AN ABSTRACT OF THE THESIS OF

Whitney K. Hopple for the degrees of Honors Baccalaureate of Science in Mechanical Engineering and Baccalaureate of Arts in International Studies with a focus in German presented on March 6, 2014. Title: Design and Manufacture of a Solar-Powered Snow Melter for Making Potable Water on Mt. Rainier.

Abstract Approved: ______________________________________________________________

John Parmigiani, Thesis Mentor

Every Spring and Summer, thousands of climbers attempt to summit Mt. Rainier. Many of them stop at Camp Muir, a base camp at 10,000 feet, where they can use restrooms, camp overnight, or refill water bottles before continuing their climb. Camp Muir currently uses a gas system to melt snow into potable water, requiring a tank of propane to be flown by helicopter to the camp at the beginning of each season. This system is costly and not environmentally-friendly. International Mountain Guides (IMG), one group who organizes trips in small groups, wants to replace this water production system with one that incorporates green energy. This publication examines possible designs of a new snow-melting device, describes the selected design, and outlines future testing and evaluation. The final design is portable, uses solar-electric energy, and makes use of both conductive and convective heat transfer to increase efficiency. The melting system is contained within a five-gallon water cooler. Energy is collected and stored using a solar panel and battery pack. The battery pack supplies power to a heating element and pump, which heat the snow and recirculate water over remaining snow. The design will be implemented during the 2014 climbing season.

Keywords: Engineering design, Snow Melting, Mt. Rainier, Camp Muir, Solar power

Corresponding e-mail address: hopplew@onid.oregonstate.edu

# Design and Manufacture of a Solar-Powered Snow Melter for Making Potable Water on Mt. Rainier

by

Whitney K. Hopple

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APPROVED:

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Mentor, representing Mechanical Engineering

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Committee Member, representing Mechanical Engineering

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Committee Member, representing International Studies

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Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College, and the International Degree Program. My signature below authorizes release of my project to any reader upon request.

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Whitney K. Hopple, Author

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# Introduction

International Mountain Guides (IMG) is an organization that leads groups of mountain climbers on one- and two-day hikes to the summit of Mt. Rainier in Southern Washington. On these climbs, IMG is required to provide potable drinking water for the climbers in their group. Their current method of water production is inefficient, costly, and not environmentally friendly. As a result, IMG wants to replace this system with one that is more cost effective, is portable, and better reflects their environmental attitudes. This paper outlines the design, manufacture, and analysis of the alternative design submitted to IMG for implementation at Camp Muir, a base camp and rest stop for their climbers at 10,000 feet on Mt. Rainier.

This paper examines the proposed design for a solar-powered snow melter under the conditions at Camp Muir on Mt. Rainier. Camp Muir, located at 10,000 feet on Mt. Rainier in Washington, is visited by thousands of mountain climbers each year. It is open in the Spring and Summer for visitors on their way to the summit. At the camp, they can eat lunch, camp overnight, or refill water bottles. Although skies are typically clear and sunny during hiking season, other environmental conditions can be harsh. Air temperatures are typically above freezing but can approach or dip below freezing at night. Climbers and their supplies can be exposed to high winds, and those who stay overnight must camp on permanent ground snow.

Often new or novice climbers will join professionally led groups, like IMG, to trek to Mt. Rainier's summit. They often stay overnight at Camp Muir, where IMG provides water to refill water bottles or cook food during their stay. Camp Muir is where IMG would like to implement the proposed design.

IMG currently uses a propane gas system to produce potable water for their climbers. This involves flying a large tank of propane by helicopter to Camp Muir at the beginning of each hiking season. The propane is used to heat a stovetop which climbers can use to melt snow into water. IMG uses insulated containers to store excess water for use as needed. This method technically functions but the fuel source raises some concerns about environmental sustainability.

Problems with the current method of water production motivated IMG to request a new system. Although this method is technically functional, it is also expensive, inconvenient, and does not reflect the environmental attitudes of IMG. The need for a large tank of propane to be flown by helicopter to the base camp is costly. This method is also inconvenient because it must be repeated every year. The additional waste of fuel required to transport the propane tanks is not economical or environmentally friendly and, as such, does not reflect the attitudes of IMG or Mt. Rainier climbing groups.

# Background

Theory dictating design specification and existing alternatives are discussed in this section. Fundamental equations used to calculate specifications and anticipated melting behavior is discussed. Alternatives considered include both primary components used to accomplish similar technical goals and designs used in similar applications. Evaluation of these alternatives shows that no solution for this application currently exists and that there is a need for a proposed design.

## Theory

Most applications of heat transfer that involve phase changes from a solid to liquid approximate the amount of heat required for phase change using the latent heat of fusion, shown in Equation[Eq. 1] [1]. As shown by this equation, the heat required is relatively simple and is only a function of the mass and fluid properties. However, the latent heat of fusion equation assumes the entire mass is experiencing latent heat at the same time. This assumption means that results are often significantly skewed in practical application.

*Latent Heat of Fusion* $$Q = ml$$ [Eq. 1]

Q = Heat [kJ]
m = Mass [kg]
l = Latent heat of fusion [kJ/kg]
  = 334 kJ/kg for water/ice

In this case, determining heat required becomes much more complex due to the nature of snow melt, variation in snow density, variation in environmental conditions, and differences in testing environment. The nature of snow melting is an example of moving boundary problems, in which not all of the snow experiences melting at the same time. To compensate for this phenomenon, the heat is instead calculated by taking into account the fluid density and the rate of volumetric snow melt [Eq. 2]. The situation is further complicated by variations in snow density depending on geographic region and weather conditions, such as recent snow fall versus snow that has been rained on then re-frozen. Furthermore, environmental conditions, such as rainfall or windiness, impact snow melt rates. Some equations have been empirically determined that can model some of this snow melt. However, even these predict natural snow melt and rarely apply to designing a device that mechanically melts snow [2].

*Latent Heat of Fusion for Snow Melt* $$Q = \rho l \frac{dN}{dt}$$ [Eq. 2]

Q = Heat [kJ]
ρ = Fluid Density [kg/m$^3$]
l = Latent heat of fusion [kJ/kg]
  = 334 kJ/kg for water/ice
dN/dt = melt rate [m$^3$/s]

In situations where water is being rained over snow, Equation[Eq. 3] can be used. This equation includes both the heat required to raise the snow temperature to freezing (sensible heat), and the heat required to change phases (latent heat) [2].

*Latent and Sensible Heat Required for Snow Melt* $$Q = \rho c \Delta T \frac{dN}{dt} + \rho l \frac{dN}{dt}$$ [Eq. 3]

Q = Heat [kJ]
ρ = Fluid Density [kg/m$^3$]
c = Specific heat of water [kJ/kgK]
ΔT = change in temperature [K]
l = Latent heat of fusion [kJ/kg]
  = 334 kJ/kg for water/ice
dN/dt = melt rate [m$^3$/s]

In addition to mathematically quantifying the relationship between power or heat input and rate of snow melt, examining overall melting behavior can help characterize expected trends. Figure 1 shows the anticipated trend of water and snow temperatures during melting processes with constant input power. In this figure, water and snow are mixed and heat is added. During the sensible heating phase, the water and snow remain in the same state. The water cools as it contacts the snow and the snow rises in temperature by the warmer rain. At about 0 °C, the snow begins to melt and change phase. This process is encompassed during latent heat transfer. Once all of the snow has melted, the water and snow completely mix and change temperature at the same rate.

