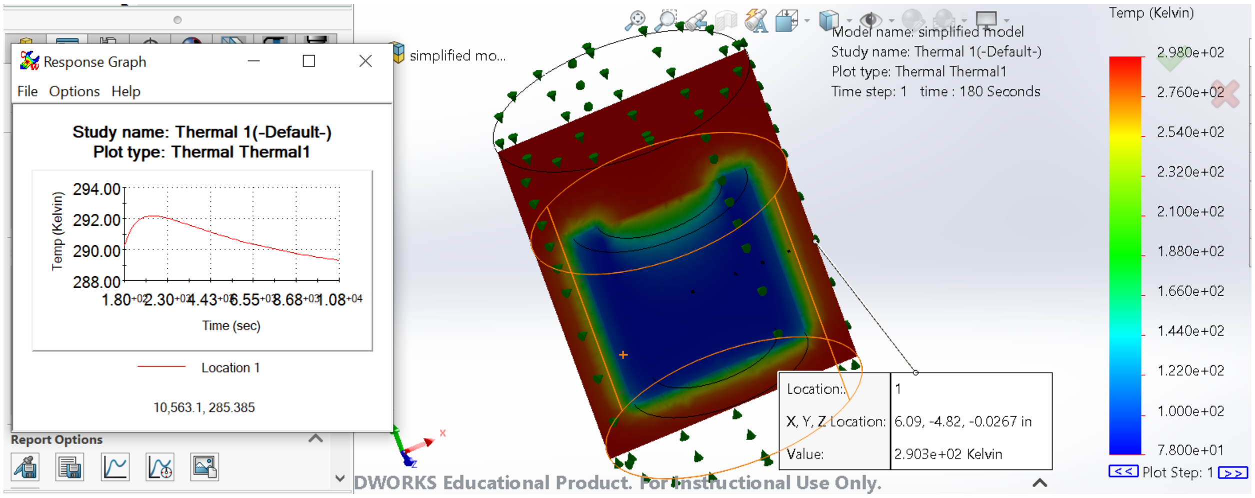
Annotations

☑ Show Node/Element Number
☑ Show X,Y,Z Location
☑ Show Value

Model name: simplified model
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Time step: 1   time : 180 Seconds

Location:	1
X, Y, Z Location:	0.0755, -4.78, -0.0267 in
Value:	8.554e+01 Kelvin

Figure 15: Thermal Response at Center



Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1

10,563.1, 285.385

Model name: simplified model
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Time step: 1   time : 180 Seconds

Location:	1
X, Y, Z Location:	6.09, -4.82, -0.0267 in
Value:	2.903e+02 Kelvin

Figure 16: Thermal Response at exterior surface

4.2 Discussion

This project faced several obstacles. In-person meetings were prohibited due to Covid-19, so no prototype could be developed. This did not impact the project design process, but there were other limitations in the tank design. If the cryogenic fluid in the tank is liquid Nitrogen, the device could only be used at cryogenic temperatures for short durations. For example, it could stay at -196 degrees Celsius for 5 hours. This limits the application to stationary, largely scientific uses. The tank would need to be consistently hooked up to a nitrogen supply, which is not feasible. If the device is used for Covid vaccines, it would require storage temperatures ranging from -80 to - 60 degrees Celsius. Dry Ice sublimates at about -80 degrees Celsius, so the lifespan would be much higher at about 60 hours. The tank would need to be refilled with Dry Ice only once every few days.

Lastly, the project budget was a limiting factor. The cost analysis only accounts for one use of the storage tank. To get more accurate results on long term use, more materials for more uses would need to be purchased.

4.3 Conclusions

The proposed design for the cryogenic storage device would prove useful for distributing vaccines in remote areas with little to no infrastructure that conventional distribution methods would have difficulties with. The design is highly portable and should be able to be carried by a single person for several days as mentioned in the results. This would allow for transit of up to 100 doses to remote areas where the current cold storage chain cannot reach. With this vaccination rates to remote areas could see a stark increase due to newfound accessibility to the communities.

