Space-Weather Ice Sensor Package Project: Final Report

ME 450 Capstone Design

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ABSTRACT

The Space-Weather Ice Sensor Package (Space-WISP) project aims to design a packaging solution for an existing sensor suite and power system that will allow it to be securely deployed on the West Antarctic Ice Sheet, survive harsh weather conditions, and collect data for the study of ice sheet dynamics and space weather. The project follows the ME Capstone Design Process Framework, and the information sources come from human sources, government agencies, research institutes, and prior experiments and products (benchmarking). The project's desired outcome can be categorized into 3 categories: a physical “build design” of the magnetometer enclosure, analyses and validation with test plans, and parameterized design models.

PROJECT INTRODUCTION, BACKGROUND, & INFORMATION SOURCES

Project Introduction

The project’s primary sponsor is Professor Mark Moldwin of Climate and Space Sciences and Engineering and Applied Physics within the University of Michigan’s Climate and Space Sciences and Engineering within College of Engineering. The secondary sponsor is Mr. Lauro Ojeda, a Research Scientist and faculty member of Professor Moldwin’s Magnetometer Laboratory who specializes in Inertial Sensing and Sensor Data Fusion with a background in Electrical Engineering and Electronics.

Prior to this project, Professor Moldwin’s Magnetometer Laboratory designed a low-power geophysical sensor package and power system to study ice sheet dynamics and space weather as part of a National Science Foundation funded project.[1] The sensor package consists of two sensors: a dual-frequency GPS to track movement and a magnetometer to measure magnetic fields.[1] The power system consists of batteries, solar panels, and their corresponding charging equipment.[1]

Professor Moldwin’s Mag Lab would like to deploy their sensor package on ice sheets in the Arctic and Antarctica to study ice sheet dynamics and space weather. Specifically, the primary scientific goal of this research project is to observe magnetosphere-ionosphere space weather signatures. Secondary goals are to observe ice quakes, to observe ice motion, and to explore the ability to detect subsurface hydrology. The need for this project is a new packaging system design for the existing sensors, electronics, and power systems that can be easily deployed, reliably secured onto an ice sheet, and survive the weather conditions of the Arctic and Antarctic.[2]

Research Background

Space weather is the study of phenomena that impact systems and technologies in orbit and on Earth.[3] Events that occur on or near the Sun such as solar flares, geostorms, and coronal mass ejections can lead to devastating consequences on Earth.[4,5] Blocked radio communication, reduced accuracy of radio navigation systems, and electrical power failures are a few of these consequences.[4,5] The scientific mechanism behind this is that these events energize the Earth's magnetosphere, which in turn accelerates charged particles down into Earth's magnetic lines causing them to crash into the atmosphere and lithosphere, especially in high latitude regions such as the Arctic and Antarctica.[3]

Space weather research can be conducted using magnetometers, sensors that measure magnetic fields, but a critical step before scientists can use magnetometer data is the baseline correction of that data to remove background noise and interference. However, the baseline correction process is a traditionally time-consuming task with no standardized technique within the scientific community. Luckily, with the assistance of machine learning, a new low-cost magnetometer system has been developed that can perform this "real-time baseline correction of magnetometer data".[5] This new system combined with a low-power PNI RM3100 magnetometer will allow research groups such as Mag Lab to analyze and predict geomagnetically induced currents in near real-time and give researchers an opportunity to study space weather events in a time and cost efficient manner.

Previous Solutions

Previously, the Mag Lab tested the initial sensor and power package in Ann Arbor, Michigan and deployed a working prototype on an Antarctica ice sheet. However, the prototype in Antarctica did not have any attachment features. Instead, the team manually dug a hole in the ice sheet, placed their boxes into that hole, and buried the boxes with snow.[2] The issue with this previous solution was that it was difficult to install, troubleshoot, and uninstall the overall system due to the time and labor required to dig holes in the ice and bury the boxes.[2]

A previous solution from the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Polar Program deployed 35 of their 2-year, Modern Cold Rapid Deploy Seismic Stations during the 2014-2015 Antarctic season, detailed in their Polar Technology Conference 2014 and 2016 presentations.[6] Similar to Mag Lab's prototype run, PASSCAL Polar Group dug holes in the ice and placed their packaging system into the hole in the ice. Their seismic station's packaging design can be seen in Figure 1.[7]

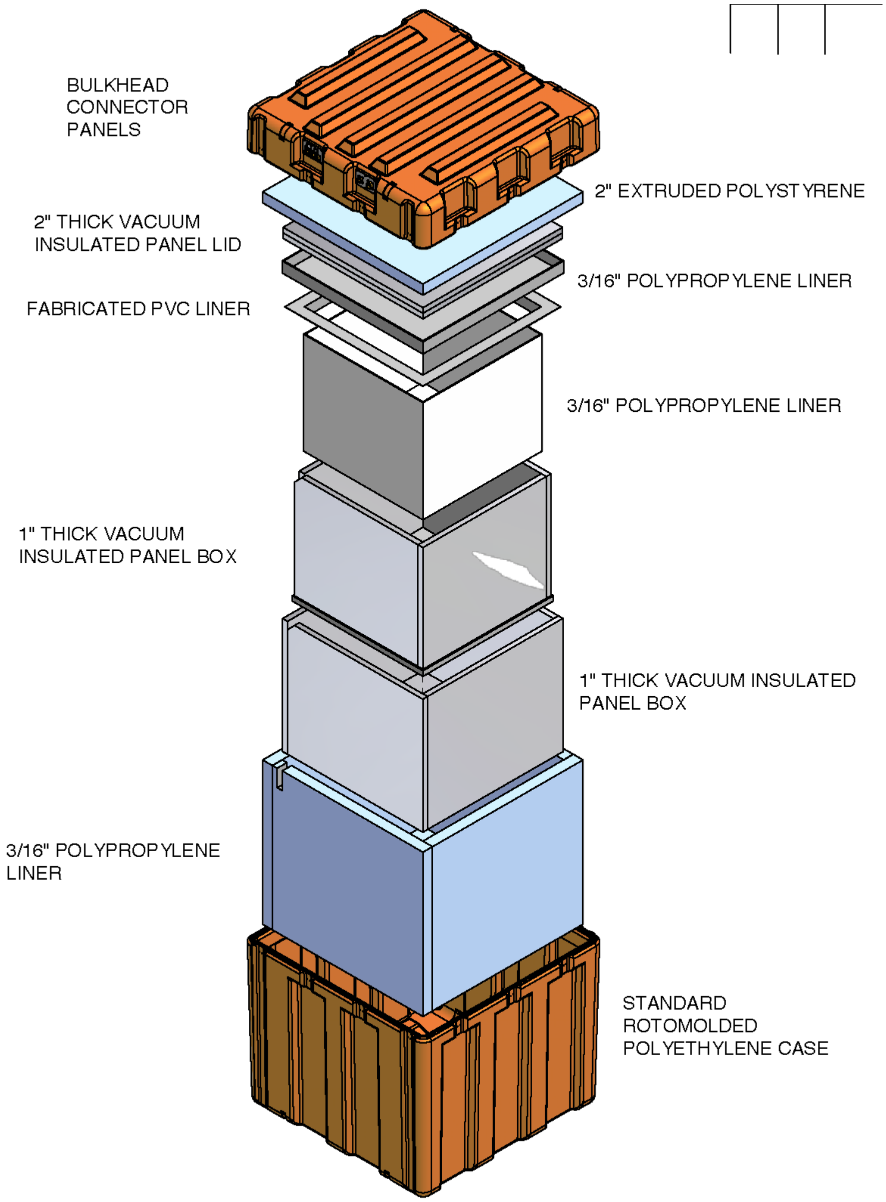


Figure 1: PASSCAL Large Station Enclosure

Our team intends to use this PASSCAL 2-year, Moderate Cold Rapid Deploy Seismic Station as a benchmark for our team's design. According to their publicly available documents, this station took under an hour for installation and approximately two hours for servicing and uninstallation.[6]

Our team is confident that our sponsors' design problem is unique. There are various electronic components that the sponsor has chosen for their sensor and power package, including microprocessors, battery charging equipment, and sensors. Mag Lab researchers have already written and verified software for the chosen hardware and verified hardware during preliminary testing. Therefore, we will need to design a packaging system that aligns with their sensor suite's specific needs, such as volume requirements, equipment operating temperature ranges, and battery pack modularity.[2]

Desired Outcomes

The primary goal of this project is to design a packaging solution for an existing sensor and power system that will allow the full system to be easily secured on an ice sheet, reliably collect data and transmit status updates, survive the environmental conditions of the Arctic and Antarctic, and allow for the ability to expand battery storage.[2] We consider a successful project outcome to be a completed design that we verified meets our high priority engineering specifications through the use of methods such as first principle models and simulations.

Information Sources

The success of this project is impacted largely by the collection of information and the sources from which we obtain that information. Our team has selected a problem-oriented design process for this semester, which is detailed in a later section, and therefore, it is critical that we understand as much of the problem, as well as related research, as possible. A list of sources we have already drawn from, or plan to draw from, is shown below in Table 1. However, it is important to note that this list is expected to grow as the semester progresses.

Table 1. Current Information Sources and Context

Information Source	Context
Professor Moldwin & Mr. Ojeda	Project Sponsors
New Jersey Institute of Technology	Heavy research experience in polar environments
NOAA	Monitors oceanic and atmospheric conditions with continuous research of polar regions
PASSCAL	Very similar experiment, dealt with same extreme environment for research
NASA	Monitors space weather, as well as the ice sheet conditions
NSF - Polar Programs	Familiar with deployment of experiments and regulations to do so

As shown in Table 1, our information comes from multiple types of sources, each very important. There are human sources, who will help us with their specific expertise and advise us based on past experiences. There are also many large repositories of information, especially from government agencies and research institutes. Finally, there are prior experiments and products, which we can use to help benchmark the project as the semester progresses.

Engineering Standards

As part of our project we wish to comply with voluntary engineering standards so that we can be confident that our design meets the requirements and specifications, to maintain safety, and so communication about suitable use for our packaging will be more clear. Although this project faces several unique challenges not commonly faced in a more regular operating environment, there are several standards applicable to it.

The first, and perhaps most pertinent, are standards for waterproofing. This is typically done using the IP scale, the British Standards Institution uses standardized tests that we can use to rank our packaging based on how permeable it is to water, ice, and snow[21]. This will allow us to say for certain that we have met our waterproof requirement, although we do not currently know what ranking we need to achieve. More research will be done to find this out.

Additionally our packaging will include, potentially several, large batteries. Although there are standards as developed by the International Air Transport Association, particular rules may differ depending on which carrier is actually transporting the batteries in question. There are, however, easily available safety protocols and suggestions posited by carriers such as UPS and others for the safe transportation of batteries. To maintain safety these protocols and suggestions would make for good guidelines to keep in mind when designing our packaging and include items such as properly labeling the battery, making sure the battery is kept separate from anything flammable, and making sure the battery will not short circuit due to loose pieces of metal[22].

Lastly our package, once installed, cannot cause harm to people or wildlife. Because of this we do not wish for our packaging to contain any sharp edges. The British Standards Institution has developed a test to classify how sharp a corner is based on the pressure it could provide when a certain amount of force is applied to it[23]. We do not know at present what score on this test we need to achieve. More research will be done to find this out.

DESIGN PROCESS

This semester we are following the ME Capstone Design Process Framework; however, we considered multiple other design processes before reaching the decision. Procedural approaches, both descriptive and prescriptive, were considered first, but they were not selected due to the fluidity of the project definition[14]. Therefore, solution-oriented, problem-oriented, and abstract approaches were considered.

After consideration of specific models, the team narrowed down the selection to a problem-oriented design process, including the ME Capstone Design Process Framework.[15] The team reached the consensus that a solution-oriented design process would be too limiting, especially as all members are new to the specific field related to designing and creating housings and attachments for sensor suites. Therefore, a problem-oriented design process best suits this project and the team. Specifically, we believe that following the ME Capstone Design Process Framework will help guide the team through a solution-agnostic approach. The Capstone Design Process allows us to gather as much information and insight about the problem as possible and allow us to make an informed initial design. Another advantage of the ME Capstone Design Process Framework is its iterative nature. The framework and its process flow are shown below in Figure 2.

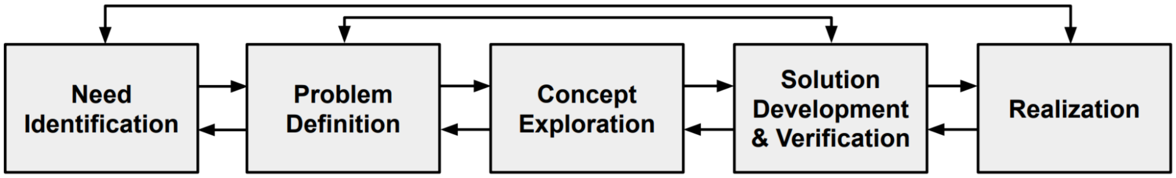


Figure 2: The ME Capstone Design Process Framework[15]. The process begins with Need Identification and after an iterative design lifecycle, ends with design Realization.

As shown by the arrows, this design process allows us to move back and forth between specific design stages. The process also creates room for more iterative design loops, such as going back to Problem Definition after Solution Development & Verification. This is vital for the Space-WISP project, as our preliminary testing will offer valuable and significant insight into the relevance and completeness of our problem statement. Finally, the ME Design Process Framework includes Need Identification and Realization stages. While these two stages are critical in the whole of the project, they might be slightly out-of-scope for ME450, especially Need Identification[15].

DESIGN CONTEXT

The stakeholders in this project are diverse and are affected to varying degrees. There are three main categories used to define the stakeholders: primary, secondary, and tertiary. Primary stakeholders are those whose lives or work are directly impacted by the problem and/or the development of the solution. Secondary stakeholders are those who are part of the problem context but may not experience the problem themselves and/or may not be directly impacted by the solution. Finally, tertiary stakeholders are those who are outside of the immediate problem context but may have the ability to influence the success or failure of a potential solution[16]. Each stakeholder has also been placed into six different role-based categories: Resource Providers, Supporters & Beneficiaries, Complementary Organizations and Allies, Beneficiaries and Customers, Opponents and Problem Makers, and Affected or Influential Bystanders[16]. Our project's stakeholder ecosystem is shown below in Figure 3 in an "onion"-style map.