**Figure 1.** Anticipated Snow and Water Melting Temperature

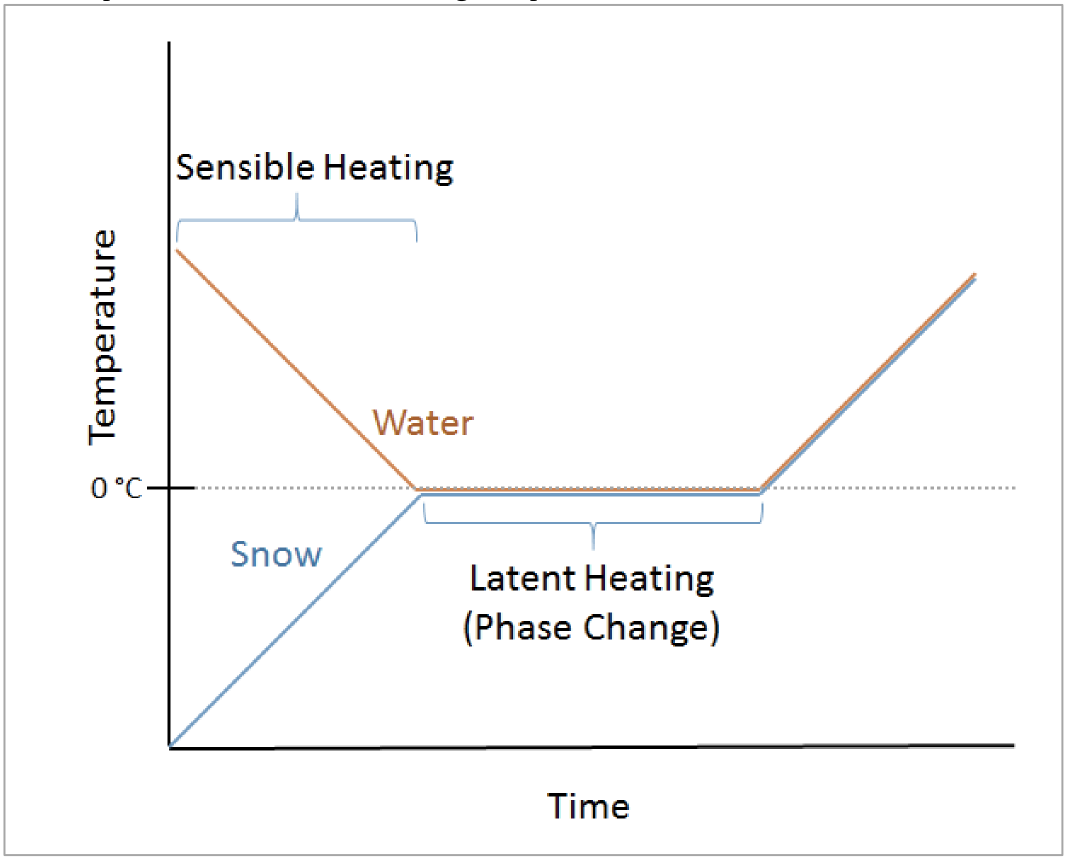


*Figure 1 shows the anticipated temperature changes of a water and snow mixture with constant power input. The temperature of water and snow converge during the sensible heating process as they mix. At about 0 °C, snow undergoes latent heating and changes phase to water. Once all the snow has melted, the snow and water completely mix and simultaneously rise in temperature.*

## Existing Alternatives

Replacing the current system has been a long-term problem because few existing products optimize efficiency of energy use and provide constant power output while being used in extreme environmental conditions. Maximizing efficiency in heat transfer applications is frequently a problem because heat loss by components to the environment is unavoidable. Inefficiency of heat transfer is worsened when used with solar-electric cells, which often only convert solar to electrical energy at 10-20% efficiency [3]. In addition, most systems that use sustainable energy provide intermittent power. Converting this intermittent power to one that is available regardless of environmental conditions adds components and complexity to designs. Few existing devices accomplish both of these goals in low-temperature settings with harsh environmental conditions.

In several recent publications, similar solar-electric and solar-thermal solutions have been examined in cases where they were used to heat water or melt snow. Typically these heating systems are not required to be portable or produce water for consumption. One simple version of heating systems required to melt snow are heated mats for driveways and walkways [4]. These mats flow an electrical current through a highly resistive material to heat a surface and keep areas clear of snow. Although these systems are sometimes embedded, many portable versions exist. The heated mats meet the requirements for the requested design for Camp Muir because they are easy to transport and can easily be adapted to sustainable energy sources. Many varieties of these mats can be rolled or stacked for transportation.

Because they are electrically powered, energy could be collected using solar or wind power, then converted and stored in a battery for later use. This method provides a sustainable alternative but is not optimal in terms of maximizing heat transfer. If cavities form around the heated surface, conductive heat transfer becomes significantly less effective. Using a conductive heat transfer approach with these mats is possible but would require substantial design integration to ensure snow contacted the heating element at all times [5].

Integrated collector storage (ICS) systems are a different form of heating unit that use solar thermal energy to heat water, typically for residential applications. In ICS heaters, a panel is installed on a roof exposed to regular and direct sunlight [6]. Under the panel is a tank of water. During the day, the sun heats the panel which heats the water in the tank. This method is beneficial because it can be used to melt snow instead of to heat water with minimal design modifications [7]. Additionally, solar thermal methods of heat transfer tend to be more efficient than solar electrical applications. However, leveling intermittent power is a considerable drawback for this application. Snow can only be melted when sunlight is available for heat and there is no way of storing energy for extended periods of time.

The most similar design to what would be needed for this application is a system implemented at Camp Muir in the Summer of 2012 by Stefan Lofgren [8]. It uses solar electric energy to circulate a working fluid. The fluid is simultaneously heated as it passes adjacent to the solar cells. This device is beneficial because of its unique application; it is used in extreme environmental conditions and uses sustainable energy to melt snow into potable water for climbers. However, power is again supplied intermittently when the sun is shining directly on the device. Additionally, the tank is significantly larger and is permanently located at the camp, meaning the device must be disassembled to be taken to or from the camp.

The design for the proposed snow melter is necessary and beneficial because few or no other existing device fit this specific application's requirements. IMG's requested device incorporated all of the previously described elements, including maximizing efficiency of heat transfer using sustainable resources, providing constant power to the device, and being portable. The extreme weather conditions contributed additional considerations to component selection and complicate the design. Traditional engineering design processes were used to determine requirements, develop conceptual designs, and manufacture and evaluate a prototype. Requirements were collected directly from the customer and used to establish benchmarks for qualification. Concepts were generated that met specific functional goals of the design. These were evaluated to ensure that all needs were met. Requirements were first established in order to dictate successive mathematical and design procedures. From these assumptions, key empirical inputs were calculated. These calculations were used in engineering design processes to generate specifications, manufacture simple conceptual prototypes, and test empirical output against predicted behavior. From this, a specific design was selected for prototyping and more in-depth evaluation.

## Device Design

The design objective was to relate customer input into standards that defined component specifications and testing processes. Customer requirements were collected and correlated to measurable engineering parameters. A House of Quality (HOQ) matrix was used to objectively rank importance of these parameters. Simultaneously, key objectives were identified in a functional decomposition. Concepts were generated using components proposed in the decomposition and a model for a prototype was selected. The most critical parameters determined by the HOQ established qualifications for concept and prototype testing.

## Requirement Definition

House of Quality (HOQ) is one tool used by engineers to outline design requirements [9]. It is a matrix that helps quantitatively determine the most important functions of a new design. A weighted importance is assigned to each customer requirements. Then, these requirements are correlated to engineering specifications by indicating whether they are strongly correlated (score of 9), somewhat correlated (score of 3), slightly correlated (score of 1), or not correlated (no score). The weighted importance and relationships generate a list of the most important engineering requirements, as shown in Table 1.