To test this design, several thermal computer simulations were run as well as hand calculations to verify all assumptions. The thermal simulations proved ineffective at measuring temperature towards our calculated limiting time due to constraints within the program. Hand calculations however filled in the gaps for proof necessary for verifying assumptions. This is covered in the results section, discussing heat transfer rates, temperature changes, and estimated storage times based on cryogen used. With this information present, the system could be fully prototyped and tested to determine it’s real-world effectiveness.

5.0 Broader Impacts

5.1 Engineering Ethics

The fundamental principles and canons of the Engineering Code of Ethics dictate that engineers “use their knowledge and skill for the enhancement of human welfare” and “hold paramount the safety, health, and welfare of the public in the performance of their professional duties” (ASME, 2021). This project focused on improving human welfare by supporting the distribution and transportation of vaccines for Covid-19. The work performed during this project was largely related to the improvement of cold storage transportation and storage infrastructure on a global scale, particularly in areas where there are severe limitations to maintaining a viable cold storage chain. Aiming to solve this problem, the project set out to improve the technological capabilities related to cold storage as a means to support the global effort to combat the pandemic. As mechanical engineering students at Worcester Polytechnic Institute, the project team recognized the problem and developed a solution within the bounds of the members’s technical understanding and expertise.

5.2 Societal and Global Impact

The concept design solution developed from this project has the potential to have a long lasting impact globally. The ongoing fight against the Covid-19 pandemic, specifically in India, highlights the reality that though developed countries may have vaccines readily available, much of the world is not in the same position. The efforts to end the pandemic worldwide are dependent on supporting global distribution and vaccination goals.

UNICEF Nepal @unicef_nepal · Mar 17

No cold chain, no immunization💉 How UNICEF's long-running efforts to assess, expand & strengthen Nepal's cold chain capacity, with support from global health partners like @gavi are helping to bolster the ongoing #COVID19 vaccination campaign.

unicef.org/nepal/stories/...

Figure 17: Unicef Tweet Demonstrating the Importance of Cold Chain Infrastructure

To help with these efforts, the team sought to improve the supply chain infrastructure of the Covid-19 vaccine by providing alternative means of cold storage and transportation. The potential impact of this device is limitless, with the positive impact of Covid-19 vaccine distribution being difficult to quantify.

5.3 Environmental Impact

The long-term environmental impact of this device is difficult to predict. Though the sensors and other electrical components require very little power to operate, they would need to be powered by batteries in the case of vaccine distribution. This over a large-scale distribution effort could generate a large amount of waste in the form of used batteries. As far as the vessel itself, there is little expectation of any long-term impact during use. The only emissions generated by the operation of the device are gaseous cryogen which are generally harmless to the environment. In the case of CO_2 emissions from the sublimation of dry ice, the quantity is small and is not generated from fossil fuels.