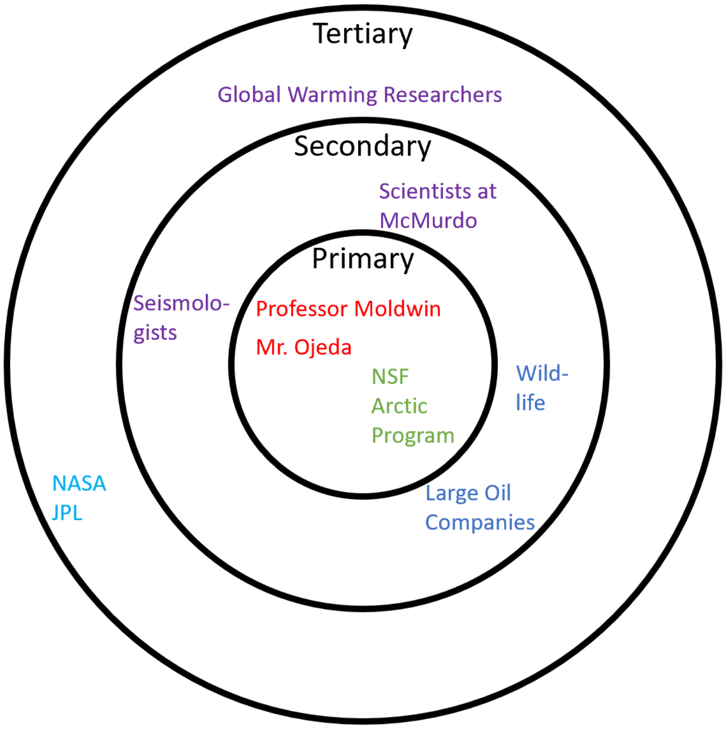


Figure 3: Stakeholder Ecosystem for the Space-WISP Project

Most stakeholders will be affected positively by this project, though first and foremost will be Professor Moldwin and Mr. Ojeda. This project directly impacts their lab, future funding, future research, and their reputation, and the project has the potential to be largely beneficial in all of these ways. The NSF Office of Polar Programs/Arctic Program and their respective scientists are also directly impacted, as they are funding this program. Assuming a successful project design and implementation, the work will reflect well on the office and help further their own research. In the long term, the research done by the sensor suite and the data collected about ice sheet melting will benefit all humans, but especially those in Island nations, for whom rising sea levels are a critical risk[17].

There are no identified stakeholders who will be negatively affected directly by the project. Initially, following deployment, there is a possibility of the sensor suite and assembly posing a risk to local wildlife, such as penguins. However, this risk will be mitigated, and it is a requirement of the system to be non-hazardous to wildlife. It is important to note that there is also potential for wildlife interaction to harm the system itself; however, we believe that the requirement for the system to be identifiable to wildlife also helps to mitigate this potential interference. Our team is also considering the impact of those affected indirectly by the manufacturing, especially with the batteries. For example, if the batteries are lithium ion, it is important for us to consider the impact of this. Lithium mines typically have a very harsh impact on the local ecosystem and environment[18], and this would be carefully considered in a Life Cycle Analysis (LCA) of the designed system. Finally, at the end of the system life cycle, there is potential for negative impact by the disposal of the materials, especially the batteries. It is important to follow procedures and standards, such as those listed above, to ensure no unnecessary and avoidable damage to other stakeholders occurs. We do not anticipate losing track of the electronics enclosure as it includes the GPS sensor. However, if other parts of the system get separated and lost, our sponsors do not plan on spending any time searching for the components. Our sponsors also do not plan on recovering the system in the extremely unlikely event that the battery enclosures end up lost in the ocean. It is also highly unlikely that the batteries would get separated from the electronics enclosure due to our chosen method of enclosure attachment, as discussed later in the Concept Selection section.

ENVIRONMENTAL SOCIAL CONTEXT

Beyond the sponsor, understanding the effects of global warming has an immense social and societal aspect, which is driving this work to be done. The two ice sheets in the world are melting at a record pace, now losing 250 billion tons of ice per year[19]. As a result, the average sea level rise is ~3.41 mm per year[19]. and this creates a direct threat to many low-lying/low-elevation island countries, especially in the Oceania region in the Pacific Ocean. A clear example of this is Tuvalu, located in Oceania. Tuvalu lies only 4.6m above sea level, and it is estimated that if the temperature on Earth rises by more than two degrees, Tuvalu will be completely submerged by the year 2100[20]. Island nations, like Tuvalu, and coastal cities around the world critically need more developed and accurate information on the effects of climate change on the polar ice sheets.

Within the context of this project, our team believes that the sponsors, Professor Moldwin and Mr. Ojeda, rank social impact just below other priorities, specifically furthering education and research. However, we do not expect the order of these priorities to affect our design or the positive or social impact of our project. Professor Moldwin and Mr. Ojeda have expressed openness to trading off price for higher quality. This could include sourcing products from more sustainable sources, so long as they are effective and the project still benefits research and education.

In the scope of ME450, intellectual property plays a very minimal role thus far, and we do not expect this to change. The team is not required to sign an IP agreement, and we do not anticipate any IP-based roadblocks in information and background gathering. There exists a potential for a patent for this project, though it is not likely nor necessary.

USER REQUIREMENTS & ENGINEERING SPECIFICATIONS

In order for our project to achieve success, it is vital to define well thought out needs based on our stakeholder's desires. A comprehensive overview of the requirements and specifications we found to be important during the information gathering process can be found in Table 2.

Table 2. List of requirements and their relevant specifications.

Priority	Stakeholder Requirements	Engineering Specifications
High	Survive harsh environmental conditions - Water-proof - Wind-proof - Temperature-proof	- Meets IPX5 waterproof standard[8] - Must be mechanically and structurally stable under prolonged 60 m/s wind speeds[9,10] - Electronics, sensors, and enclosures must not go below -40 ℃[24] - Batteries must not go below -20℃ - Wiring insulation must withstand -40 ℃[11]
High	Solar panels and antennae have a clear line of sight to the atmosphere	- Bottom of solar panels must have a clearance of 1 m from ice sheet surface at deployment[11]
High	No interference with sensors' data collection	- No ferromagnetic materials within 8 m of the magnetometer sensor.
High	Safe battery storage/operation	- If batteries have potential to offgas, they must be housed in an enclosure with a pressure relief valve.[2]
Medium	Can install safely with 2 person team	- One person shall not carry loads exceeding 51 lbs[27] - Must not require power tools for maintenance - Connectors must be only capable of interfacing with proper port - Must meet NSF Packing and Shipping Instructions Standards[12]
Medium	Non-hazardous and identifiable to wildlife and humans	- Must not contain features that have radii < X mm - System can be spotted from X m away
Low	Low cost	- Must cost less than $2k

Determining Requirements & Corresponding Engineering Specifications

The main way that we determined these criteria was through the process of interviewing our primary stakeholders: Professor Mark Moldwin and Mr. Ojeda. Professor Mark Moldwin and Mr. Ojeda have been in close contact with the NSF for years and were able to relay their relevant desires through our conversations. These criteria were refined through various research our team conducted independently on existing technology and standards. We also looked into other existing technologies and products as a way to gather insight on potential unforeseen requirements as well as what specifications have achieved success for requirements similar to our own.

Benchmarking

One of the most relevant products we have looked into so far has been the packages offered by Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL)[6]. This company essentially takes Pelican Cases and retrofits them with insulation and ports for their specific needs. They have developed successful methods with stakeholders very similar to our own such as The Department of Energy (DOE) and the NSF. Because they are using similar instrumentation and are being deployed in polar regions around the world like our own project is planning to do, we are currently in the process of reaching out to them. We are expecting them to have requirements very similar to our own such as water-proofing, wind-proofing, thermal considerations with electronics and power systems, and shipping standards.

Another technology which is relevant is the Antarctic Automatic Weather Stations (AntAWS)[9]. This was a type of weather station developed specifically for the Antarctic region by a group of scientists at Shandong Normal University in Jinan, China. Their devices are usually some form of metallic truss tower that is buried deep under the snow and acts as a base for all their sensors, solar panels, and power systems to attach to. Again by nature of their project, they will most likely have very similar requirements that need to be met just as our own so we are planning to reach out to them and do more research.

As with both companies they have pretty labor intensive installment processes that usually include excavating a significant amount of snow. The NSF has made it clear to our sponsors that they want to basically be able to take our device and just drop it without having to do much more work at all. This is really where most of the major difficulties of our project will live.

Prioritizing Requirements

We also wanted to prioritize our requirements to give us a better idea of the importance of each one to the success of our mission. We will now more clearly explain what each of the three priority levels mean. Starting with high priority, these items are all requirements that if not met would most certainly mean an unsuccessful mission. Moving to medium priority, these items are all things that our sponsors have made clear to us are very much desired but at the end of the day will not be deciding factors on the success of our project. Lastly are our low priority items which simply are nice to have but can technically be worked around in the future if need be.

Tackling High Priority Requirements

Some of the most vital requirements to our project are ones related to the extreme weather conditions found in the regions to be deployed. The coastal regions of Antarctica where this is being deployed can experience over 1,000 mm of snowfall despite the quite dry inner Antarctic regions[11]. This makes for keeping water sensitive components a very real challenge. Normally, it is as easy as using a standard o-ring but things might prove to be more difficult than that since the areas will be experiencing colds as low as -40 ℃ which, o-ring selection, could be catastrophic[11]. Our plan moving forward with this is making sure that we consult different gasket material selection papers and try to figure out what some of our benchmarking products use[13]. Along with these very low temperatures arise a couple other difficulties. The first being keeping the electronics and batteries within operating temperatures using passive thermal management and the second being to prevent insulation on any external electrical connections from cracking.

Another concern with potentially high amounts of precipitation are the antenna and solar panels being covered by this snow. One of the ways that we plan to deal with this is elevating it off of the ground which we have confirmed to be common practice among similar projects, namely PASSCAL and AntAWS.

We have also inherited some high priority tasks through conversation with Professor Mark Moldwin and Mr. Ojeda. They have explained that their current 12V marine car batteries have a possibility to offgas which can create problems with airtight enclosures and the surrounding electronics in the enclosure[2]. Mr. Ojeda has also informed us that the exact amount of energy capacity needed is going to be dynamic throughout the design process which means it is vital that we design with modularity in mind[2].

One last requirement we are becoming increasingly aware of the challenges it will bring along is having our system be easily installed and uninstalled. The reason for this is that it will most likely directly conflict with our windproof requirement. Having something secure in the extreme wind of the Antarctic region is not in itself a novel design task and has been achieved by both of our benchmarks however it usually involves labor intensive digging. We are yet to find anyone who has developed a method to quickly drop off the package but also withstand the extreme winds and we believe that this is where the real bulk of this project will live.

CONCEPT GENERATION

For concept generation, our team used a brainstorming method. We met in the library, in a space that had a lot of room to write on a whiteboard. We decided to use a functional decomposition approach while brainstorming to simplify and organize the brainstorming process, and to make sure each key function was focused on and had concepts generated. The functions we chose to break our project down into were the primary enclosure attachment method, solar panel and antenna attachment method, and the thermal management of the internals electronics, particularly those that are temperature sensitive. With these functions divided, we focused on one function at a time, brainstorming and writing down, drawing, and describing any and all concepts that came to mind. We tried our best to defer judgment during the brainstorming phase, as we did not want to limit what our solution space could potentially look like. Below are concepts we came up with for each function we identified.

Primary Enclosure Attachment Method

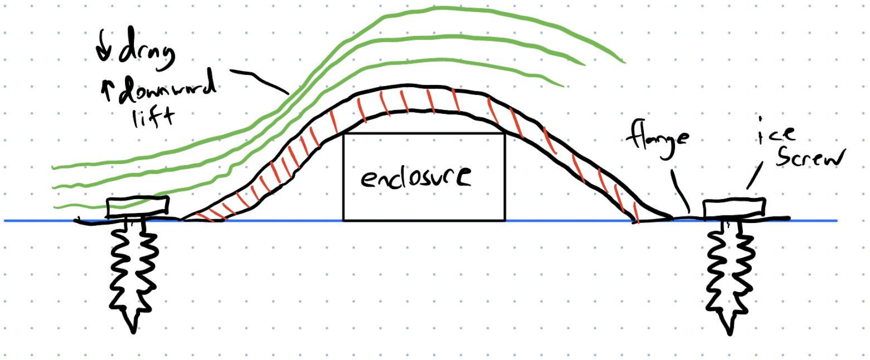


Figure 4: Surface Dome Enclosure Concept

Our first concept for enclosure attachment is for an aerodynamic dome to be placed above the packaging on the surface of the ice, as shown in Figure 4. This dome would reduce drag force, and potentially downwards lift. It would also help distribute drag force between anchor points.

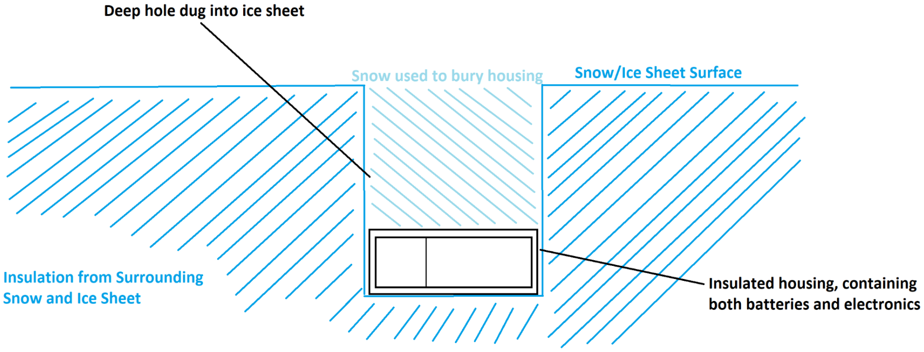


Figure 5: Fully Buried Enclosure Concept

Our second concept proposes fully burying the enclosure underneath the ice, as shown in Figure 5. This would afford complete protection from the wind, as well as take advantage of the natural insulation from the surrounding ice.

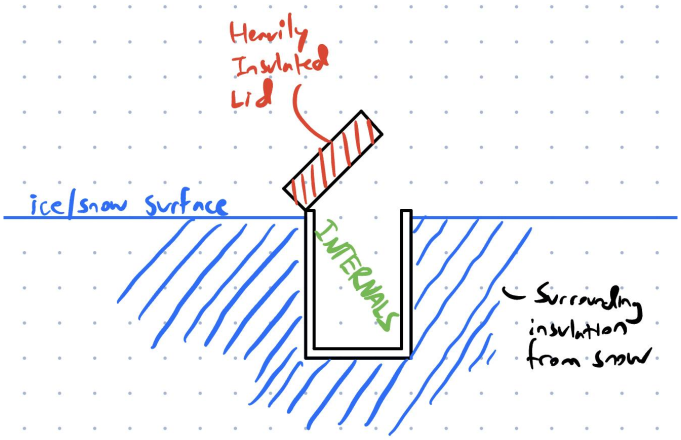


Figure 6: Partially Buried Enclosure Concept

Our third concept is a partially buried enclosure, as shown in Figure 6. The idea behind this design is to bury the enclosure such that the top of our enclosure is level with the surface of the ice at the time of installation, with a lid that can be opened from above to provide easy access to the internal equipment.