Customer requirements, or qualitative descriptors of the desired product, were collected directly from Tye Chapman, a representative of IMG [10]. The most important specifications were that the device needed to be portable, powered using sustainable energy, and reliable in extreme weather conditions. Mr. Chapman specifically described the maximum dimensions for the device as being "tabletop sized" in order to fit in a tent during in-season use and off-season storage. Sustainable energy, preferably solar or solar-electric power, was requested to exemplify the green energy goals of IMG and Mt. Rainier. Reliability at low temperatures and high altitudes was the last major customer requirement. This included resilience to extreme conditions including high wind speeds and near freezing temperatures.

**Table 1.** House of Quality

| | | SYSTEM ENGINEERING REQUIREMENTS | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Target | v | v | v | v | ^ | ^ | v | | ^ | ^ | v | v | v | ^ | ^ | v |
| | | Logistics | | | | Mechanical Components | | | | | Energy Conservation/ Efficiency | | | | Water Production | | |
| CUSTOMER NEEDS | Customer Weights ( 1= least important, 10 = most important) | Size | Mass | Weight | Cost | Allowable Mechanical Stress | Allowable Mechanical Strain | Number of Manufactured Parts | Number of Interfaces/Human Activation Required | Number of Interchangeable or Purchased Parts | Melting Heat | Heat Lost to the Environment | Power Consumed | Time needed to Charge Battery or Batteries | Water Production per Hour | Water Tank Volume | Parts per Billion of Contaminant |
| Small as possible, "countertop sized" | 9 | 9 | 3 | 3 | 3 | | | | | | | | | | 1 | 9 | |
| Replaceable Parts | 8 | | | | 1 | | | 3 | | 9 | | | | | | | |
| Durable | 10 | | | | 1 | 9 | 9 | | | | | | | | | | |
| Filters water, potable water | 2 | | | | | | | | | | | | | | | | 9 |
| Continuously Melts Snow | 6 | | | | | | | | | | 9 | 1 | 3 | 3 | 9 | 3 | |
| Solar Powered Only (i.e., no Propane) | 4 | | | | | | | | | | | | 3 | 9 | 1 | | |
| Withstands Heavy Winds (>100 MPH) | 8 | | | 1 | | 3 | 3 | | | 1 | | | | | | | |
| Easy to Use | 8 | | | | | | | 1 | 9 | | | | | | | | |
| Lightweight, Easy to Transport | 7 | 3 | | 9 | | | | | | | | | | | | 1 | |
| Makes a Sufficient Quantity of Water | 10 | | | | | | | | | | 9 | 9 | 9 | 1 | 9 | 3 | |
| | Raw score | 102 | 27 | 98 | 45 | 114 | 114 | 32 | 72 | 80 | 144 | 96 | 120 | 64 | 157 | 136 | 18 |
| | Scaled | 0.65 | 0.172 | 0.624 | 0.287 | 0.726 | 0.726 | 0.204 | 0.459 | 0.51 | 0.917 | 0.611 | 0.764 | 0.408 | 1 | 0.866 | 0.115 |
| | Relative Weight | 7% | 2% | 7% | 3% | 8% | 8% | 2% | 5% | 6% | 10% | 7% | 8% | 5% | 11% | 10% | 1% |
| | Rank | 7 | 15 | 8 | 13 | 5 | 5 | 14 | 11 | 10 | 2 | 9 | 4 | 12 | 1 | 3 | 16 |

*Table Table* **1** *shows the House of Quality (HOQ) for the design of a solar powered snow melter for IMG. The left column includes customer requirements while the row along the top describes engineering requirements. The middle of the table shows the relationship between these customer and engineering requirements. The bottom of the table ranks the engineering requirements in order of importance.*

Engineering specifications, or measureable outcomes of the design, were derived from the customer requirements. Size, power, and durability were translated into technical goals. Considerations regarding overall dimensions and weight described the need for the device to be small. Water produced per hour and heat efficiency were included to ensure that power input would generate a sufficient volume of potable water. Maximum stress and strain values correlated to reliability and durability of the device. Some other considerations were taken into account to ensure safety and increase ease of use.

According to the HOQ, the most critical requirements were water produced per hour, internal/melting heat, water tank volume, and maximum stress and strain that the device could withstand. These outcomes quantitatively reflect the customer's emphasis on the importance of efficient energy use and water production. The water production rate and heat generated showed that correlating a melting rate of snow to power input was critical in defining component specification. This relationship was used to determine experimental procedures once a design was selected.

## Functional Decomposition

From the derived specifications, a functional decomposition was used to determine specific criteria for the components. Functional decompositions are intended to focus efforts on achieving tasks or goals instead of building designs around a specific component or components. They operate by breaking down system into smaller sub-goals. Each sub-goal is connected to other sub-goals by a flow of energy, mass, or signals. Only once sub-goals and their relationships to surrounding functions are identified are components proposed. Designs are created by using different combinations of these components.

The functional decomposition of this system is shown in Figure 2. It begins with the actuation, collection, and conversion of solar energy. This energy is then stored for use as needed. When water is needed, snow is collected and put into a container. The stored energy generated from solar power can then be used to melt the snow in the container. This snow will then be filtered and output as potable water.

**Figure 2.** Functional Decomposition

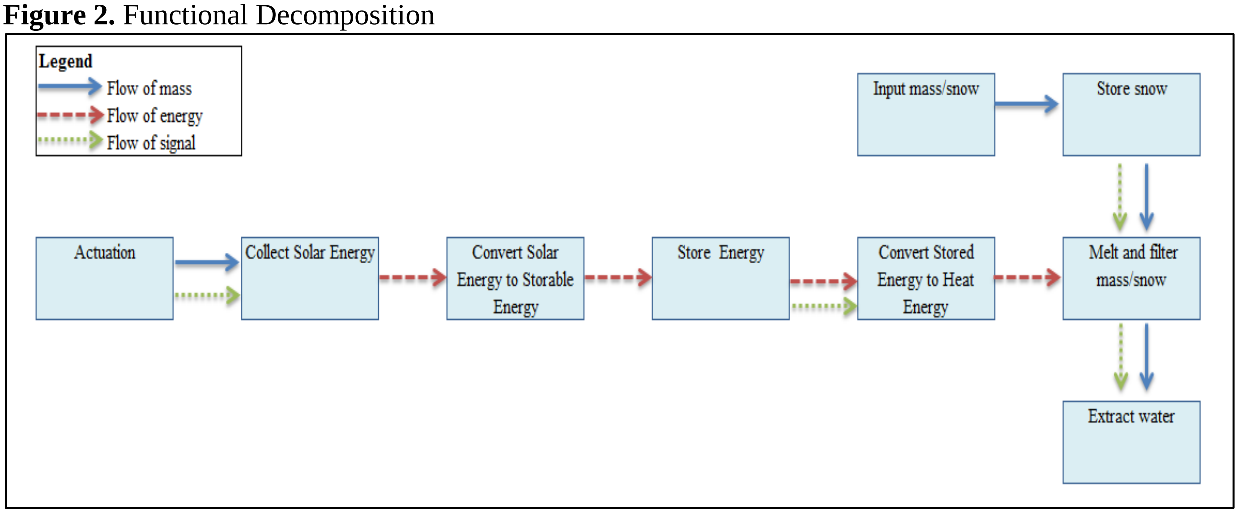


*Figure 2 shows the functional decomposition of mass, energy, and signal flow between sub-goals of the overall system. The flow beginning at the left of the diagram follows the collection, storage, and conversion of solar energy. The flow beginning at the top of the figure shows the input of snow into a containment system. The output of potable water is at the bottom of the figure.*

Components that met sub-goals and sub-processes were identified in order to generate proposed designs. Methods of collecting solar energy that were considered include direct solar heating, a solar collector, and solar-electric power. In the direct solar heating design, a reflective surface could be used to collect and store energy by concentrating sunlight on a specific area. A solar collector, designed similarly to the larger snow melter at Camp Muir, was also considered. This device would function in the same way, except it would be manufactured on a smaller scale. Finally, solar electricity and solar panels were considered because they are easy to work with and can store power for an extended period of time.