5.4 Codes and Standards

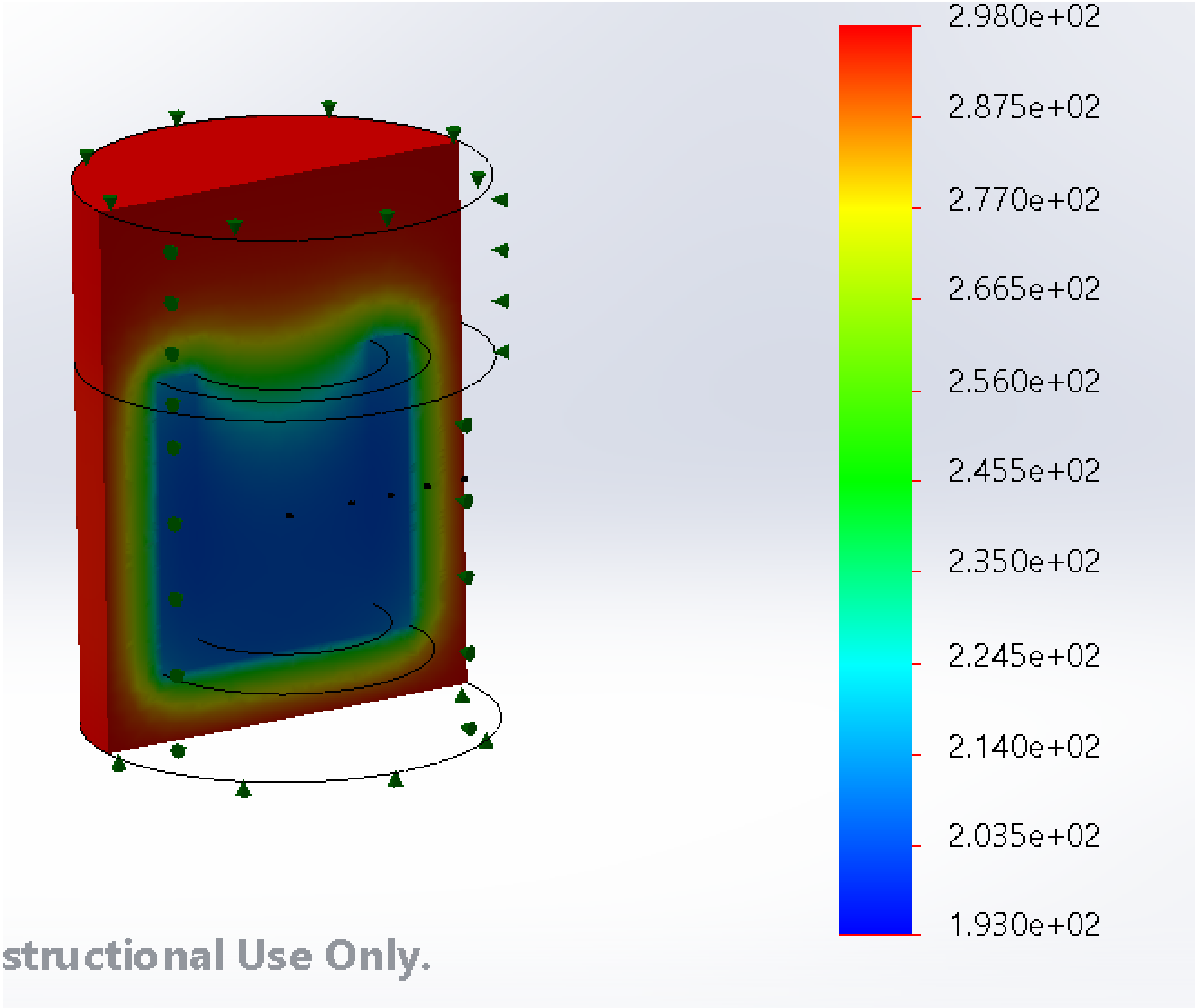
Beyond the adherence to the Engineering Code of Ethics and the associated principles and canons, there were no specific technical codes or standards utilized in this project. In general, safety and effectiveness of the design were the strongest aspects that were considered.