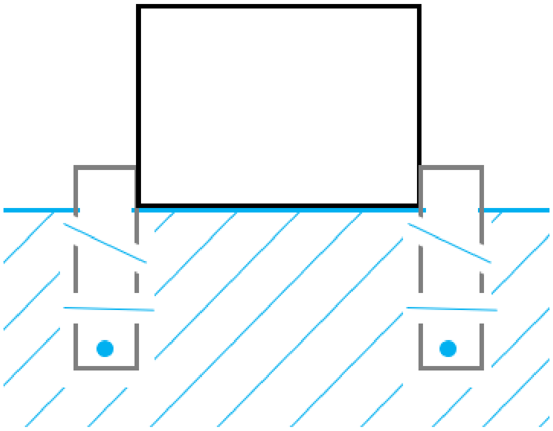


Figure 7: Four Legs Buried Concept

Our fourth concept gives our packaging four legs, each with a couple through holes bored into them, as shown in Figure 7. These legs would be buried while the packaging remains on the surface. Liquid water created from drilling into the ice, as well as any provided, would flow through the holes in the legs and freeze, freezing the structure into the ice sheet.

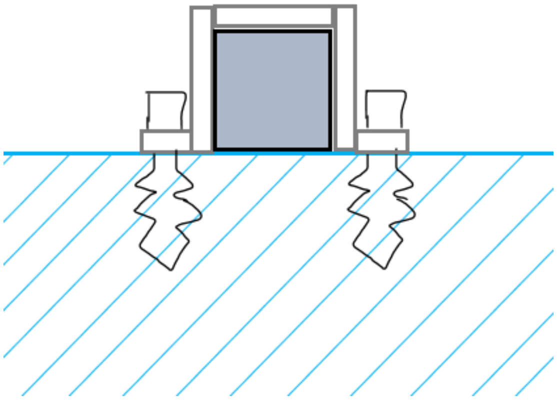


Figure 8: Surface Mounted Frame Concept

Our fifth concept utilizes a frame that fits over our package and uses multiple ice screws, which would be drilled into the ice to affix the structure to the ice sheet, as shown in Figure 8.

Solar Panel and Antenna Attachment Method

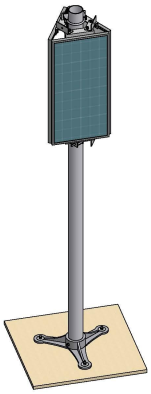


Figure 9: Pole on Base Plate Concept

Our first concept for solar panel and antennae attachment, as shown in Figure 9, has the solar panels and antenna attached to a pole with a base plate. The base plate would need to be buried a couple feet under compact snow in order to stay upright.

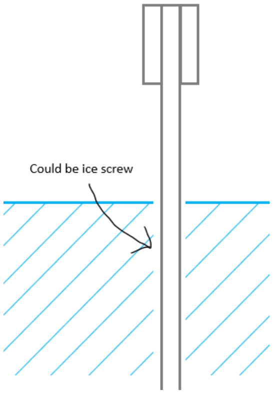


Figure 10: Pole Buried Concept

Our second concept, as shown in Figure 10, is for the solar panels and antenna to be attached to a very long pole with a large segment being buried deep into the ice. The piece of the pole buried could also be an ice screw for added security.

Figure 11: Weather Balloon Concept

Our third concept, as shown in Figure 11, involves attaching the solar panels and antenna to a weather balloon to have them float above, but relatively close to, the ground. This would afford greater tolerance to extreme wind speeds.

Figure 12: Pole Attached to Enclosure Concept

Like several of the previous ones, our fourth concept also has the solar panels and antenna attached to a pole. However it proposes that instead of being attached separately, the pole be attached directly to the package itself using clamps, as shown in Figure 12. This eliminates the need for a completely separate attachment method.

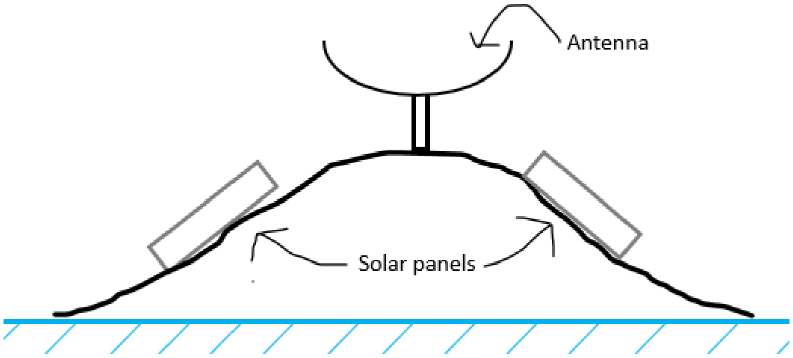


Figure 13: Surface Dome Concept

Our fifth concept, as shown in Figure 13, works with the surface dome attachment concept from earlier. It sees the solar panels attached to the side of the surface dome, and the antenna to the top.

Thermal Management

Figure 14: Dense Thermal Insulators Concept

Our first concept for thermal management would insulate the inside of our package using thick layers of a high density insulator, such as fiberglass, as shown in Figure 14.

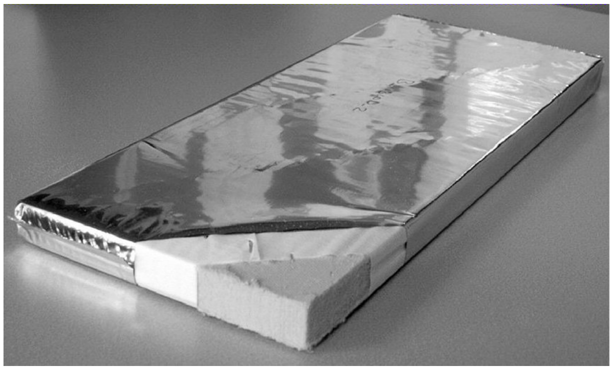


Figure 15: Vacuum Insulated Panels Concept

Our second concept is similar to the dense thermal insulators. It would utilize multiple layers of custom sized vacuum panels to insulate the interior of the package, as shown in Figure 15.

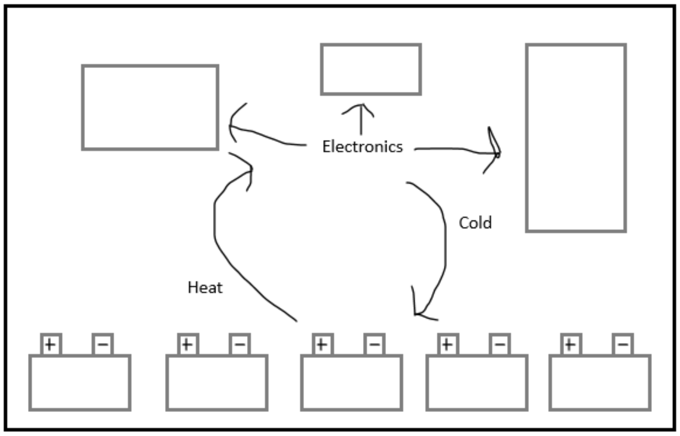
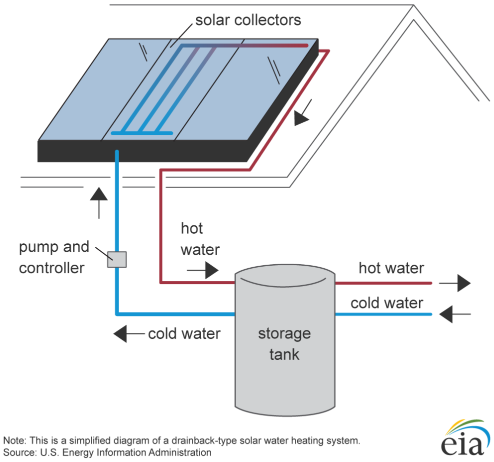


Figure 16: Passive Battery Heating Concept

Our third concept makes use of the waste heat generated by the batteries while powering the other electronics, as shown in Figure 16. By placing the batteries lowest in the package, the heat from batteries will rise and push the colder air near the other electronics downwards, creating a convection current and warming the electronics.

Figure 17: Internal Heater Concept

Our fourth concept makes use of an active heating element, such as a heater coil string throughout the package, to warm the electronics within, as shown in Figure 17.



Note: This is a simplified diagram of a drainback-type solar water heating system.
Source: U.S. Energy Information Administration

Figure 18: Solar Heating Concept

Our fifth concept involves a solar heat collector which could be used to heat the interior of the package using a heat exchanger, as shown in Figure 18.

CONCEPT SELECTION PROCESS

Following the brainstorming sessions and concept generation phase, our team moved onto concept selection for the project. Starting with more than 80 designs, we first broke them down into sub-function categories, namely: Enclosure Attachment, Solar Panel/Antennae Attachment, and Thermal Management. To initially narrow down the separate lists, each concept was compared to the corresponding sub-function requirements. If the concept clearly could not feasibly meet two or more of these requirements, it was removed from consideration. If the concept met all or all but one of the sub-function requirements, it was selected for further consideration. This process narrowed down our concept list significantly. For each sub-function, the remaining options were then compared to each other to check for excess similarity. Multiple concepts were found to be essentially the same in practice, just expressed differently. These similar concepts were merged into one. Following this process, each sub-function had five remaining concepts.

Weighting of Requirements

Before the remaining concepts could be compared quantitatively, our team used a hierarchical analysis matrix approach to obtain weights for our requirements, as shown in Figure 19. This matrix was created by ranking the system requirements' relative importance against one another.

	Withstand environmental conditions	Line of sight	Sensor Interference	Power Expansion and Battery Safety	Ease of Install / uninstall	Identifiable / Non-Hazardous	Low Cost	**Total**
Withstand environmental conditions	1	1.25	1.25	1.25	2	3	5	**14.75**
Line of sight	0.8	1	1	1.5	1.5	2	5	**12.8**
Sensor interferance	0.8	1	1	1.5	1.5	2	5	**12.8**
Power Expansion/Safety	0.8	0.63	0.5	1	1.6	2.25	5	**11.775**
Install/uninstall ease	0.5	0.5	0.67	0.625	1	1.5	3.33	**8.125**
Identifiable / Non-Hazardous	0.33	0.5	0.3	0.44	0.67	1	2.5	**5.74**
Low Cost	0.2	0.2	0.2	0.2	0.3	0.4	1	**2.5**

Figure 19: Hierarchical Analysis to Weigh Requirements

In this matrix, each requirement was given a comparative score to other requirements, signifying the relative weight and importance of each. The inverse was then inputted for the other requirement, i.e., if since "Withstand environmental conditions" were weighted at 1.25 against "Line of Sight", the inverse puts "Line of Sight" at 0.8 against "Withstand environmental conditions". The individual weights were then totaled horizontally to calculate the total weight for each requirement.

Enclosure Attachment

Our team first addressed the Enclosure Attachment sub-function category. The five final concepts considered were: A surface dome to attach the enclosure to the ice surface, fully burying the enclosure in the ice sheet, partially burying the enclosure so that the top of the housing is flush with the ice sheet's surface, four legs built into the enclosure that would be placed into four drilled holes in the ice, and placing the enclosure into a separate mount, already attached to the ice sheet surface. Drawings of these five concepts are shown in Figures 4-8. The concepts were then put into a Pugh chart, shown below in Figure 20.

Criteria	Weight	Surface Dome	Fully Buried	Partially Buried	4 Legs Buried	Surface Mounted Frame
Withstand environmental conditions	14.75	2	3	2	1	1
Install/uninstall ease	8.13	2	1	2	3	3
Identifiable / Non-Hazardous	5.74	2	3	3	1	1
Low Cost	2.50	1	3	3	3	2
Total	**31.12**	**59.7**	**77.1**	**70.5**	**52.4**	**49.9**

Figure 20: Pugh Chart for Enclosure Attachment

In the Pugh chart, each design concept was rated on a scale from 1-3 for each requirement. This score was then multiplied by the criteria weight, and the total score was calculated for all five design concepts. Looking at the Pugh chart, the rating is shown in each cell; however, this is compared to the other four concepts. The concepts chosen, while they each have their disadvantages, are the five best for this sub-function. They all meet, to differing extents, every sub-function requirement.

The surface dome concept's advantages come from its ease of installation, its non-hazardous nature, and its ability to withstand environmental conditions. A dome housing cover attached to the ice sheet's surface is quite novel for similar Antarctic experiments, and the dome shape would allow wind to pass over the housing without suggesting it to direct wind forces. The dome concept is also relatively easy to install, with only ice screws needed to secure it to the surface of the ice. Additionally, the round nature of the dome insulation helps make it safe to wildlife. However, it is still exposed to wildlife interaction, so it does not score as high as other concepts. The main disadvantage of the dome is the expected cost. The insulatory and durable material needed to make the dome is expected to come close to the cost limit of $2,000.

The fully buried concept advantages come from its ability to withstand environmental conditions, its non-hazardous nature, and its low cost. Burying the enclosure fully into the ice sheet protects it from almost all weather elements, including excess snow (and melting) and high winds. The burying method also makes it almost impossible for any animal to come into contact with and interfere with the enclosure, making it very safe for them and the enclosure. Finally, the burying method requires no additional equipment other than a shovel, so it is very low cost. The only disadvantage of the fully buried concept is its ease of installation. Installation would likely take 1-2 hours of digging; however, this is common for similar experiments and normal for polar scientists.

The partially buried method, with the top of the enclosure flush with the ice surface, is very similar to the fully buried concept in terms of advantages and disadvantages. There is a slightly lower advantage associated with the possibility of snow melt causing water to contact the top of the enclosure. However, the housing would still be protected from the harsh Antarctic winds. Again, being buried, the enclosure poses a very minimal risk to wildlife. The low cost advantage is the same as the fully buried concept. The ease of installation though is slightly better than the fully buried method, since it would not require as much digging; an estimated > 30 minutes of digging is all that is required for installation.

The 4-legs-buried method's advantages come from the concept's ease of installation and low cost. To install the enclosure with four legs rigidly attached to it only requires four simple holes to be drilled into the ice. The enclosure then would be placed so that the legs slide into these drilled holes. The total installation time is expected to be five minutes or less. Additionally, the addition of these four legs to the enclosure itself would be very inexpensive, and only a power drill is required for attachment onto the ice surface. The disadvantages of the 4-legs-buried method comes from the concept's ability to withstand environmental factors and its non-hazardous nature. The attachment to the surface of the ice sheet subjects the enclosure to the ice sheet's extreme wind and snow conditions. However, the enclosure would still be waterproof, and the legs would provide stability in high winds.

The surface-mounted frame concept's advantages come from its ease of installation and relative low cost. The frame would be attached to the surface of the ice sheet using L-brackets and ice screws. The enclosure itself would then be placed inside of this frame. The frame itself is also expected to not come near the cost limit; however, it is a more expensive option than some of the other concepts. The disadvantages of the surface-mounted frame come from its ability to withstand environmental conditions and its non-hazardous nature. Similarly to the 4-legs-buried concept, the attachment to the surface of the ice sheet subjects the enclosure to the ice sheet's extreme wind and snow conditions. However, the enclosure would still be waterproof, and the surface-mounted frame would provide stability in high winds.

The final scores of the Pugh, as well as the specific advantages and disadvantages of each concept, were compared, and the fully buried concept was selected for our design.