Methods of energy storage included batteries and materials or fluids known for storing heat. Batteries are commonly used and easy to transport and replace. Materials that easily hold heat, such as aluminum, were also considered because of their nearly infinite life. Eliminating the need for energy storage all together was also incorporated into proposed designs using direct thermal heating.

Mechanical systems considered included mechanical heating elements, heated filters, and pump systems. Heating elements were commonly applied to maintain above freezing temperatures in tanks. The possibility of manufacturing a heated filter was examined. Lastly, pump systems with a heated working fluid were analyzed to determine if circulating a hotter fluid could increase efficiency.

### Selected Design

Of these three examined designs, one with the following components was selected:

- Solar-electric system with batteries – converting solar energy to electrical energy made it easy to store using conventional devices
- Heating element – the heating element could melt an initial volume of snow and maintain system temperature above freezing
- Pump - water could be recirculated over the top of remaining snow to increase efficiency

Using these components met all of the requirements of the functional decomposition. Neither the direct solar heating or solar collector are capable of storing heat for extended periods of time. Batteries can be easy to find and to use, and they can be found with very long storage cycles. A two-part mechanical system with a heating element and pump was selected to increase system efficiency.

## Fabrication, Testing, and Design Modifications

To determine the relationship between power input and rate of snow melt, the device was manufactured and tested under similar conditions to those at Camp Muir. During this process, an initial prototype was build, failure modes were identified, modifications to the design were made as needed, and the final design was used to collect data relating a known power input to volume of water produced.

### Prototype Design Specification and Manufacture

A prototype was built to determine the relationship between melting rate of snow and power input. The selected design for the prototype is shown in Figure 3. A five-gallon bucket was used as the containment system. A 5W Norpro electric heating element was hung from the top of the bucket. A pumping system was also manufactured to recirculated melted snow over the top of the water. Additionally, a GoalZero solar panel and battery pack were selected. The solar panels and battery pack were omitted for testing. Instead, components were plugged into a standard wall outlet.

Following the functional decomposition, the snow melting system functions as follows; snow is inserted into the tank through the lid. Because few small pumps are self-priming, a small amount of water must be in the bottom of the container. The lid is closed and heating element and pump are plugged into the solar-charged battery, or, in this case, wall outlet. The heating element hangs into the snow pack and melts the snow it contacts. The melted snow trickles to the bottom of the tank where the pump recirculates it over the top of the remaining snow. A copper coil fixture with 3/32” holes drilled every inch is attached to the lid. Water drips through the holes to evenly distribute it over the remaining snow, much like rain. A coarse filter removes any unnecessary branches or leaves from the snow as it melts. Water can then be drained from a spigot below the filter.

**Figure 3.** Diagram of the Prototype Snow Melter

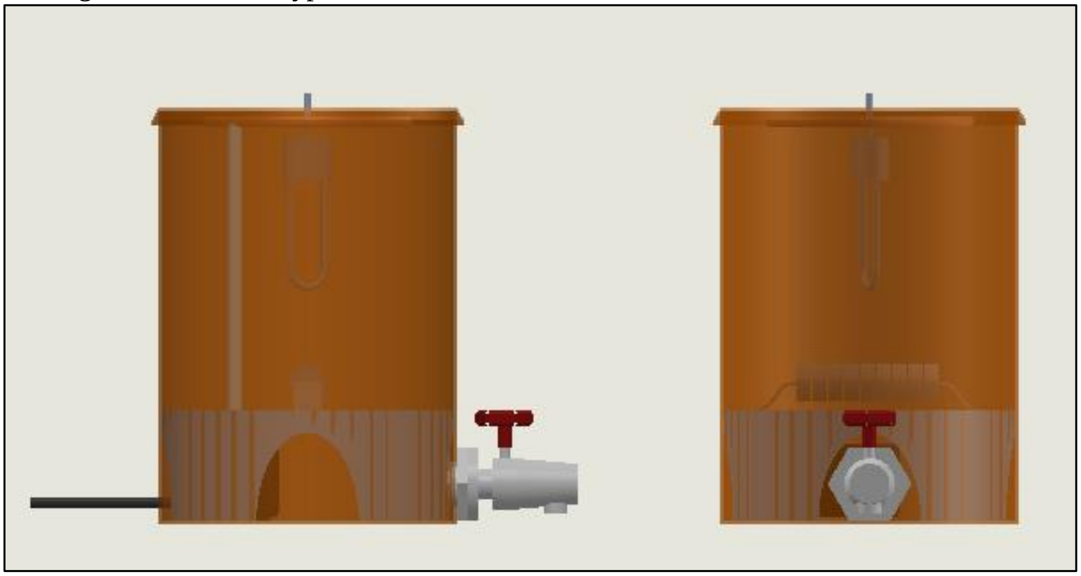

*Figure 3 shows the design of the prototype snow melter. The heating element is suspended from the top. The pump system is snow with its extension cord mounting through the tank body and the water connected to a circulated system in the lid. The spigot is also displayed mounted at the bottom of the tank wall.*

The preliminary proposed design is shown in Figure 4 and details about the selected components are included in the bill of materials (BOM) in Table 2. The circulation system, filter, and container all required in-house manufacturing while the heating element and pump were unmodified purchased components.

The circulation system required the most manufacturing. First the copper tubing was coiled into a spiral with the outer diameter matching the diameter of the bucket lid. Then 3/32" holes were drilled every inch on one side along the length of the tubing. A 17" segment of food-grade clear plastic tubing was cut to connect the pump at the bottom of the tank to the copper tubing. A hose clamp secured the plastic tubing at each end. Hose clamps were also used to secure the copper tubing to the underside of the bucket lid.

The filter also needed to be manufactured. A second five gallon bucket was used to make the frame, ring, and handle. The plastic filter material was cut into a ring and secured with silicone and two ¼-20 screws. Perpendicular to the screws, the handle was mounted with two additional ¼-20 screws. Four slots were cut into the frame to provide clearance for components mounted in the wall of the bucket.

A five-gallon bucket, and spigot with sealing bung were used to make the container for the snow and water. A hole was drilled near the bottom of the five-gallon bucket for the bung. The bung was inserted and sealed with a non-toxic silicone sealant. The heating element and pump cable were also mounted into the wall of the bucket. This was done by drilling a clearance hole for the cable, and sealing the hole with grommets and silicone. Grommets were used with hardware to provide additional mechanical support. All holes were checked for leaking after manufacture. Figure 5 shows an iteration of the completed design.