5.5 Economic factors

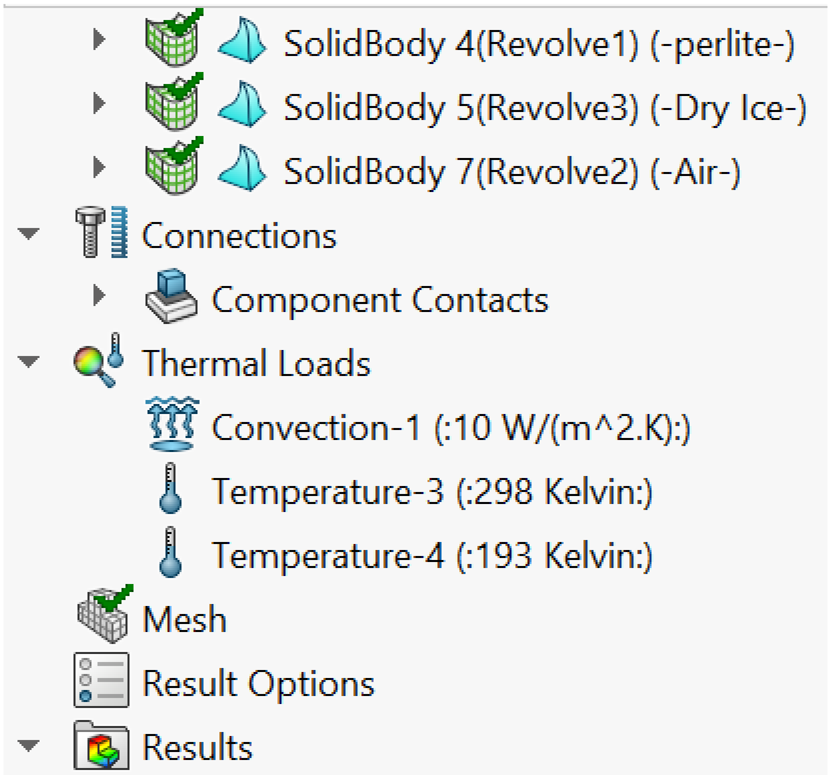
The overall prototyping cost of the design has been established. However, since the focused, current application is related to a public health crisis, consideration related to continued costs need to be considered. The most obvious ongoing cost is the cost associated with replenishing the cryogen. Strictly considering the prototyping cost of dry ice as a medium, the cost for one 2.5-day period is about $60. This cost multiplied across potentially hundreds of units and over a period of months, if not years could be a crippling ongoing cost. While considering this is important, there is also an expectation that unit price could be reduced over time, and that government organizations and governments themselves would be the primary market. It is likely that most governments could support this cost.

Appendices

Appendix A: Solidworks Thermal Models



Thermal simulation temperature distribution using dry ice (3 Hours)



SolidBody 4(Revolve1) (-perlite-)

SolidBody 5(Revolve3) (-Dry Ice-)

SolidBody 7(Revolve2) (-Air-)

Connections

Component Contacts

Thermal Loads

Convection-1 (:10 W/(m^2.K):)

Temperature-3 (:298 Kelvin:)

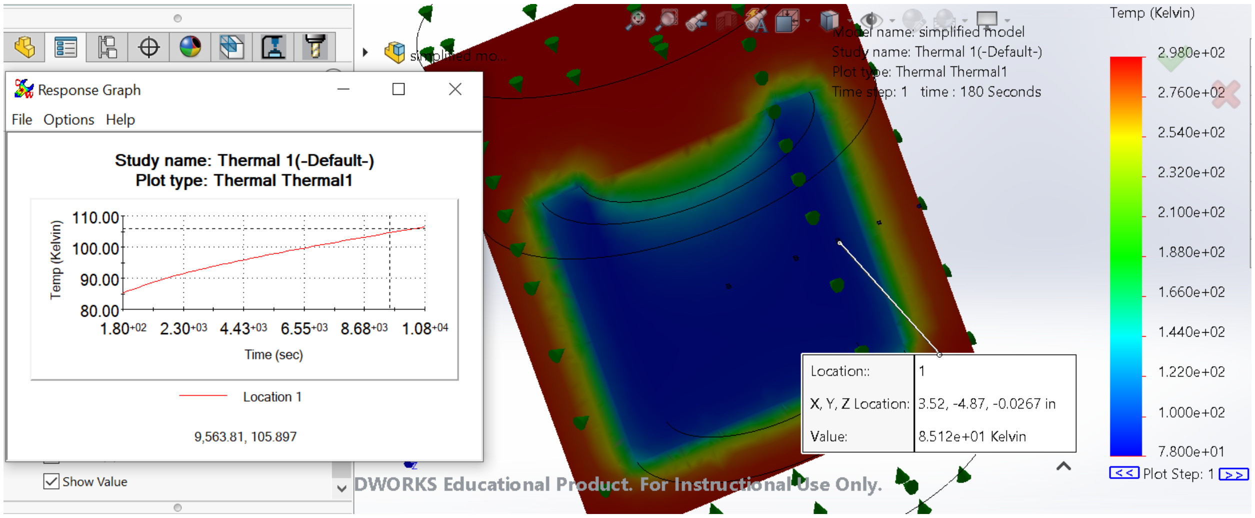
Temperature-4 (:193 Kelvin:)