Solar Panel/Antennae Attachment

Our team then addressed the Solar Panel/Antennae attachment sub-function category. The five final concepts considered were: A pole mounted to a buried base plate, a long pole buried into the deep into the ice, a pole mounted directly to the (buried) enclosure, a weather balloon tethered to the ground with the antennas and solar panels attached to it, and attachment directly to the outside of a dome enclosure. Drawings of these five concepts are shown in Figures 9-13. The concepts were then put into a Pugh chart, shown below in Figure 21.

Criteria	Weight	Pole on base plate	Pole buried	Pole attached to enclosure	Weather balloon	Surface dome
Withstand environmental conditions	14.75	3	2	3	1	2
Line of sight	12.80	3	3	3	3	1
Sensor interference	12.80	3	3	1	3	2
Power Expansion/Safety	11.78	3	2	1	1	1
Install/uninstall ease	8.13	3	2	3	1	3
Identifiable / Non-Hazardous	5.74	3	3	3	1	2
Low Cost	2.50	3	3	3	1	2
Total	**68.49**	**205.5**	**170.8**	**156.3**	**119.7**	**120.5**

Figure 21: Pugh Chart for Solar Panel and Antennae Attachment

In the Pugh chart, each design concept was rated on a scale from 1-3 for each requirement. This score was then multiplied by the criteria weight, and the total score was calculated for all five design concepts. Looking at the Pugh chart, the rating is shown in each cell; however, this is compared to the other four concepts. The concepts chosen, while they each have their disadvantages, are the five best for this sub-function. They all meet, to differing extents, every sub-function requirement.

The buried base-plate mounted pole concept has advantages compared to other concepts in every requirement category. The base plate adds more surface area to provide reaction forces when the pole and its attachments are subjected to wind forces from the environment. The pole also provides a clear line of sight for the antennae to the sky and provides ample clearance from snow build up for the solar panels. The base plate concept does not require the pole to be close to the enclosure/housing, so there is very little potential for sensor interference. The base-plate mounted pole concept is agnostic to the power expansion and can easily and safely support it. The concept would be easy to install, with only a bit of digging into the sheet required to bury the base plate, which can be connected to the pole prior to going out to deploy the system. The pole is also very identifiable and will be round, ensuring there are no sharp edges. Finally, the pole itself is expected to be well under the $2,000 budget.

The long pole buried directly into the ground concept has advantages in regards to its line of sight, lack of sensor interference, non-hazardous and identifiable nature, and its low cost. Similar to the buried base-plate mounted pole concept, the long pole buried directly into the ground concept provides a clear line of sight for the antenna to the sky and provides ample clearance from the snow build up for the solar panels. The concept does not require the pole to be close to the enclosure, so there is also very little to no potential for sensor interference. The pole is also very identifiable and will be round, ensuring there are no sharp edges. The pole, similar to the previous concept, is expected to be well within the budget. This concept will handle the harsh weather environment well, especially snow build up. However, there is less surface area to react against strong moments caused by strong winds than the base-plate concept has. Finally, the deep hole required to support such a long pole could potentially be difficult to drill, though the installation after drilling is very simple and straightforward.

The pole mounted directly to the enclosure/housing concept's advantages come from its ability to withstand environmental conditions, its clear line of sight, its ease of installation, its identifiable and non-hazardous nature, and its low cost. Similarly to the buried base-plate mounted pole concept, the pole mounted to the enclosure has much larger area to support it against high winds. The pole also provides a clear line of sight for the antennae to the sky and provides ample clearance from snow build up for the solar panels. The pole could easily be mounted to the enclosure using C-clamps, and, assuming a buried enclosure, no additional digging or set up is required for installation. Again, the pole is also very identifiable and will be round, ensuring there are no sharp edges. Finally, the pole will be well under the set budget. The disadvantage of this concept comes from the potential for sensor interference and potential difficulties with power expansion.

The weather balloon tethered to the ground with the antennas and solar panels attached to it (weather balloon) concept's advantages come from the line of sight it provides and its lack of sensor interference. Being removed from the ground and free from snow build up, the weather balloon concept provides a very clear line of sight. Additionally, the distance between the enclosure and the balloon itself will be sufficient enough as to ensure no sensor interference occurs. The weather balloon's disadvantages are from its ability to withstand the environmental conditions, its ability to support power expansion, its ease of installation, and its cost.

The attachment directly to the outside of a dome enclosure (dome) concept's advantages mainly comes from its ease of installation, its low cost, as well as its ability to withstand environmental conditions. The concept assumes a surface-level dome enclosure attachment for the main housing, which would allow for easy access and direct installation onto the side of the dome. This concept does not require modifications to the dome, so the cost would be moderate and within budget. Additionally, the angle of the dome and its secured attachment to the ground would help protect the antennas and solar panels from the wind. The disadvantages of the dome concept come from the line of sight it provides, its ability to support power expansion, and potentially its non-hazardous nature. The dome is directly mounted to the ice sheet surface, so attaching the solar panels there creates an issue with their line of sight. It is very possible that it will snow enough to block the solar panels from the sun. The dome concept allows for more solar panels to be attached; however, the size of the dome limits the potential for expansion. Finally, there is potential for wildlife interaction if the solar panels and antennae are attached to the dome, which is close to the ground.

The final scores of the Pugh, as well as the specific advantages and disadvantages of each concept, were compared, and the buried base-plate mounted pole concept was selected for our design.

Thermal Management

Our team then addressed the Thermal Management sub-function category. The five final concepts considered were: dense thermal insulators, vacuum insulated panels, passive battery heating, active heating via an internal heater, and a heat sink harnessing and converting solar energy. Drawings of these five concepts are shown in Figures 14-18. The concepts were then put into a Pugh chart, shown below in Figure 22.

Criteria	Weight	Dense thermal insulators	Vacuum insulated panels	Passive battery heating	Internal heater	Solar heating
Withstand environmental conditions	14.75	2	3	2	3	1
Sensor interference	12.80	3	3	2	1	3
Power Expansion/Safety	11.78	3	3	2	1	1
Install/uninstall ease	8.13	3	3	3	1	1
Low Cost	2.50	3	2	3	1	1
Total	**49.95**	**135.1**	**147.4**	**110.5**	**79.5**	**75.6**

Figure 22: Pugh Chart for Thermal Management

In the Pugh chart, each design concept was rated on a scale from 1-3 for each requirement. This score was then multiplied by the criteria weight, and the total score was calculated for all five design concepts. Looking at the Pugh chart, the rating is shown in each cell; however, this is compared to the other four concepts. The concepts chosen, while they each have their disadvantages, are the five best for this sub-function. They all meet, to differing extents, every sub-function requirement.

The dense thermal insulators concept's advantages come from every applicable sub-function requirement, except its ability to withstand environmental conditions. Dense thermal insulators will not interfere with any sensor within the enclosure, they are very easily installed before deployment, and they are agnostic to and safely support power expansion. Additionally, dense thermal insulators are relatively inexpensive, and the concept is well within the project budget. The only slight disadvantage of the dense thermal insulator concept is its ability to withstand environmental conditions. Though the material is quite good at providing thermal insulation, it is not as effective as some of the other final concepts.

The vacuum insulated panels concept's advantages come from every applicable sub-function requirement except cost. Vacuum panels are very effective at withstanding environmental conditions in the Antarctic due to its high thermal efficiency. Additionally, vacuum panels will not interfere with the enclosure, they are easily installed before deployment, they will not cause any sensor interference, they are quite safe and unaffected by power expansion. The only disadvantage of vacuum panels comes from their cost; however, they will likely still fit within our budget.

The passive batteries' clear advantages come from the management strategy's ease of installation and low cost. This design does not require any additional materials or installation into the enclosure housing, rather this method takes advantage of the heat output from the enclosed batteries. Through free convection, the batteries passively supply heat to the internal electronics. There are no true disadvantages to the passive battery thermal management strategy; however, the system is not as effective as the other options. Additionally, depending on the battery type selected, there is potential for sensor interference, though our team will work to minimize battery interference. Finally, this method is directly dependent on and affected by a potential power expansion, though not necessarily in a negative way.

The internal heater concept's advantage comes from the management strategy's excellent ability to withstand environmental conditions due to high thermal efficiency. The concept, however, has no other clear advantages. The internal heater's disadvantages come from all other sub-function requirements. Placing an active heater inside of the enclosure poses a very big risk of sensor interference, depending on heater type. Additionally, the heater will require additional components and have a significant power draw, which is a significant and expensive drawback.

The solar heating concept's advantage comes from its lack of sensor interference. The design places a simple heat sink(s), powered by solar panels, inside of the enclosure. However, this thermal management strategy is complex, expensive, and quite inefficient in terms of thermal output.

The final scores of the Pugh, as well as the specific advantages and disadvantages of each concept, were compared, and our team elected to go with a compound system, consisting of vacuum panels, dense thermal insulators, and passive battery heating. These three concepts work well together and will help ensure the best thermal management for the enclosure. If, through our engineering analyses, the team discovers that not all three are needed to meet the engineering specifications, we will cut one or two in order to save cost.

Future Concept Selections and Analyses

The team plans on conducting more concept selection analyses, namely on: a battery system, the placement of the magnetometer, cable insulation, and connector choice. The battery system and magnetometer placement analyses will be completed in the very near future; however, more collaboration with graduate members of the Mag-Lab and the project's sponsors will be needed for this. The analyses on cable insulation and connectors will follow, as they are dependent on the two prior analyses.

ENGINEERING ANALYSIS

Power Draw and Battery Options

The first area we examined for our analysis was the power draw of the entire system, primarily consisting of the solar panel charge controller, DC converter, Arduino, and sensors. Using a 12V DC power supply and multimeter, the MagLab team measured the continuous voltage and current draw of the package without the GPS and a conservative estimate of power consumption of the GPS by the MagLab researchers, we found our system will have a continuous power draw of 5W. At our design temperature for the batteries of 20℃, the batteries' actual capacity will be 50% of the rated capacity. Additionally, we factored in a 90% efficiency for the DC converter and a 1.2 safety factor. For 3 months of complete darkness in an Antarctic winter, we calculated that our battery system would need to be 28.8 kWh. However, this number will likely increase as we develop our analysis on solar panel energy generation. There will likely be several months of the year where there is partial sunlight and darkness, requiring energy consumption to come from the battery system.

As our sponsors have communicated to us that there is a wide range of intended usage cases for this system, we plan on providing the resources for them to use two different types of batteries: a secondary (rechargeable) Lead-Acid AGM battery and a primary (non-rechargeable) Lithium Thionyl Chloride battery, as shown in Figure 23 below.

Figure 23: Lead Acid AGM (left) and Lithium Thionyl Chloride Cell (right) Batteries

Table 3 shows the comparison between the Lead Acid AGM and Lithium Thionyl Chloride batteries.

Table 3. Comparison of Lead Acid AGM and Lithium Thionyl Chloride Battery Options

Battery Type	Model	Price ($)	Rated Capacity (Wh)	Weight (lb)	Mass Energy Density (Wh/lb)	Volumetric Energy Density (Wh/in^3)	Price per capacity ($/Wh)	Enclosures required for 3 months
Secondary Lead Acid AGM	Solar Xtender PVX-1040T	423	1248	68	19.8	1.8	0.34	~24
Primary Lithium Thionyl Chloride	SAFT LS33600 D Size (40x)	930	2448	8	306	14.9	0.38	~1

One of the Lithium Thionyl Chloride battery packs, as described above in Table 3, consists of 40 of the SAFT LS33600 D Size cells.

As shown in Table 3, the primary Lithium Thionyl Chloride (LTC) batteries have a gravimetric energy density ~15 times that of the secondary Lead Acid AGM batteries and a volumetric energy density ~8 times that of the secondary Lead Acid AGM batteries. These factors lean heavily in favor of the primary LTC battery system as they dramatically decrease the number of required enclosures for the battery system. Due to the Lead Acid batteries weight of 68 pounds each, we recommend no more than 1 Lead Acid AGM battery per enclosure. Therefore, for the 3 month example shown above in the power draw analysis, the Lead Acid battery system would require 24 enclosures while the LTC battery system would only require 1 enclosure.

Regarding cost, as seen in Table 3, the main similarity between the two battery types is the price per Watt-hour of rated capacity. However, it is important to note that with the increased number of enclosures required and accompanying components such as insulation and connectors, the cost of the Lead Acid battery system will be significantly greater. Finally, due to the significantly higher volume and mass of the Lead Acid battery system, shipping costs will be greater as well.

Our sponsors initially intended to use non-lithium batteries due to the concern of required paperwork to ship lithium batteries. However, they have reconsidered based on the provided information and are open to using both Lead Acid and Lithium Thionyl Chloride batteries in the future.

Strength & Stability

One of our major design challenges is ensuring that the solar panel and antenna structure is able to perform properly under the extreme weather conditions. Based on research conducted for the regions this system will be deployed, we are expecting wind gusts up to 60 m/s or about 135 mph. This will cause significant loading on the structure and could result in 3 different modes of failure. The first, and most concerning, is a stability failure. This failure would involve the structure tipping over due to drag force on the structure. If this happened, the solar panels would no longer have proper irradiative exposure and be unable to supply necessary power requirements to keep the system running. It would also obscure the required clear line of sight to the atmosphere for the antennae to successfully communicate data. The second mode of failure would be if any actual material in the structure were to yield. Again this could lead to the solar panels and/or antennae being obstructed and cause the critical issues that come along with that laid out above. The last mode of failure we are concerned with is fatigue failure. This is a resulting failure that happens when cyclic loading is present despite being at amplitudes lower than the yield strength of a material. Below we will go into more detail on these three failure modes and our analysis that has been done thus far as well as our analysis moving forward.

Stability Analysis. The first steps we took in the stability analysis was to develop a simple free body diagram representative of our structure and the loads applied to it.

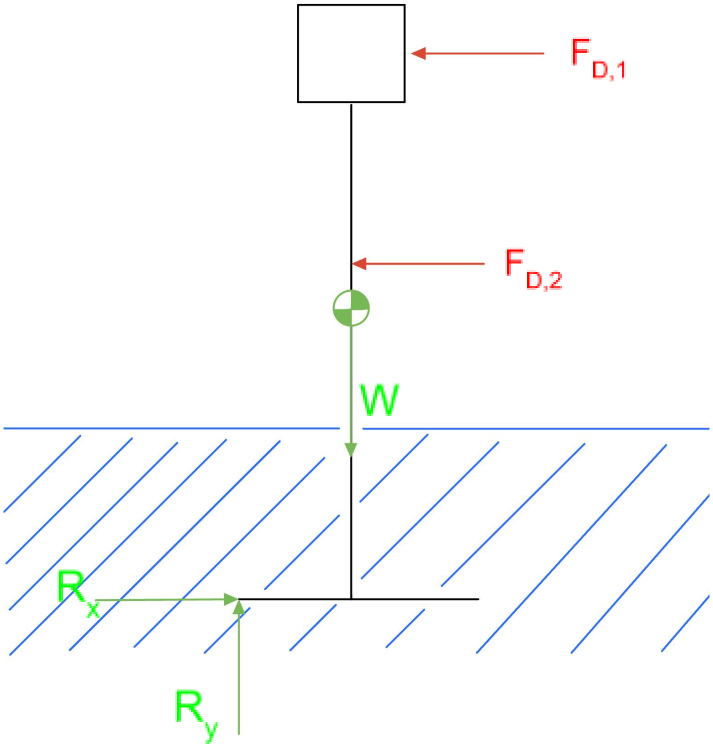


Figure 24: Free body diagram of solar panel and antenna structure.