**Figure 4.** Components of the Prototype Snow Melter

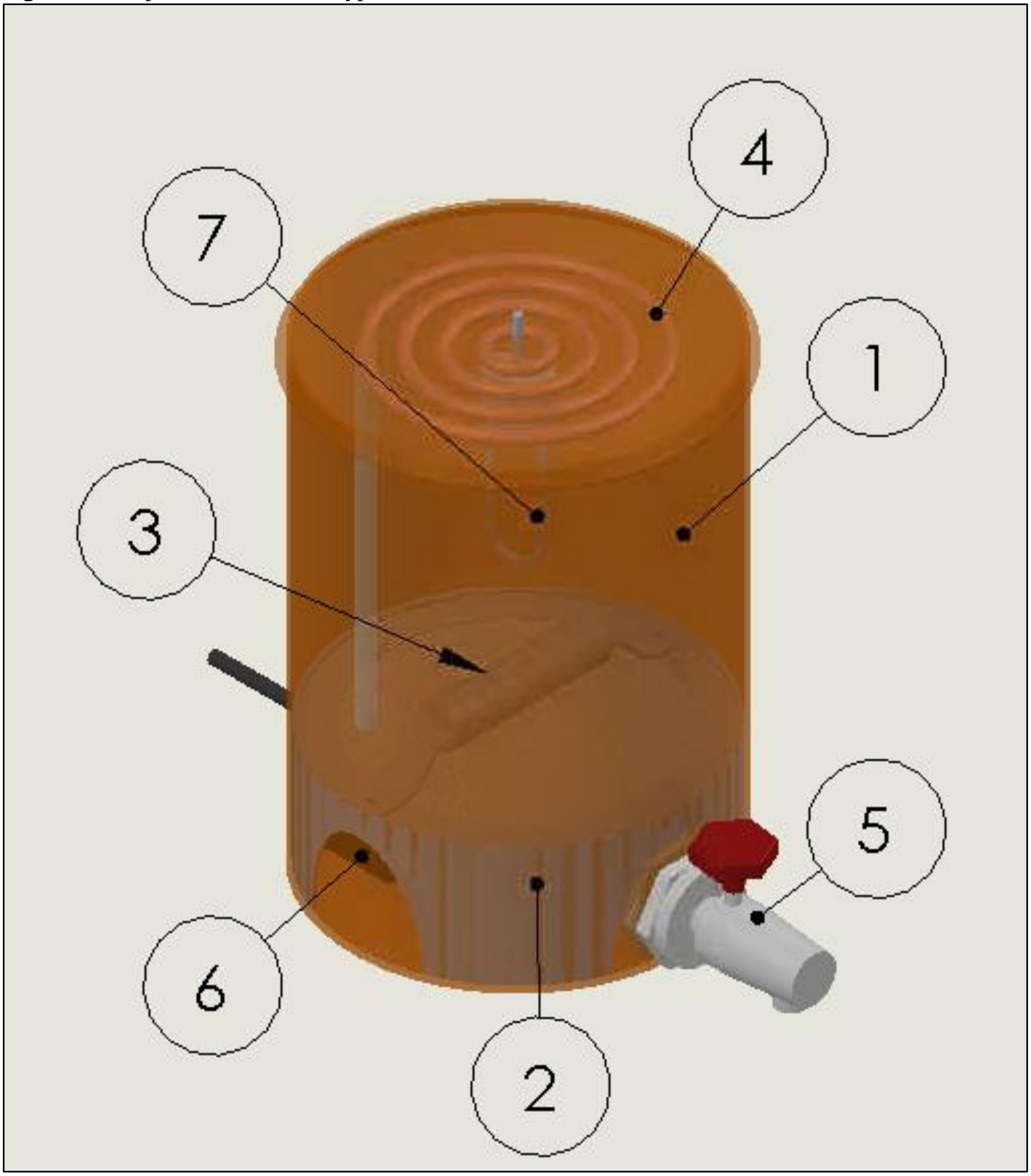


*Figure 4 shows a diagram of the prototype snow melter with the main components numbered. Hardware is not shown in this diagram. The containment system, heating and recirculation elements, filter, and pump are displayed.*

**Table 2.** Components of the Prototype Snow Melter

| | Name | Description | Supplier/Manufacturer and Part Number | Manufacturing Description |
|---|---|---|---|---|
| 1 | Tank | Plastic 5-gallon bucket | Home Depot (131227) | Drill holes in bucket for spigot and pump cable; drill holes in lid for U-clamps securing copper coil and heating element |
| 2 | Filter | Plastic and plastic mesh | | Manufacture plastic body from second 5-gallon bucket base; cut and adhere mesh to plastic framework |
| 3 | Filter Handle | Plastic | | Cut and secure from second plastic 5-gallon bucket |
| 4 | Copper Coil | 3/8"X10' refrigeration coil | 647791 | Cut to length and bend into coil |
| 5 | Spigot | 3/4" plastic spigot with 1 1/2" seal | Flo-Rite (57WFLO) | |
| 6 | Pump | 11.5 W pond pump | Little Giant PES-A 63GPH | |
| 7 | Heating Element | 5 W coffee/tea heating element | Norpro Immersion Heater, Ace Hardware (67934) | |
| | Solar Panel (not shown) | 11"X28"X1" | Goal Zero Boulder 15 | |
| | Battery (not shown) | 120 W (max) Solar Generator | Goal Zero Yeti 400 | |

**Figure 5.** Photographs of Prototype Design


(a) (b) (c)

*Figure 5(a-c) show images of an iteration of the design, the only difference being the mounting location of the heating element. Figure 5(a) shows an external view of the device. The spigot can be seem mounted to the side, as well as the heating element cord. Figure 5(b) show the internal structure of the system. The copper coil on the lid is where water is recirculated from the pump at the bottom of the tank. The white filter can also be seen. Figure 5(c) shows the system without the filter. The heating element and pump are both visible at the bottom of the tank.*

The solar panel and battery specified were both Goal Zero products. Goal Zero was specifically requested by the customer because their products are easy to use and are designed to withstand harsh environmental conditions. The battery, the Yeti 400, has two 12V outlets built into the pack. The Boulder 15 solar panel remains compact and portable. These two components are shown in Figure 6. Total charge time is approximately 24 hours but may be reduced if solar panels are added together. The total weight of the system is less than 35 pounds, making it easy to transport up and down the mountain.

**Figure 6.** Goal Zero Yeti 400 Battery Back and Boulder 15 solar Panel


*Figure 6 shows the GoalZero Yeti 400 battery (left) and Boulder 15 solar panel (right), which were selected for the design. The Yeti 400 was selected because it supplies a sufficient power and has two outlets for the pump and heating element. The Boulder 15 is portable and can charge the Yeti 400 in about one day. This time can be reduced by purchasing additional solar panels, which are designed to "stack" with one another and decrease battery charge time. Number of solar panels used is up to the discretion of IMG.*

## Relating Power to Melting Rate

Snow melt rate is one approximation for performance of mechanically melting snow. A prototype was manufactured and tested to correlate power input to melt rate of snow. The snow melt rate was compared with other measured values of snow melt to verify calculations. First, an equation was derived based on the geometry of the tank to relate power to melting rate. Then, the device was testing using components of known power input to determine the experimental melting rate of the snow. Once verified, the amount of power required to produce a given volume of water was applied to the system proposed for IMG.

[Eq. 3 was applied to the geometry of this device to predict melting rate of a known power input. For this application, the snow was assumed to have a constant surface area and melt downward, as shown in Figure 7. The surface area was assumed to be approximately constant because water was relatively evenly distributed across the surface of the snow. Using this assumption, [Eq. 4 was adapted from Equation [Eq. 3 and the relationship between heat and power to apply to this specific situation.