Mesh

Result Options

Results

Parameters used in dry ice thermal simulation



Response Graph

Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1

Location 1

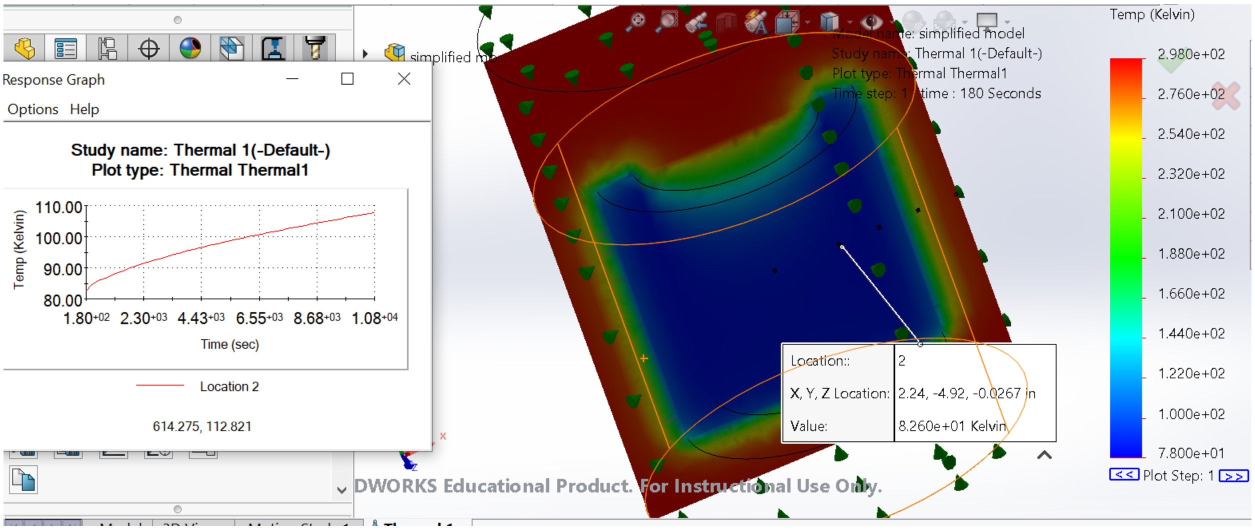
9,563.81, 105.897

☑ Show Value

Model name: simplified model
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Time step: 1 time : 180 Seconds

Location::	1
X, Y, Z Location:	3.52, -4.87, -0.0267 in
Value:	8.512e+01 Kelvin

Thermal response showing temperature over time of liquid nitrogen chamber



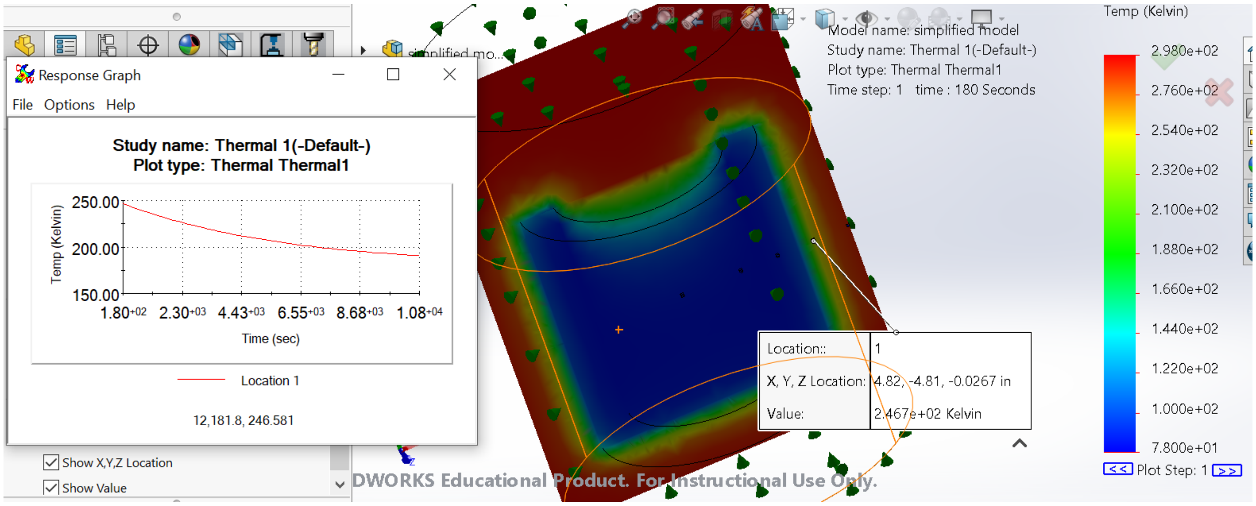
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1