It is noteworthy to point out some of the assumptions in this model. There are two forces $F_{D,1}$ and $F_{D,2}$ which represent the resulting drag on the solar panels and cylindrical pole respectively. In reality these forces will be distributed linearly along the vertical axis but for the purposes of our analysis have been compressed into a single force each resulting at their respective geometries centroid. We have also compressed the reaction forces supplied by the snow to a single point located on the edge of the baseplate. In reality the snow will supply reaction forces that are distributed along the pole as well as surfaces of the baseplate. Modeling this however would be extremely complicated and time consuming due to the dynamic nature of snow and its non-newtonian characteristics.

For each of the drag forces they can be calculated using Eq. 1 below.

$$F_D = \frac{1}{2}\rho v^2 C_D A_C \tag{1}$$

The air density values, ρ, comes from data recorded in the relevant regions, the air velocity, v, comes from the maximum 60 m/s gusts to be expected, the drag coefficients, C_D, comes from the geometry of the solar panels being a plate and the pole being a vertical cylinder, and the cross sectional area, A_C, also comes from the geometry of the pole and solar panels.

For the weight of the system it is a function of the geometry of the baseplate and structural pole as well as their material, the weight of the solar panels, the weight of the antenna, and the depth and density of the snow.

The reaction forces can be neglected since in our analysis we calculate our moments about that point. Doing this results in the Eq. 2 below.

$$Wx = F_{D1}(depth + 1 + solar\,panel\,height/2) + F_{D2}(depth + 0.5) \tag{2}$$

x is the moment arm for the restoring torque of the weight which is half of the footprint of the baseplate. While the moment arm for the drag forces are due to the depth at which it is buried, the height of the pole, and the height of the solar panels.

Using all of these determinant parameters we were able to create a more dynamic analysis by solving for the maximum allowable wind speed in a spreadsheet. It allows all parameters to be individually adjusted and calculates the new wind speed value.

Our team found the most sensitive parameter to be the footprint length of the baseplate which also happens to be an easy parameter to design and manufacture around which is why that will be our focus for meeting the stability requirement.

Our results indicate with our current knowledge of the parameters that burying the structure 1 m under the snow with a 1.5 m diameter baseplate can successfully handle 61 m/s winds before tipping over.

This analysis will also serve as part of the deliverable to our sponsors to aid them in future work and visual detail on how it works can be seen in the Appendix in Figure 19.

Material Yield. On top of a failure in the stability of the entire system we want to also ensure that there will be no material yield in the pole. The pole will experience a bending moment that will result in tensile and compressive stress along the axis of the pole. This can be calculated using Eq. 3 below.

$$\sigma_z = \frac{M(z)_x y}{I_x} \qquad (3)$$

Where M_x is the maximum moment felt along the pole, y is the maximum distance from the neutral stress axis, and I_x is the second moment of area of the cross section.

The maximum moment will be located at the bottom where it connects to the baseplate. This was calculated by modeling the entire pole as a cantilever beam as shown below in Figure 25.

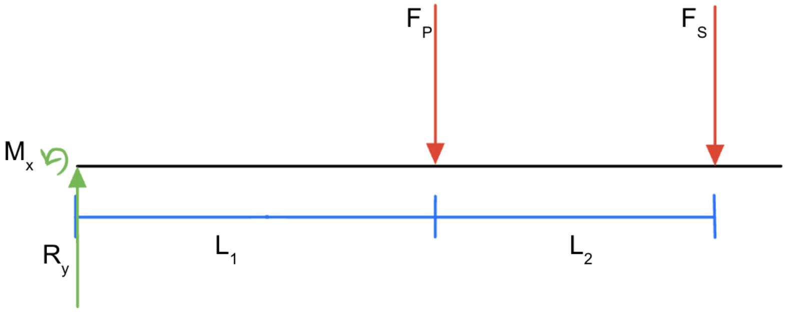


Figure 25. Cantilever beam model for yield analysis.

If we calculate our moments about the left end, we find the result to be Eq. 4. shown below.

$$M_x = F_p \times L_1 + F_S \times (L_1 + L_2) \qquad (4)$$

Where M_x is the maximum moment in the pole, F_p is the resulting drag force on the pole, L_1 is the resulting location at which the pole drag force is applied, F_s is the resulting drag force on the solar panels, and L_1+L_2 is the resulting distance at which the solar panel drag force is applied.

Using the numbers for our current design we find the value of the maximum moment to be 1359 N-m.

Now we need to find the second moment of area. For the tubular cross section that we are using with our pole it is calculated below in Eq. 5.

$$I_x = \frac{\pi}{4}\left(R_o^{\ 4} - R_i^{\ 4}\right) \tag{5}$$

Where R_o and R_i are the outer and inner radius of our pole respectively. For the pole we are selecting to use we found the second moment of area to be 1.256×10^{-6} m^4. Lastly the location furthest from the neutral stress axis, y, will just be the outer radius of our selected pole with a value of 0.0445 m.

Now that we have all the values to calculate the maximum stress we can plug these back into Eq. 3 to find a maximum expected stress of 48 MPa. Our pole is made of 6061 Aluminum which has a yield strength of 241 Mpa yielding a safety factor of 5.

Thermal Management

The third area of analysis that is critical to the success of our design is thermal analysis, which will ensure that all components are within their operating temperatures. Since our system is already very limited on the amount of power available for consumption, active heating will not be an option for our thermal management. Our team elected to look mainly at insulation for our enclosures as a means of thermal management. This is due to its affordability and proven success in similar arctic conditions. For our analysis, we started by working backwards, first determining our desired steady state conditions, which are derived from operating temperatures. From there, our team worked to calculate the thermal resistance required and select our insulating materials based on these derived values. The two materials our team primarily considered for internal insulation were vacuum panels and high density insulators, such as foam board.

To begin our analysis and to analyze the system, our team elected to develop a first principles analysis, focusing specifically on the enclosure system. Since our final design has the batteries in a separate enclosure, to add modularity and flexibility with mission deployment timelines, our team initially focused on only the thermal analysis of the sensor suite enclosure.

To perform this analysis our team used the composite wall resistance method, where the resistances of the enclosure shell, the vacuum panels, and the dense thermal insulator are added together in a resistance circuit. Assuming that the temperature of the ice sheet touching the outer shell of the enclosure is constant, we were able to apply a simple composite wall convection calculation, as shown below in Eq. 6.

$$\Sigma R = \frac{L_{wall}}{(K_{wall}A_{wall})} + X[(\frac{k_{rout}A_{rout}}{L_{rout}}) + 2(\frac{k_{vac}A_{vac}}{L_{vac}})]^{-1} \tag{6}$$

Where:
X = number of insulation walls installed
k_{wall} = coefficient of thermal resistance for the housing wall
k_{rout} = coefficient of thermal resistance for the dense thermal insulation layer
k_{vac} = coefficient of thermal resistance for the vacuum panel

Here there are two vacuum panels per layer, and they combine with the routing insulation in parallel and are added to the resistance of the wall. This insulation set-up and design is shown below in Figure 26.

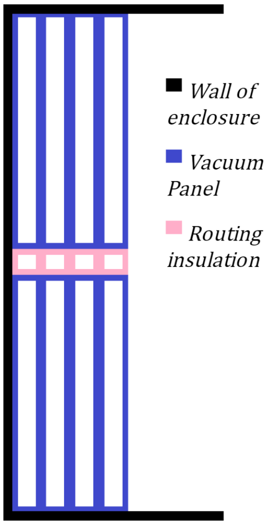


Figure 26: Thermal Insulation Diagram

Using the above found resistance and Eq. 7, as shown below, we found the heat transfer rate at an instant in time.

$$Q_{dot} = \frac{T_{int} - T_{\infty}}{\Sigma R} \tag{7}$$

After discussing with Professor Boehman, a heat transfer professor in the mechanical department, the team decided that the best method to proceed with the analysis was to do a time-step procedure.

To do the time step-produce, we first calculated the initial thermal energy inside of our sensor suite enclosure. Then, using the already found heat transfer rate, we multiplied it by our “decided time-step” of a week to determine how many Joules were lost during the time step. Using the difference of the initial internal thermal energy level and the amount of energy lost, the new internal energy was calculated. Using this value, the new internal temperature was found.

However, through this process, we discovered that, without active heating, the amount of thermal insulation needed to regulate the temperature drop is geometrically unreasonable. Specifically, if we assumed an initial internal enclosure temperature of 0℃, an ambient ice temperature of -20℃, and 10 layers of the thermal insulation wall design on either side of the enclosure, the temperature of the interior would be expected to reach steady state in just over an hour. The amount of insulation needed without active heating is extremely impractical and near impossible for our purposes. Though after initial concern, our team discovered that this is not the worst case.

After reviewing literature on the insulative properties that the ice sheet would display with our buried enclosure, our team found that according to a University of Chicago[26] study of temperature gradients in ice sheets, the temperature around three to four meters deep into the sheet begins to be agnostic to the surface temperature and conditions. This is an important discovery because that is well within the accepted range of operating temperatures for our sensor suite’s electronics. Data from this experiment and study is shown below in Figure 27. However, more research into literature needs to be done, and our sponsor has informed the team that he has more information on temperature gradients within the ice sheet.

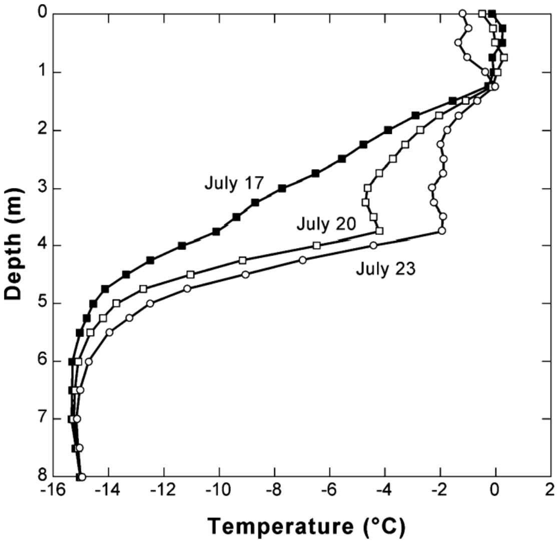


Figure 27: Temperature vs. Depth in Ice Sheet

Because of the information gathered from the University of Chicago[26] study, we have begun to focus more on our waterproofing method for the sensor enclosure, rather than the thermal insulation. A large part of this, and a major design change that the team is making is to not insulate the sensor suite enclosure beyond the shell itself. This is because the temperature range for the electronics goes down to -40℃, and based on the literature, the ambient ice temperature will not reach that point if it is buried sufficiently deep. However, the insulation is still important, especially for our battery enclosure or enclosures. This is because the battery will almost certainly lose efficiency at lower temperatures. So looking forward, the focus on the thermal analyses will continue to be on the battery enclosures, rather than the sensor suite enclosure, and this analysis is linked closely to which battery is selected. The steady state temperature will be found by using the method as described above and Eq. 7. However, now there will also be an added heat generation component. The added heat generation will contribute to the system's heat transfer as a convective component. The team will determine the value of the convective component by the internal resistance of the battery and the current that flows through it. We have reached out to the battery manufacturer for this number, and the analysis will be completed once more information is gathered.

Given that we have enough time, our team also hopes and plans to test a smaller prototype of the battery enclosure to measure and find the steady state temperature during operation.

BUILD DESIGN DESCRIPTION

Our team's build design is a subset of the final design and includes the magnetometer sensor packaging system. This design includes an off-the-shelf IP67 rated enclosure that is completely made of plastic and a cable penetrator to route the cables from the magnetometer to outside of the enclosure. Figure 28 below shows the Mayouko waterproof package and Figure 29 shows the penetrators that our team has elected to use.

Figure 28: Enclosure for Magnetometer Sensor

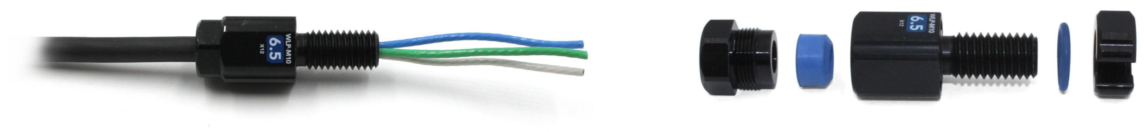


Figure 29: BlueRobotics WetLink Cable Penetrator

To install the penetrator onto the magnetometer enclosure, we will first drill a clearance hole for the thread specification being used. A normal fit class hole will suffice as tight tolerances are not required for proper penetrator performance. From there we will fit our wire through the penetrator and create a seal between the wire and bolt using the plug mechanism seen in Figure 28. Lastly, we will put the assembly through the clearance hole and tighten it with a nut that will create a seal between the wall and the face seal o-ring also depicted in Figure 29.

Below in Table 4 is our current Bill of Materials (BOM). It is important to note that this is a living BOM and the team will continue to update the list as our design solution finalizes and becomes more detailed. An important note is that this BOM will soon be expanded to include the paper/tapeto be used in the waterproofing test, however, as of now we are still searching for the best available product. As of now, the components provided by the Mag-Lab are not included, and

Table 4: Bill of Materials, specifically off-the-shelf components our team has purchased for the build design

Component	Manufacturer	Part #
Magnetometer Enclosure	Mayouko	Waterproof Hard Case, 11.6"L×8.3"W×3.9"H
5.5mm WetLink Penetrator	Blue Robotics	WLP-M10-5.5MM-LC

Structural Pipe	McMaster-Carr	5038K142
3” NPT Female Flange	JME Ellsworth	BTFH3AL
M10 x 1.5 Bolt	McMaster-Carr	91290A526
M10 x 1.5 Nut	McMaster-Carr	90593A008
Thread Sealant	LOCTITE	135486
Whitewood Plywood	Lowes	520359

The purpose of this build design is to produce a tangible product for our sponsor that they can utilize for their future deployments. This prototype will also be used by our team to test the effectiveness of a new product being incorporated into the final design: BlueRobotics WetLink Cable Penetrators. These penetrators will be used on all enclosures in our system, so ensuring that they work on one allows us to reasonably assume that the system will be effectively waterproof given the same components and installation methods. The test that will be performed on this prototype verifies that our design and selected components will satisfy the need for a waterproof system, one of our most critical stakeholder sub-requirements. Therefore, while the build design is only one enclosure, we are confident that it can be used to validate the design of the final build.