**Figure 7.** Approximated Melting Behavior of Snow in a Cylindrical Tank

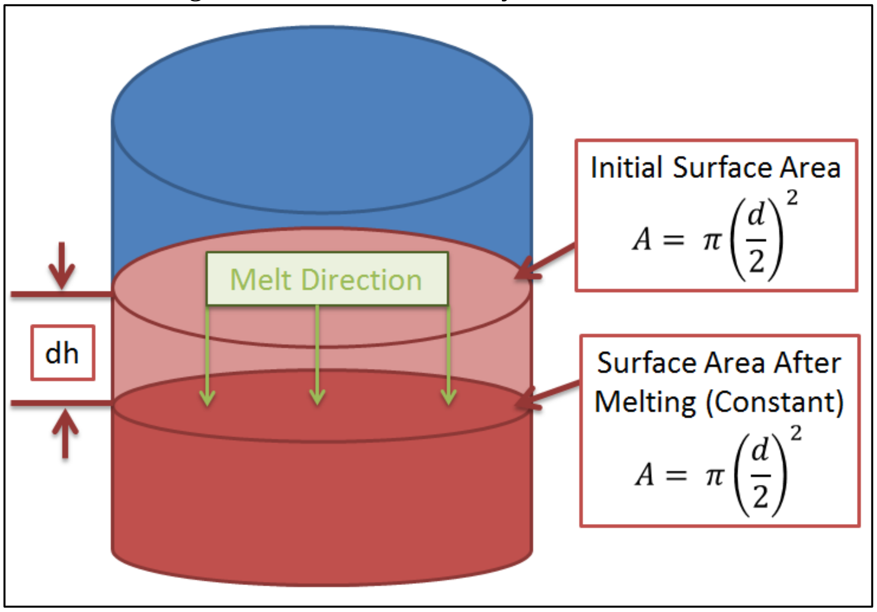


*Figure 7 shows a simplified diagram of a column of snow melting. This column of snow represents the snow in the tank during experimentation. The blue area is the total tank. The pink section is some initial volume of snow, and the red section is the volume of snow after some melting has occurred. The snow is modeled as melting along the height of the column only. The surface area is approximated as constant.*

*Power Required for Snow Melt in a Cylindrical Container* [Eq. 4]

$$P = \frac{Q}{t} = \rho c \Delta T\left[\pi\left(\frac{d}{2}\right)^2\right]\frac{dN_h}{dt} + \rho l\left[\pi\left(\frac{d}{2}\right)^2\right]\frac{dN_h}{dt}$$

Q = Heat [kJ]
t = time [s]
ρ = Fluid Density [kg/m$^3$]
c = Specific heat of water [kJ/kgK]
ΔT = Change in temperature [K]

d = Tank Diameter [m]
l = Latent heat of fusion [kJ/kg]
= 334 kJ/kg for water/ice
$dN_h/dt$ = vertical melt rate [m/s]

An experiment was conducted by evaluating how much snow was melted by the device under similar environmental conditions. The tank was tested in both actual outdoor conditions with real. It was allowed to calibrate outside (i.e., turned off, without water or snow in the tank, under a covered and dry area) for thirty minutes. Then, the tank was filled with a known volume of water and snow. Initial temperatures of the water, snow, and air were recorded. The tank was then turned on and allowed to run for one hour.

Water and snow temperature were measured every three minutes using a laser temperature sensor. This was done by removing a small sample of water from the spigot and measuring the temperature with the laser temperature sensor. This sample was then poured back into the bucket through the clearance hole in the lid. Snow temperatures were measured by opening the lid just enough to sense the snow with the laser. Snow melting observations were also recorded to more accurately describe melting behavior relevant to this study.

## Design Modifications

Initial testing resulted in component failure in several areas. Sealing failures and failure of the heating element meant that data could not be collected during experimentation. These issues were remedied by making changes to both the design configuration and its selected components.

Frequent leaking problems of the manufactured tank and evaluation by the customer led to changes in the configuration of the design. The five-gallon bucket was replaced with a five-gallon insulated water cooler to eliminate leaking. All electrical cables could be threaded through the lid and the water cooler included a built-in spigot. Because only the lid required additional manufacturing to make clearance for cables, the device no longer leaked. Customer feedback from IMG also indicated that the internal filter could be entirely omitted. Any sanitation required would be provided by IMG and/or the climbers as needed.

Failure of the heating element led to the replacement of this component for the final design. Although the Norpro heater was designed to work in both air and water, the plastic coupler melted when left in air for more than a few minutes. Instead, an electrical in-line water freeze protection cable was used. These types of heaters are intended to be wrapped along outdoor pipes carrying water. The cable is electrically powered and maintains a temperature just above freezing. They are weather resistant and waterproof, making them ideal for this type of application. To account for differences in component geometry, the freeze protection cable was hung into the water at the bottom of the tank, and wrapped to follow the circulation coil in the tank lid.

### Testing Results and Discussion

Initial and final conditions of the test are shown in Table 3. Changes in water and snow temperature with time are also displayed in Figure 8. Relevant observations were collected by multiple viewers. These observations were documented and played a critical role in determining the melting rate.

**Table 3.** Environmental Conditions During Freezer Testing

| | |
|---|---|
| In-line Heater Power | 42 W |
| Pump Power | 11.5 W |
| Total Power | 53.5 W |
| Average Outdoor Air Temperature | -2.6 °C |
| Initial Volume of Water | 2.4 L |
| Initial Volume of Snow | 4.0 L |
| Total Experiment Time | 60 minutes |
| Total Volume of Water in Tank After Melt | 3.84 L |
| Total Volume of Water Melted from Snow | 1.44 L |

Comparing Figure 1 to experimental results in Figure 8 shows that similar trends are present during sensible and latent heat transfer. The water and snow converge near the melting point of snow and are approximately constant through the duration of the experiment. Small dips in water temperature are noted when large chunks of snow fell into the water to explain deviation from constant temperature.

Observed melting behavior was used to determine overall melt rate. About 70% of the snow volume melted at 21 minutes and 90% had melted by 36 minutes. After 21 minutes, large gaps in the snow pack had formed where water dripped between snow and not over the top. As a result, melting rate decreased significantly after this point. Because the melt rate had changed after this point, the data collected at 21 minutes was used to determine the melting rate. This assumed that 70% of the total volume of water produced had melted by due to the total power input in 21 minutes.