614.275, 112.821

Model name: simplified model
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Time step: 1 time : 180 Seconds

Location:	2
X, Y, Z Location:	2.24, -4.92, -0.0267 in
Value:	8.260e+01 Kelvin

Thermal response showing temperature over time at edge of storage volume using liquid nitrogen for cooling



Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1

12,181.8, 246.581

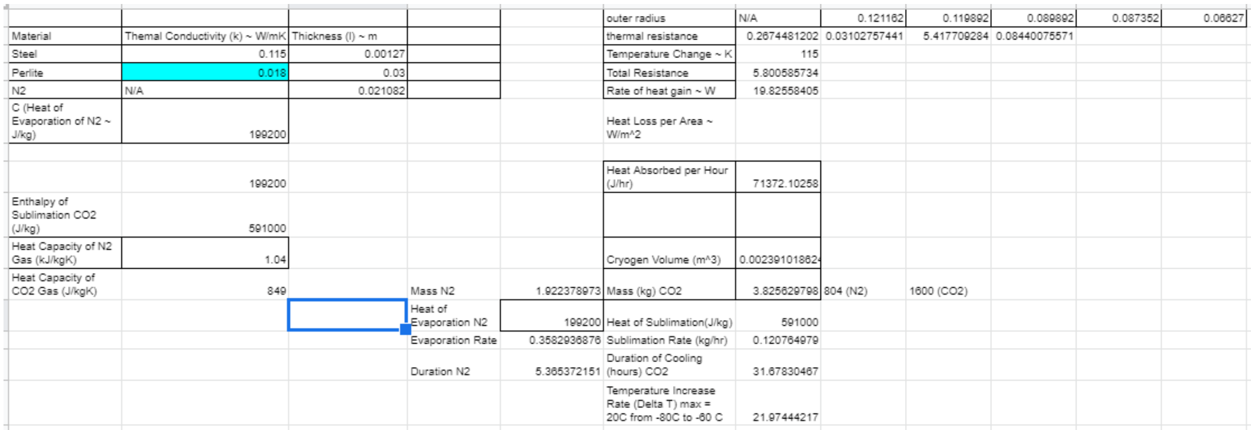
☑ Show X,Y,Z Location
☑ Show Value

Model name: simplified model
Study name: Thermal 1(-Default-)
Plot type: Thermal Thermal1
Time step: 1 time : 180 Seconds