FINAL DESIGN DESCRIPTION

From our concept selection process, we decided to fully bury any enclosure that houses electronics, sensors, and batteries and mount the solar panels and antennae on a metal pole attached to a wooden base plate that is buried under two feet of compacted snow, as shown below in Figure 30. There will be a total of three enclosure systems: one for the magnetometer sensor, one for the electronics, and one for the batteries. It is important to note that the battery system is designed to be modular, so there can be multiple battery boxes and additional boxes can be easily added to the system.

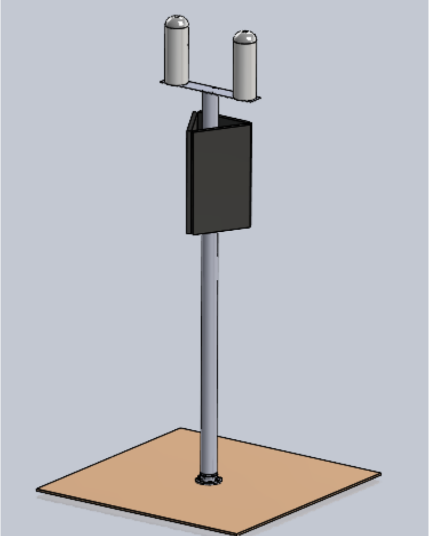


Figure 30: Full stack system design (left) and solar panel/antennae attachment (right)

The electronics and battery enclosures will be buried in a large hole near the solar panel and antennae structure. Meanwhile, the magnetometer enclosure will be buried 8 meters away from these enclosures and solar panel/antennae system, due to its sensitivity to data interference from ferromagnetic materials.

For the thermal insulation method, the battery enclosure will have insulation panels installed consisting of vacuum insulated panels with dense thermal insulators for wire routing, as shown in Figure 30. The actual set up of the composite insulation walls is shown above in the Engineering Analysis section, in Figure 31. The battery enclosure will also rely on the heating produced by the cells themselves. Meanwhile, the magnetometer and electronics enclosures will not require insulation, due to their functionality in very cold temperatures.

Figure 31: Selected Concepts for Thermal Management

In order to meet the engineering specifications for IPX5 waterproofing standards, our team selected the Blue Robotics WetLink Penetrator, as shown above in Figure 31. Blue Robotics reports this penetrator to be able to withstand being submerged up to 950m deep for three years, which is well beyond the needs and scope of our design, so we are confident that this selection will work for our purposes. Furthermore, our team will conduct the IPX5 waterproof test on the penetrator after installation into the magnetometer enclosure box, as detailed below in the verification and validation plan section. Based on our expected results of the verification and the verification performed by the manufacturer, we are confident that the selection of these penetrators are effective for our system.

The enclosures for the batteries and the electronics are still being actively researched; however, both enclosures will be rated at least at IPX5. We expect the batteries to be primary Lithium Thionyl Chloride batteries manufactured by Saft. However, if our sponsor elects to use secondary batteries, the battery enclosure will have a pressure relief valve.

After conducting an analysis on the stability of the solar panel/antennae structure we determined one of the most sensitive parameters to be the baseplate footprint. It just so works out that this is also a very feasible parameter to design around as well as manufacture. Our preliminary results show a baseplate footprint of 1 m to be suitable. The exact geometry of this is an active discussion within the team that will be finalized in the coming week. The two main concepts are a circular base and a square base. The circular base is advantageous as the footprint and restoring torque moment arm will be constant despite wind speed direction. The square base is advantageous from a manufacturing standpoint as it would require a small number of cuts with low precision machinery. Lastly, there is consideration of segmenting the baseplate into multiple pieces to achieve a lower volumetric footprint which is a slight concern from our sponsors with shipping.

The sponsor had no influence on our team's concept selection, outside of their direct influence on our stakeholder requirements. A more objective selection process likely would not have changed our selected concept(s). The comparison between the top two contenders for our enclosure attachment methods was very straightforward and did not require any sort of metric comparison. For the solar panel and antennae attachment method, the top contender was either the same or better in every metric than the second best contender, resulting in a 20% higher score. For the thermal management solutions, we decided to move forward and explore the top three options, which all had 30%+ higher scores than the bottom two options.

The selected concepts for both the enclosure attachment and solar panel/antennae attachment are well enough defined to be analyzed rigorously using engineering methods.

The final deliverables for this project can be categorized into 3 categories: a physical "build design" of the magnetometer enclosure, analyses / test plans, and parameterized models.

The physical "build design" of the magnetometer enclosure is described in detail in the prior section entitled Build Design Description. Our goal is to conduct a waterproof test on this enclosure with the magnetometer and cable penetrator installed.

The analyses include solar panel energy generation and power draw analyses, solar panel and antennae pole stability and frequency response analyses, and heat transfer and thermal insulation analyses. The test plans include user-friendly waterproofing and pressure release test plans.

The parameterized models are meant to be used by our sponsors' research team to modify our design parameters based on differing circumstances such as the ice sheet's temperature gradient, surface wind speeds, and the location and latitude. The thermal model will provide the user with a required thickness of insulation with input parameters of external environmental temperature, a desired internal enclosure temperature, and an insulating material's thermal conductivity value. The solar panel and antennae pole stability model will provide the user with base plate dimensions with input parameters of maximum regional wind speed, depth of the base plate, and solar panel dimensions. The solar panel energy generation model will provide the user with the required battery system rated capacity with input parameters of latitude and number of operating months in summer and winter seasons. The overall system deployment method and design is shown below in Figure 32.

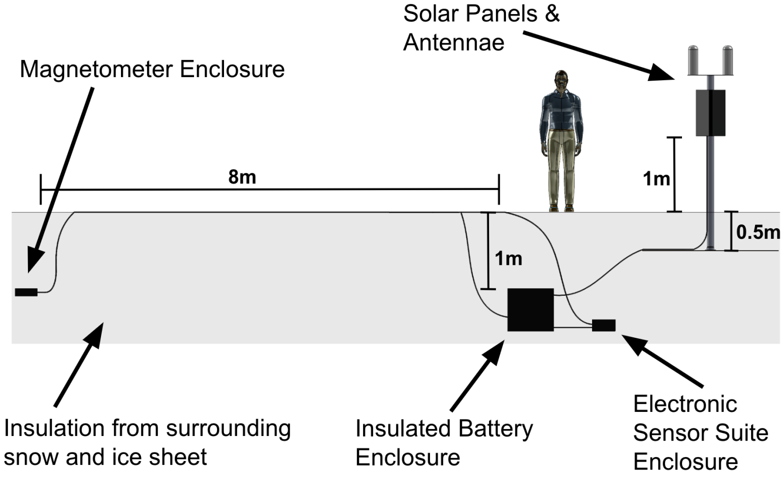


Figure 32: Final deployment design

VERIFICATION AND VALIDATION

Our team verified every engineering specification previously described. If our team is not able to complete a verification or validation task by the completion of ME450, we will provide a detailed plan on how to complete these critical steps. Based on our analyses so far, our design is 100% compliant with all listed stakeholder requirements and engineering specifications.

Verification of Specifications of Critical Requirements

The team's first critical stakeholder requirement is that the system shall survive harsh environmental conditions, which includes the sub-requirements of the system being water-proof, wind-proof, and Antarctic temperature-proof. The engineering specifications for these sub-requirements are that the system meets IPX5 standards, must be mechanically and structurally stable under prolonged 60 m/s wind speed, the electronics' and sensor's temperatures must not go below -40℃, the battery enclosure must not go below -20℃, and finally the wiring insulation must be able to withstand -40℃.

Verification of IPX5 Waterproof Standard

To verify the IPX5 standards, our team conducted a standardized verification test on the magnetometer enclosure. The procedures for this test are standard practice and are well documented. Because of this our team believes this test produced accurate results. According to standard we sprayed our enclosure with a nozzle from every practical direction for three minutes. The nozzle used in this test must have an internal diameter of 0.63 mm, the flow rate must be at least 12.5 liters per minute, and the pressure must be adjusted so that it meets the required flow rate[21]. Additionally, in the future, this test should be conducted at cold temperatures to ensure our enclosure remains waterproof under thermal contraction. In order to detect if any water has ingressed into the enclosure, our team used hydrochromic pressure sensitive adhesive placed inside of the enclosure and affixed near the most likely points of failure. Since no water entered the enclosure, these strips of tape remained inert and visually indicated that our enclosure meets our waterproofing requirement. A limitation of this test is that we cannot guarantee the quality or reliability of the waterproofing any off the shelf box our sponsor may wish to buy. We are only able to test on the specific product we choose to use to make our enclosure prototype, and as such we can only interpret the results of this test as verification of the manufacturer seals for this specific product as well as verification of our own design for sealing the cable holes drilled into our enclosure. However, should our sponsor choose to purchase another product, performing this test again will reveal any reliability issues or false claims by the manufacturer.

Verification of Stability under High Wind Speeds

To verify that the system is stable under prolonged 60 m/s wind speed, our team performed a first principles stability analysis on the antenna attachment/pole system. This is the only part of the entire system that will be exposed to the wind, and we are confident that this is sufficient. Our team used 60m/s as the wind speed, as this is near the record for highest recorded wind speed on the West Antarctic Ice Sheet, and first-principles is sufficient for our purposes (FEA is not needed). We have also developed a spreadsheet that accounts for any parameter or design changes to determine the maximum allowable wind speed. Detailed information on this analysis can be found in the Analysis section. Additionally, our team has developed a potential testing plan for how this requirement could be verified empirically once a prototype of the solar/antennae structure exists. The prototype must consist of the baseplate, flange, pole and weights to emulate the weight of the snow that will be on top of it in reality. From there one must attach a crane scale to the pole where the load will be applied. Attaching the crane scale higher up is preferred to lower. This is for two reasons. Firstly, the higher up the load is applied a lower force will be needed to emulate the resulting drag torque. To build off of that, the lower the applied load will be the less of a chance of the structure slipping before tipping. Since the torque from the drag force is the mechanism that causes the structure to tip over, we believe emulating this torque and other conditions of the structure is a valid method to verify this requirement.

Verification of Material Yield Under High Wind Wind Speeds

We have also verified that the material we have selected will not yield under the maximum expected wind speeds. We did this by modeling our pole as a cantilever beam with drag loads. A more detailed description of our analysis can be found in our Analysis section on p. 30.

Verification of Temperature Stability using Insulation

To verify that the electronics' and sensor's temperatures do not go below -40℃, the batteries do not go below -20℃, and that the wiring insulation is able to withstand -40℃, our team performed a first principles thermal analysis on the system. As stated above, the thermal analysis has been completed for the electronic/sensor suite, and the system will maintain a temperature above the required -40℃. The team completing the thermal analysis for both the battery enclosure. A limitation of this verification method is that it does not currently account for contact resistance between layers of insulation; however, this makes our insulation needed numbers more conservative and safer, assuming that the thermal resistance of the system is lower than its true value. The key result of this verification method is the amount of insulation needed in each component of the system, which is provided as a result in the associated Matlab model.

Verification of Clear Line of Sight, Data Collection Interference, and Battery Safety

The team's remaining critical stakeholder requirements are that the solar panels/antenna must have a clear line of sight to the atmosphere, there must be no interference with the sensors' data collection, and the system must have the ability for safe storage of the batteries. The engineering specifications for these requirements are, respectively, that there is at least a clearance of 1m from the ground, there are no ferromagnetic materials within 8m of the magnetometer, and that if the chosen batteries have a potential to offgas, they must be housed in an enclosure with a pressure relief valve.

To verify all three of these engineering specifications, our team will use analysis by design. Specifically, for the pole/antennae, our team will design the pole to be tall enough to ensure 1m of clearance from the ground. For the magnetometer, our team will examine the Bill of Materials to ensure that any component/part with ferromagnetic properties will be placed at least 8m away from the magnetometer. Finally, for the batteries, our team will provide the sponsor with the information to choose either of the battery options, with a preference for the Lithium Thionyl Chloride batteries that do not have the potential for off-gassing and provide high energy density. The limitation for the first two verification plans arise from the potential of the scientist who deploys the system deploying it incorrectly. The limitation that arises from the third verification plan is that if the selected battery is the Lead-Acid AGM, they might potentially off-gas. Our team recommends empirical testing prior to any deployment to ensure that the box's pressure relief valve functions properly.

Verification of Specifications of Medium and Low Priority Requirements

The team has two medium and one low priority stakeholder requirements. They are, respectively, that the system must be easy to install and uninstall, must be non-hazardous and identifiable to wildlife and humans, and must be low-cost. The engineering specifications for the ease of install and uninstall are that the system takes <2 hours to install for a 3 person team and<3 hours to install for a 2 person team, must not require power tools for maintenance, the connectors must only be capable of interfacing with proper port, and must meet NSF Packaging and Shipping Instruction Standards. The engineering specifications for the non-hazardous requirement is that the system must not contain features that have radii <X mm and can be spotted from X m away. The engineering specification for the low priority requirement is that the system costs under $2,000.

To verify all three of these engineering specifications, our team will use analysis by design. Specifically, our team will ensure that the burying depth of the system is no more than the depth PASCAAL used, as their system took only 2-3 hours to deploy. For safety, our team will ensure that the antenna pole is a height that allows the system to be seen from Xm away and design the pole and solar panel edges to have radii < Xmm. Finally, we will use the BOM to ensure that the total cost of the system remains under $2,000. One limitation, again, is that in practice these rely on the scientist deploying the system to follow procedure correctly.

System Validation Plans

Currently the team plans to validate that the system meets the user's needs by creating plans for the stakeholder to deploy and implement the design in a non-Arctic, mid-latitude location. This will help to validate that the system functions as intended, without requiring the shipping and deployment to the West Antarctic Ice Sheet.

PROBLEM DOMAIN ANALYSIS

Problems and Challenges

Upon closer inspection of our problem, some key challenges start to emerge, most notably the issue of testing any prototypes we create. The polar ice caps, the environments that our package is expected to operate in, are difficult to simulate in a lab. Currently we cannot test the ice sheet securement method of our package as we do not have access to a substantially large and thick enough sample of ice. The current prevailing thought is that our final prototype will have to be deployed in Greenland for this sort of testing, and to test against multiple extreme conditions simultaneously.

The inability to validate our concepts at a larger scale is a notable design challenge. Not being able to fully simulate the environments for which we are designing will make it more difficult to develop the concepts we create. One potential work around is to extrapolate data about how our package is likely to perform based on tests in our local environment using materials that mimic ice. This, however, presents its own set of challenges. This extrapolation would have to be done for two different environments and any extrapolation may not be very accurate, which may lead to time lost due to developing dead end concepts. Our best course against this would be to design our package to pass our specifications with a large safety factor. This course of action may be especially useful if, as predicted, we are unable to make a high fidelity prototype during the timeline for this project.