**Figure 8.** Changes in Water and Snow Temperature during Experimentation (Annotated)

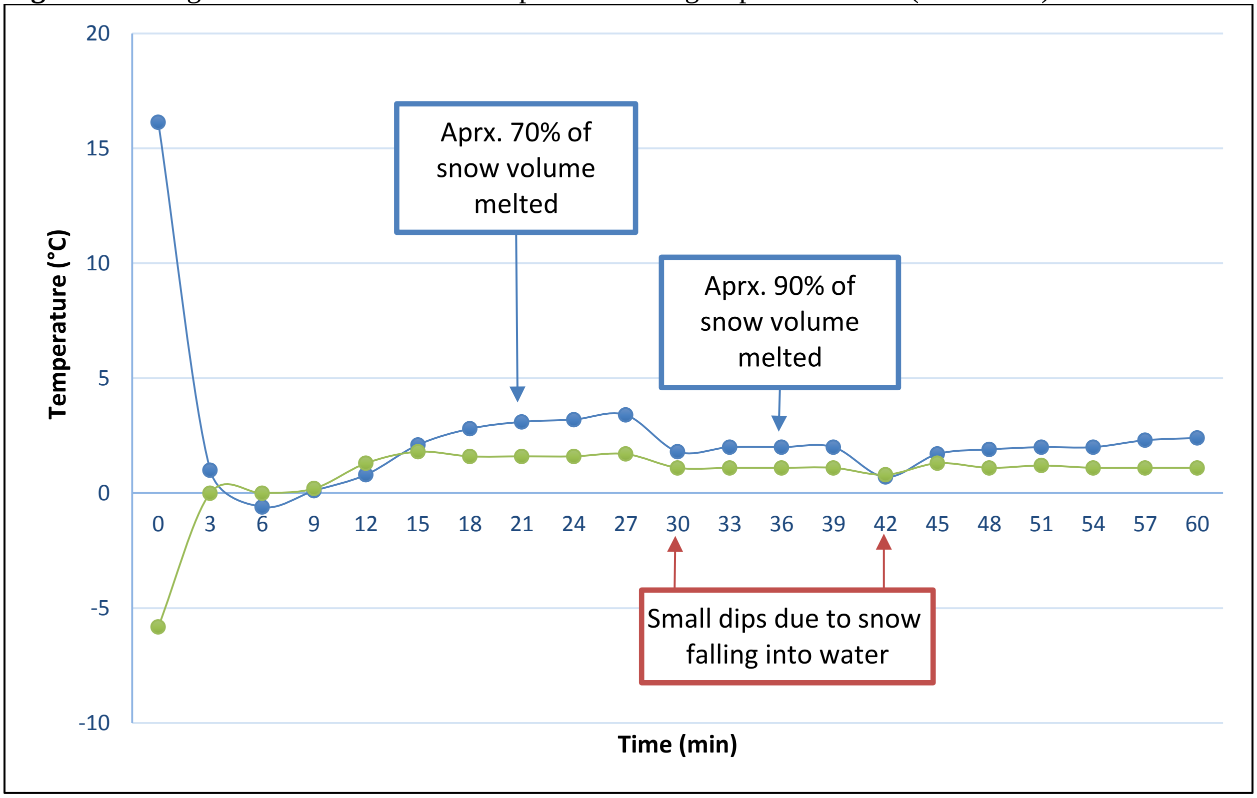


*Figure 8 shows the change in measured temperature of water samples taken during the experimentation process. Both the water and snow temperature were measured using a laser temperature sensor. Annotations are included to document relevant observations. About 70% of the snow in the tank melted after 21 minutes, and large holes in the snow surface were present. At 36 minutes, nearly all of the snow had melted. At 30 and 42 minutes, the temperature of water dips when large chunks of snow fall into water in the bottom of the tank.*

Table 4 shows the properties used to calculate the melting rate according to [Eq. 4 and compares the calculated melting rate to those found in literature. The vertical melting rate determined by the experiment was 2.90 µm/s. This melting rate was compared to snow melt rates collected by the US Navy under "heavy rain, [and] windy" conditions. Because this is within the same order of magnitude as theoretical snow melt, this correlation between melt rate and power was used to determine requirements for the final design.

**Table 4.** Fluid Properties Used to Determine Snow Melting Rate

| **Property** | **Symbol** | **During Experiment** |
|---|---|---|
| Total Power | P | 53.5 W |
| Time | t | 21 minutes |
| Water Density | ρ | $kg/m^3$ |
| Specific Heat of Water | c | J/kgK |
| Change in Temperature | ΔT | 6.9 K (6.9 °C) |
| Tank Diameter | d | 0.254 meters (10") |
| Latent Heat of Ice/Water | h | 334 kJ/kg |
| **Vertical Melt Rate** | **$dN_h/dt$** | **2.91E-6 m/s (9.90 in/day)** |
| **Theoretical Melt Rate** [11] | **$(dN_h/dt)t$** | **0.953E-6 m/s (3.24 in/day)** |

Error in calculations may arise from differences in environmental conditions, limited available information about theoretical melting rates, and additional contributors to experimental melting rate. Available theoretical melting rates were still in uncontrolled environments as opposed to mechanically produced melting. The rates found in literature all reflected data collected by measuring water runoff from mountainous regions. Additionally, rates from this source were limited to a seven combinations, including "heavy rain, windy," "light rain, windy," and "light rain, light wind." The conditions that most closely match the experiment outlined in this document were in "heavy rain, windy" conditions. Lastly, have a system with a temperature maintained above freezing may have caused the experimental melting rate to be greater than those found in literature. Despite these discrepancies, the magnitudes of vertical melt rates found in literature are similar to those determined experimentally, meaning this relationship between power and melt rate can be used to determine overall melt time for the total volume required by IMG.

# Final Design

Results from testing the final design were verified to ensure that a sufficient quantity of water could be provided within one day. The total time to melt the required water was calculated.

## Application of Experimental Results

The rate of snow melt determine during experimentation was applied to the customer requirements at Camp Muir to determine how long it would take to melt snow into the required volume of water. Table 5 shows these calculations.

**Table 5.** Time Needed to Melt Required Volume of Snow for Hikers on Mt. Rainier

| | |
|---|---|
| Experimental Relative Volume of Snow to Water | 0.36 [L/L] |
| Volume of Water Required per Person | 5 L |
| Number of People per Day | 12 |
| Total Volume of Water Required per Day | 60 L |
| Heat Required for Experiment | 67.4 kJ |
| Heat Required for Application at Camp Muir | 2.81 MJ |
| Time Required for Melt at Camp Muir | 14.6 hours |

Each of the 12 members in IMG's hiking groups requires 5 L of water per day, resulting in 60 total liters that need to be produced. Experimentation showed that 67.4 kJ could produce 1.44 L of water in 21 minutes. If input power of components remains the same, 2.81 MJ of heat is required to produce the 60 required liters of water. This will take a total of 14.6 hours.

## Final Design Description and Use

Images of the final design are shown in Figure 9 and 10, and photographs are included in Figure 11. Figure 9 shows the water cooler tank with clearance hole for electronic cables in the lid. Figure 10 shows a cross section of the tank. The in-line heater and copper circulation system are both shown on the underside of the lid. An updated BOM is also included in Table 6.