Location:	1
X, Y, Z Location:	4.82, -4.81, -0.0267 in
Value:	2.467e+02 Kelvin

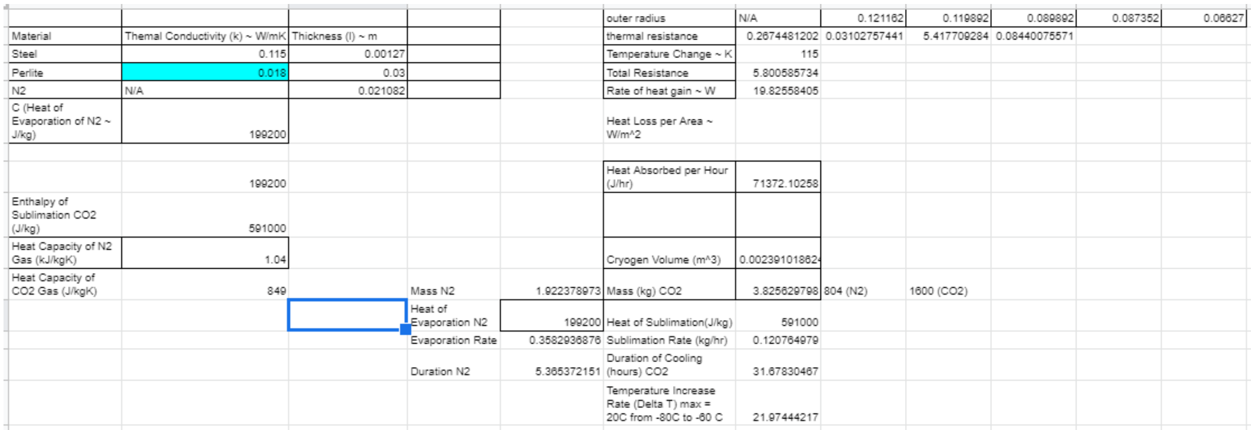
Thermal response showing temperature over time at center of insulation module using liquid nitrogen for cooling

Appendix B: Heat Transfer Calculations



					outer radius	N/A	0.121162	0.119892	0.089892	0.087352	0.06627
Material	Themal Conductivity (k) ~ W/mK	Thickness (l) ~ m			thermal resistance	0.2674481202	0.03102757441	5.417709284	0.08440075571		
Steel	0.115	0.00127			Temperature Change ~ K	115					
Perlite	0.018	0.03			Total Resistance	5.800585734					
N2	N/A	0.021082			Rate of heat gain ~ W	19.82558405					
C (Heat of Evaporation of N2 ~ J/kg)	199200				Heat Loss per Area ~ W/m^2						
	199200				Heat Absorbed per Hour (J/hr)	71372.10258					
Enthalpy of Sublimation CO2 (J/kg)	591000										
Heat Capacity of N2 Gas (kJ/kgK)	1.04				Cryogen Volume (m^3)	0.00239101862					
Heat Capacity of CO2 Gas (J/kgK)	849		Mass N2	1.922378973	Mass (kg) CO2	3.825629798	804 (N2)	1600 (CO2)			
			Heat of Evaporation N2	199200	Heat of Sublimation(J/kg)	591000					
			Evaporation Rate	0.3582936876	Sublimation Rate (kg/hr)	0.120764979					
			Duration N2	5.365372151	Duration of Cooling (hours) CO2	31.67830467					
					Temperature Increase Rate (Delta T) max = 20C from -80C to -60 C	21.97444217					

Showing Sheets spreadsheet used for calculations disregarding convection



					outer radius	N/A	0.121162	0.119892	0.089892	0.087352	0.06627
Material	Themal Conductivity (k) ~ W/mK	Thickness (l) ~ m			thermal resistance	0.2674481202	0.03102757441	5.417709284	0.08440075571		
Steel	0.115	0.00127			Temperature Change ~ K	115					
Perlite	0.018	0.03			Total Resistance	5.800585734					
N2	N/A	0.021082			Rate of heat gain ~ W	19.82558405					
C (Heat of Evaporation of N2 ~ J/kg)	199200				Heat Loss per Area ~ W/m^2						
	199200				Heat Absorbed per Hour (J/hr)	71372.10258					
Enthalpy of Sublimation CO2 (J/kg)	591000										
Heat Capacity of N2 Gas (kJ/kgK)	1.04				Cryogen Volume (m^3)	0.00239101862					
Heat Capacity of CO2 Gas (J/kgK)	849		Mass N2	1.922378973	Mass (kg) CO2	3.825629798	804 (N2)	1600 (CO2)			
			Heat of Evaporation N2	199200	Heat of Sublimation(J/kg)	591000					
			Evaporation Rate	0.3582936876	Sublimation Rate (kg/hr)	0.120764979					
			Duration N2	5.365372151	Duration of Cooling (hours) CO2	31.67830467					
					Temperature Increase Rate (Delta T) max = 20C from -80C to -60 C	21.97444217					

Showing Sheets spreadsheet used in calculating heat transfer with convection

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