Currently our most significant challenges are (1) calculating the amount of insulation required for the battery enclosure, which depends on an unknown value for the internal resistance of the chosen batteries as explained below in the Unknowns section and (2) characterizing the natural frequency of our solar panel attachment structure to ensure it does not resonate with the wind causing failure. In response to the first challenge we are developing a thermal model with internal heat generation as a variable input and amount of insulation required as an output. This model serves as our analysis, and we will be able to calculate how much insulation we need once we obtain a value for the internal resistance of the batteries. In response to the second challenge we are conducting research into what wind frequency is expected in the West Antarctic Ice Sheet. From there we plan to characterize the natural frequency of the solar panel structure and ensure that our design is outside of the researched frequency range.

Information Gathering

As part of concept generation and development, we would like to consult with the New Jersey Institute of Technology as suggested by our sponsor, who may possess special knowledge and expertise that may prove useful for this project. Information including past and current methods of securing housing to ice sheets, insulating equipment, and transportation of equipment, both to the polar regions and to the specific deployment location, would offer great insight to guide the initial concept exploration for this project and potentially allow non-viable concepts to be eliminated sooner. In addition, other groups such as the National Science Foundation Office of Polar Programs and PASSCAL may also be able to provide their knowledge and unique experience to this project. Our team did not directly contact any of these organizations, but we would suggest that MagLab communicates with them in the future.

Unknowns

As with any engineering undertaking, there are many unknowns associated with this project. Most currently take the form of the unknown numbers in our requirements and specifications table. These numbers, however, theoretically could be measured and calculated. There are a few unknowns that we will not be able to know before we create our design, and therefore must be designed to accommodate.

The largest remaining unknown is the exact internal resistance of the chosen battery type. This is a significant unknown, as the internal resistance of the batteries directly affects the waste heat the batteries give off, which in turn directly informs the design decision of how much insulation is required in the battery enclosure to maintain a steady state temperature within operating range. Manufacturers typically do not provide this value on their published specification sheet, however, this value can be estimated using comparable battery values. In the developed and provided thermal analysis model, an estimated internal resistance for the battery is used. However, the user of this model can, and should, change this value to be reflective of the final batteries selected.

DISCUSSION

Problem Definition

If we had more time and resources, we would have further explored the empirical validation aspect of thermally insulating the battery enclosure(s) by purchasing both lead-acid and lithium thionyl chloride batteries, a battery enclosure, and the recommended insulation types. Then, we would have run empirical tests to determine the enclosure's internal temperature by running the batteries on a realistic load with the enclosures inside of a freezer set at a conservatively low temperature.

Design Critique

The strength of our design is that it allows for the required flexibility of our sponsor's changing needs for both prototype and actual deployments. The design provides recommendations on which products to choose, but does not eliminate the option to choose an alternative product. For example, while our research has shown us that primary lithium thionyl chloride batteries are superior for this project's needs to the secondary lead acid batteries, the lead acid batteries are definitely still an available option that our sponsors can use within our design.

The weakness of our design is that because it involves so many different subsystems with different functions, we lacked the time to complete a physical prototype of the final design. We recommend that our sponsors use our models and recommendations to produce physical prototypes for the battery enclosure and solar panel / antennae structure.

In hindsight, we believe that if we had spent more time in the beginning of the information gathering process figuring out the priorities of our sponsors, we might have been able to focus on fewer subsystems as a team and completing more of the design process for those subsystems rather than split up subsystems among ourselves, which turned out to limit the contributions of each group member on all of the subsystems. If we had the chance to start over, we would have focused on fewer subsystems and completed more physical prototypes and empirical testing.

Risks

One challenge that we encountered during our design process was that the use cases for the overall system weren’t as rigidly defined as we had initially believed from our initial meetings with our sponsor. Some variables such as the deployment location, deployment length, and power supply availability turned out to have a wider range of options then we anticipated. We addressed this challenge by using the most conservative use cases / most extreme conditions to ensure that our final design would satisfy all of the requirements.

One risk associated with our end-user for our final design was the risk of the use of ferromagnetic materials in our chosen off-the-shelf products. We discovered that the product that we had purchased for the build design of our magnetometer enclosure had actually included metal in its pins, something that was left out of its product description online. Another risk was the weight of the battery enclosures. Initially, we had them weighing up to 200 lbs, but we decided that this was too heavy, after considering OSHA’s recommended maximum weight a person should carry being 51 lbs. After considering the weight of the enclosure and insulation, we decided that the maximum enclosure weight should not exceed 153 lbs, assuming a team of 3 people.

REFLECTION

Notable Factors

As our semester is coming to an end there are a variety of factors that we have been reflecting on. Firstly, we have recognized that despite the project being relatively small scale, it still is a part of a very important technological movement. Enhancing the ability to gather data in harsh regions such as the Antarctic is going to lead to a greater understanding of our climate and planet as a whole which could have huge beneficial implications from a public wellbeing standpoint. That being said, we also must recognize the shortcomings of the required materials and manufacturing processes associated with our product. Namely, the use of batteries containing lithium and/or cobalt. Not only are the processes to extract these elements from the earth hurtful to the environment, but the processes are often done utilizing child labor and wage rates barely high enough for an individual not to starve.

We also believe our product is another step in a positive direction for the economy as technology progresses. With better and better technology allowing greater access to regions that were once thought to be very remote, there will be an influx in research projects. These research projects will increase demand in a market for products similar to our own as well as generate jobs in a variety of related areas.

To keep track of the various impacts our project may have, we also developed a stakeholder map that we were able to consider throughout our entire design process. For greater detail this map can be found in Figure 3 on p. 7.

Influence of Identity

Something else that we paid close attention to throughout the semester is the differences between each teammate and how exactly that could serve to create a richer outcome in our project. The biggest factor in how our identities influenced each other was the variety of engineering experience. For example, when discussing potential solutions for making watertight connectors one team member with underwater vehicle experience jumped to that industries solution while another team member with more automotive experience jumped to that industries solution.

The influence of identity between our team and our sponsors however was primarily dictated on the basis of there being discrepancy in power between our team members and sponsors. This is purely due to the nature of joining on a project that has already been established by the sponsors. They were the ultimate influence on most of our final requirements which our entire design was built out from.

Inclusion & Equity

Implementing inclusive practices throughout the duration of the semester was an important goal for us in an effort to diversify our viewpoints as much as possible. This included always letting team member's opinions be heard, meeting weekly with our sponsors, and collaborating with other students in our section to breathe fresh ideas into our design space.

For prioritizing ideas for our project we wanted to make sure to always seriously consider feedback from our sponsors since they are ultimately the ones who we are striving to satisfy. Within our team however we usually were able to simply weigh the benefits and drawbacks of different ideas and civilly land on the most optimal solution.

As our project progressed throughout the semester it was interesting to see what ideas each member brought to the table. When all given the same problem to tackle, each team member may have a solution totally different from another. This was very beneficial since it allowed us to fully explore the design space our project was confined to and decide on what option was truly the best in meeting our established requirements.

Ethics

Fortunately, our project did not have any serious ethical dilemmas to be handled. Although, as mentioned earlier in the Notable Factors section of this report on p. 45, the processes for extracting the necessary elements for the batteries used in our product unfortunately involves directly harming certain individuals and the environment around them. Our team still believes this to be justifiable given the wealth of knowledge that will come from having a better understanding of polar regions in the world. Perhaps this wealth of knowledge may eventually lead to mitigating some of the existing problems that our product has.

RECOMMENDATIONS

One of the most important decisions that needs to be made is the selection of what type of battery will be used. Between the two options of using either a lead-acid or a lithium thionyl chloride battery we highly recommend using the latter. This will provide a much safer final product as the implications of off-gassing can be ignored. Lithium batteries are also much more energy dense so the enclosures that will be deployed will weigh a lot less. This will be beneficial financially in terms of their cost of transportation, as well provide higher safety standards to the field researches that ultimately must carry the batteries.

Additionally our team recommends using an insulating foam board as the material for the dense thermal insulator for routing wires through the battery enclosure. Specifically, a Foamular board with R-5 rating would work quite well.

CONCLUSIONS

Our team worked to finish the design and analysis of a packaging and deployment solution for an existing sensor suite onto the West Antarctic Ice Sheet. As our team has worked through the problem definition process we have become more acutely aware of the open ended nature of the problem. Additionally, we have researched and found previous projects and backgrounds to use for extensive and thorough benchmarking. We have developed a dynamic set of requirements and specifications, which we used to guide our concept generation and selection. After creating over 20 different variations of designs, the team selected our Alpha Design: a fully buried enclosure with a base-plate mounted solar panel, with vacuum panels, dense thermal insulators, and passive battery heating as athermal management strategy. Our team is moving forward with performing engineering analyses, both with first-principles and simulations and tests.

After performing rigorous engineering analyses, our team revised our final design to be a buried base-plate mounted solar panel/antenna pole and three separate enclosures: for the electronics, the magnetometer, and the batteries. The battery enclosure will be insulated to help maintain an optimal interior temperature for the batteries to perform efficiently. Both the magnetometer enclosure and the electronics enclosure will be buried sufficiently deep to be insulated from the extremes of ice sheet's temperature and weather. Cable ports on the enclosures will be waterproof up to IPX5 standards with cable penetrators.

The final deliverables for this project can be categorized into three categories: a physical "build design" of the magnetometer enclosure, analyses and test plans, and parameterized models for our sponsor's and their team to use if design change is required. Our team fabricated and tested the build design and have completed the creation of the different parameterized models.

Throughout the semester our team has developed what we believe are the necessary requirements and specifications to successfully achieve the desires of our sponsors. We also came up with designs to meet each of these requirements. Our designs, however, are analysis dependent meaning that there are multiple parameters that affect exact design details such as dimensions and material selection. Because of this, providing dynamic analysis models as well as guides to manufacture the physical solutions to our sponsors was very important to us. On a similar note, we also wanted to provide any sort of empirical testing procedures to our sponsors to supplement our analysis driven verification. All of these deliverables have been developed to be as user friendly and clear as possible. Along with those, we also have provided the procedures to deploy all of the different components in a fully operational system in the expected polar regions.

ACKNOWLEDGEMENTS

Our team would like to acknowledge our project sponsors, Professor Mark Moldwin and Mr. Lauro Ojeda, as well as the graduate students in the MagLab for their support throughout their sponsorship of this project. Additionally, we would like to thank our section instructor, Randy Schwemmin, for all of his mentorship and instruction throughout the semester.

AUTHOR BIOGRAPHIES

Scott Ai

I'm Scott Ai and I've lived in Chicago, Illinois my entire life. Growing up attending schools in a city like Chicago, I have always had the opportunity to participate in diverse groups and learn from a wide range of life experiences. I had no idea what I wanted to pursue when I first joined the University of Michigan's College of Engineering. After taking ME 250, I realized that the field of Mechanical Engineering provided a rare opportunity for the combination of creative problem solving, team collaboration, and design concept realizations.

After my graduation this spring, I plan on staying in Michigan to work for Yazaki North America, developing high voltage automotive products such as connectors. I began interning at Yazaki this past summer and ended up continuing to work part-time as a Co-Op during the Fall semester. It was a very rewarding experience and I'm excited to put my mechanical engineering skills to use in a full-time role in industry.

When I'm not working or studying, I like to spend my time exercising and learning about politics, history, and sustainability. As I dived deeper into these topics, I started to really understand the power and importance of educated civic engagement and activism to almost every aspect of our lives.

Thomas (Tommy) Brunner

I'm Tommy Brunner, and I'm from Okemos, Michigan where I've grown up and lived my whole life. Since a young age, I always really liked learning about the fundamental laws responsible for making reality what it is. So when I began looking at areas to study in college the idea of mechanical engineering seemed the most intriguing to me as it was a sort of way to package these fundamental laws into applicable theories and use them to our advantage.

Last summer I was fortunate enough to work at NASA Johnson Space Center developing augmented reality technologies for future Artemis missions. This furthered my desire to work in an area that is working towards something meaningful and good for humankind as a whole. That is the one thing I've found to make me happy in the workspace so that is what I am looking for in a future full time job come this summer.

That being said, I also don't want to make work my life and I have plenty of hobbies. Outside of my academic and career work I really enjoy cooking different cuisines, going to the gym, playing IM basketball, golfing with my friends, reading/writing, and listening to Jazz records.

Joseph (Joe) Carey

I'm Joe Carey, and I am from Traverse City, Michigan. That being said, I grew up in a military family and moved quite often, and I lived in 12 houses just before coming to college! I have lived in Rhode Island, Colorado, Wyoming, Nebraska, Washington D.C., and then, of course, Michigan.

Mechanical engineering has always interested me because seeing a tangible outcome of my work, especially design work, is incredibly fulfilling for me. I have also always loved how mechanical engineering is applicable to almost every field in the world; there's limitless possibilities.

Following graduation this spring, I am moving out to the Denver, CO area to work for Lockheed Martin! Specifically, I will be working for Lockheed Martin Space, and I am incredibly excited. This previous summer I interned at Raytheon Missiles & Defense out in Tucson, AZ. I loved the work and realized how much I enjoy working in defense, but I also realized that I can *never* live in the desert for an extended period of time.

Outside of engineering, I really enjoy learning about both language and history. I am a German Studies minor, and I love being able to use a different part of my brain than I typically do in my mechanical courses. I have been to Germany twice, and I would love to live there at some point.

Cutter Klein

My name is Cutter Klein, and I grew up in Madison, Mississippi; briefly lived in Columbus, Mississippi; and now I am here in Ann Arbor. For as long as I can remember I was fascinated by how things worked and why things did the things they did. I grew up exploring that natural curiosity tinkering, taking apart, and studying during my younger years small devices and toys, and later in my life I started taking up car and electronic repair. In addition to this I sought out a scientific path in school from the moment I was first allowed to choose.

Engineering allows me to learn and test and to figure things out, and it allows me to use my hands to do so. It also allows me to be create things of my own and to be a problem solver. I unfortunately have not held an internship and therefore have not worked in industry, however throughout my academic career I have been part of many engineering projects all of which I have been glad to be a part of, and I cannot wait to get out there and see what I can do.

After graduation I plan to work in industry. I do not have a particular dream job or sector in mind as I believe many different things would be satisfying to me. In fact one of the reasons I chose mechanical engineering specifically is because of the very broad range in which you could work. I can't say for certain what I will be doing or even where I will be living, but I can say I want to do something that uses my degree.

Outside of engineering I mainly enjoy playing video games, learning about history, watching cartoons, cooking delicious meals, and hanging out with my friends.

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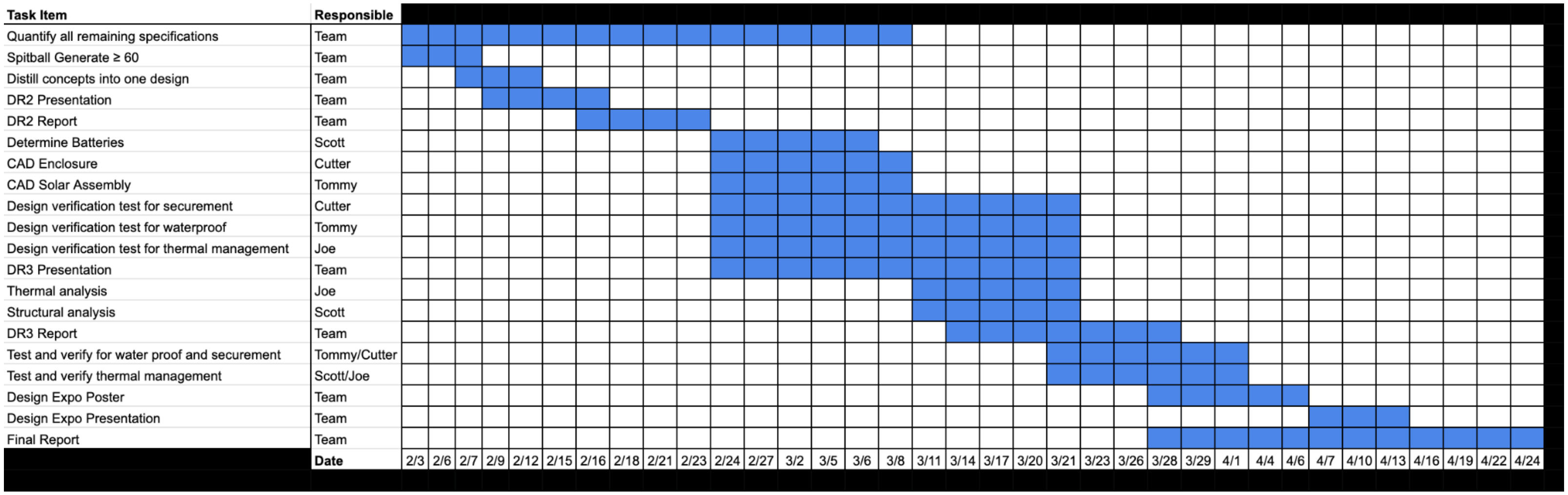
APPENDICES

Appendix A



Task Item	Responsible																																			
Quantify all remaining specifications	Team	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦																			
Spitball Generate ≥ 60	Team	🟦	🟦	🟦																																
Distill concepts into one design	Team			🟦	🟦	🟦																														
DR2 Presentation	Team				🟦	🟦	🟦	🟦																												
DR2 Report	Team							🟦	🟦	🟦	🟦																									
Determine Batteries	Scott											🟦	🟦	🟦	🟦	🟦																				
CAD Enclosure	Cutter											🟦	🟦	🟦	🟦	🟦	🟦																			
CAD Solar Assembly	Tommy											🟦	🟦	🟦	🟦	🟦	🟦																			
Design verification test for securement	Cutter											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦														
Design verification test for waterproof	Tommy											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦														
Design verification test for thermal management	Joe											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦														
DR3 Presentation	Team											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦														
Thermal analysis	Joe																	🟦	🟦	🟦	🟦	🟦														
Structural analysis	Scott																	🟦	🟦	🟦	🟦	🟦														
DR3 Report	Team																		🟦	🟦	🟦	🟦	🟦	🟦	🟦											
Test and verify for water proof and securement	Tommy/Cutter																					🟦	🟦	🟦	🟦	🟦	🟦									
Test and verify thermal management	Scott/Joe																					🟦	🟦	🟦	🟦	🟦	🟦									
Design Expo Poster	Team																								🟦	🟦	🟦	🟦	🟦							
Design Expo Presentation	Team																													🟦	🟦	🟦				
Final Report	Team																								🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Date	2/3	2/6	2/7	2/9	2/12	2/15	2/16	2/18	2/21	2/23	2/24	2/27	3/2	3/5	3/6	3/8	3/11	3/14	3/17	3/20	3/21	3/23	3/26	3/28	3/29	4/1	4/4	4/6	4/7	4/10	4/13	4/16	4/19	4/22	4/24

Appendix B

Concepts Generated for Enclosure Attachment Function

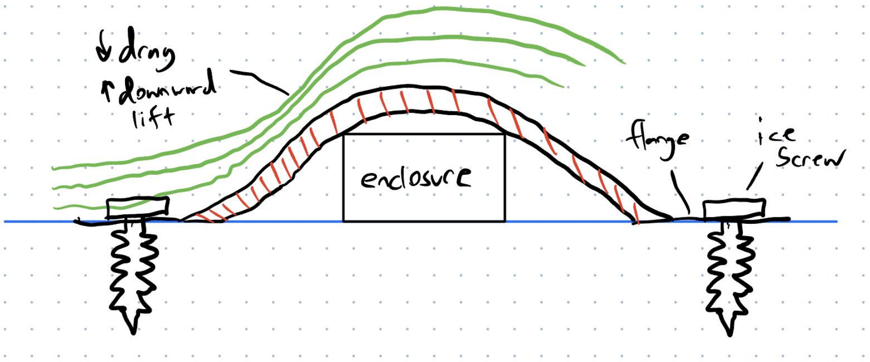


Figure 33: Surface Dome Enclosure Concept

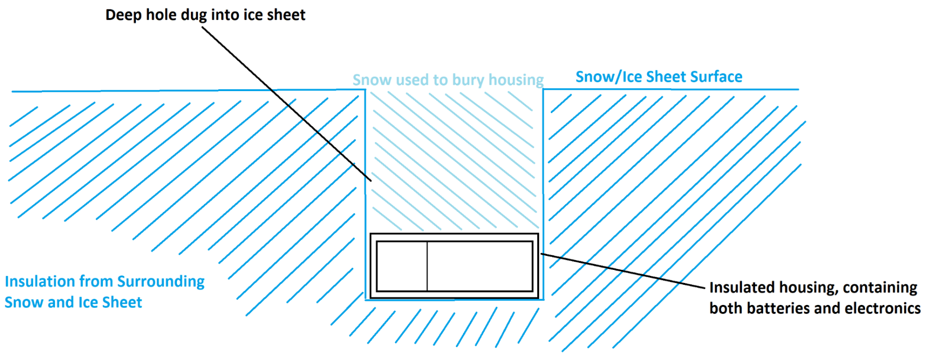


Figure 34: Fully Buried Enclosure Concept

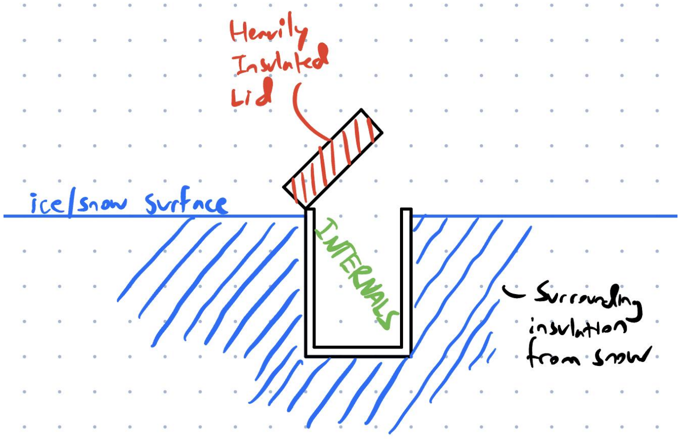


Figure 35: Partially Buried Enclosure Concept

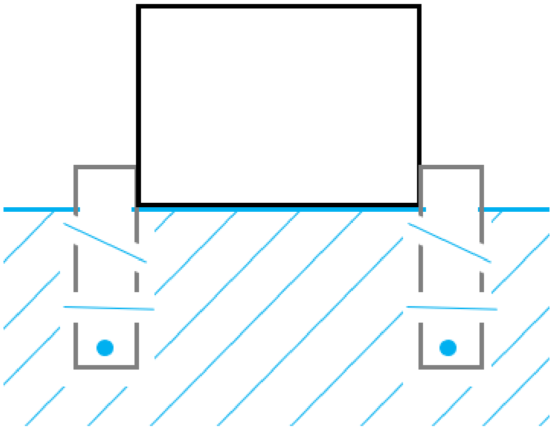


Figure 36: Four Legs Buried Concept

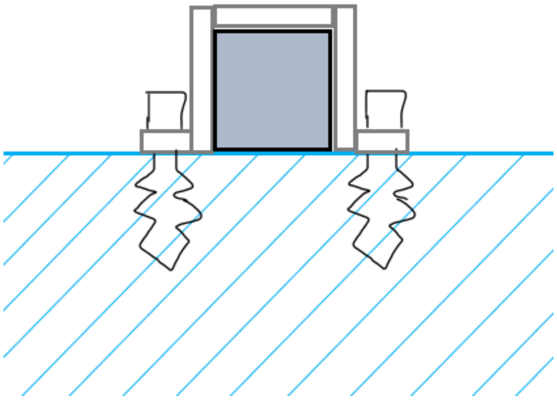


Figure 37: Surface Mounted Frame Concept

Concepts Generated for Solar Panel and Antenna Attachment Function

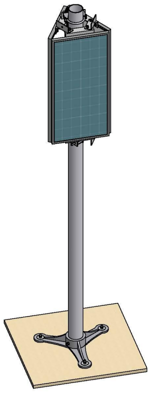


Figure 38: Pole on Base Plate Concept

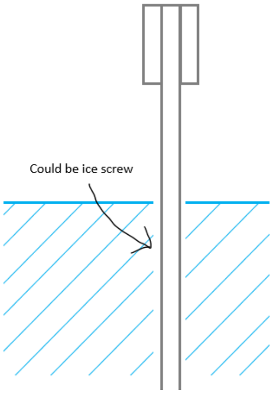


Figure 39: Pole Buried Concept

Figure 40: Weather Balloon Concept

Figure 41: Pole Attached to Enclosure Concept

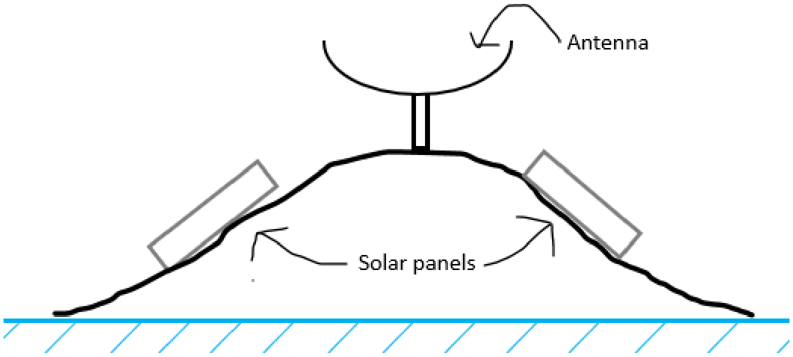


Figure 42: Surface Dome Concept

Concepts Generated for Thermal Management Function

Figure 43: Dense Thermal Insulators Concept

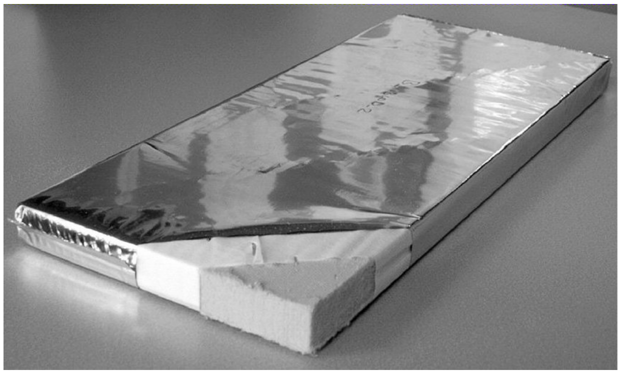


Figure 44: Vacuum Insulated Panels Concept

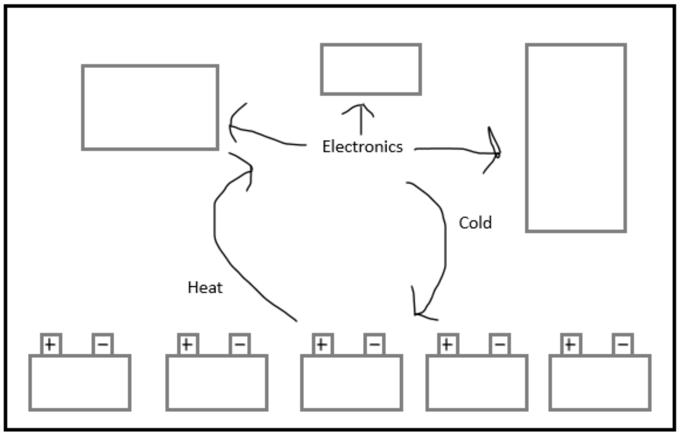
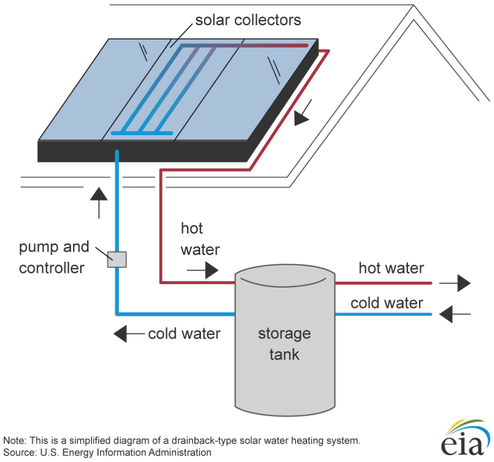


Figure 45: Passive Battery Heating Concept

Figure 46: Internal Heater Concept



Note: This is a simplified diagram of a drainback-type solar water heating system.
Source: U.S. Energy Information Administration

Figure 47: Solar Heating Concept

Appendix C

Working Stability analysis

Foot Print Length(m)	Pole Outer Radius(m)	Pole Inner Radius(m)	Snow Depth(m)	Snow Density(kg/m3)	Air Density(m)	Width solar(m)	Height Solar(m)	Pole Density(kg/m3)	Cd Solar	Cd Pole
1	0.102	0.09	1	300	1.4	0.75	1	2710	1.28	0.86
Solar Moment Arm(m)	*Pole Moment Arm(m)*	*Total Weight(kg)*				Base Plate Thickness(m)	Base Plate Density(kg/m3)	Solar Panel Weight(kg)		
2.5	1.5	1029.155973				0.0127	500	2.8		
Maximum Windspeed Velocity(m/s)										
61.57103776										

Figure 48. Example of working spreadsheet stability analysis.

BILL OF MATERIALS FOR THE BUILD DESIGN

Item	Quantity	Source	Part Number	Cost	Link
Enclosure	1	Mayouko	N/A	$25.73	https://www.amazon.com/dp/B091BXDX7G?psc=1&ref=ppx_yo2ov_dt_b_product_details
Penetrator	1	WetLink	WLP-M10-5.5MM-LC	$12.00	https://bluerobotics.com/store/cables-connectors/penetrators/wlp-vp/
Indicator Tape	11	TapeCase	0.125-5-3M 5557 White Polyester Adhesive Water Contact Indicator Tape	$10.50	https://www.amazon.com/dp/B00MO2TWY2?psc=1&ref=ppx_yo2ov_dt_b_product_details