**Figure 9.** Final Snow-Melter Design

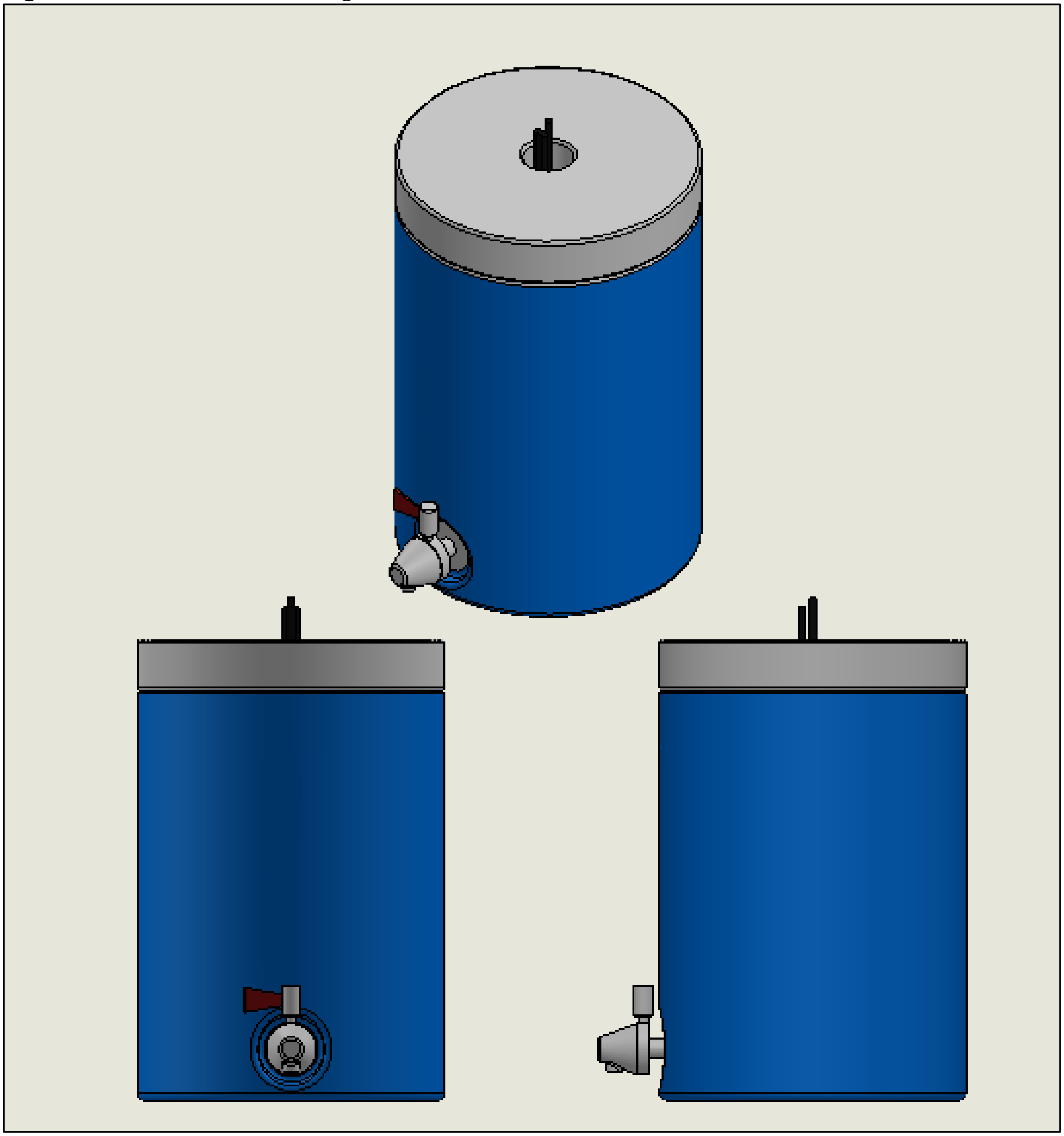

*Figure 6 shows several views of a model of the final design. The two cables coming out of the top of the lid connect to the in-line heater and the pump. Threading cables through the lid and using a tank with a built-in spigot eliminated the possibility of leaking as a result of poor sealing during manufacturing.*

**Figure 10.** Cross Section of Final Snow Melter Design

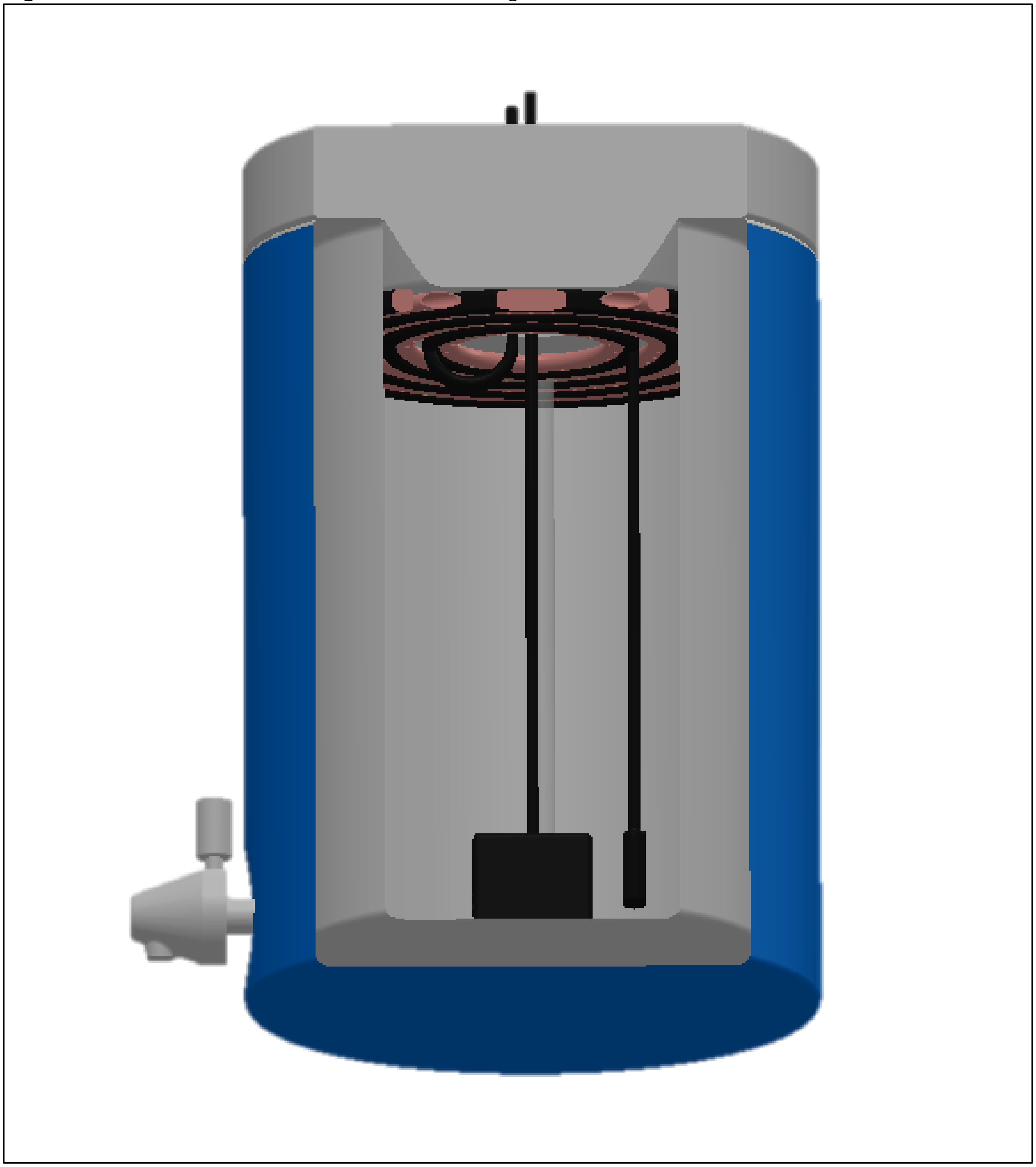

*Figure 7 shows the final design with a section removed from the model. The brown copper coil and black heating element can be see wrapped on the underside of the lid. The pump is still at the bottom of the tank. The clear tube connects it to the circulatory copper coil, and its cable runs through the lid. The black cable hanging into the tank is the heating cable and its temperature sensor. Hanging the sensor in the snow ensures the tank will be maintained at above freezing temperatures.*

**Figure 11.** Photographs of the Final Design


(a)

(b)

(c)

*Figure 11(a-c) show images of the final design. Figure 11(a) shows the outside of the tank. Figure 11(b) shows the internal configuration. The pump rests in the bottom of the container and is connected to the recirculation system mounted to the lid. The end of the heating element can also be seen hanging into the tank. Figure 11(c) shows the recirculation system in more detail. The copper coil has 3/32" holes drilled every inch along its length to simulate rain falling over the snow. The heating element has been secured to wind with this coil. Its temperature sensor and part of the heating element are suspending within the tank to continue melting inserted snow.*

**Table 6.** Components of the Prototype Snow Melter

| Name | Description | Supplier/Manufacturer and Part Number | Manufacturing Description |
|---|---|---|---|
| Tank | 5 gallon insulted water cooler | Bi-Mart, Coleman (300000735) | Drill holes in bucket for spigot and pump cable; drill holes in lid for U-clamps securing copper coil and heating element |
| Copper Coil | 3/8”X10’ refrigeration coil | 647791 | Cut to length and bend into coil |
| Pump | 11.5 W pond pump | Home Depot, Little Giant PES-A 63GPH | |
| Heating Element | 6’ in-line water freeze protection cable | Home Depot, Frost King Electric Water Pipe Heat Cable (474258) | |
| Solar Panel (not shown) | 11”X28”X1” | Goal Zero Boulder 15 | |
| Battery (not shown) | 120 W (max) Solar Generator | Goal Zero Yeti 400 | |

They key changes in the BOM include removing the spigot and filter, replacing the container with an insulted water cooler, and changing the heating element to an in-line freeze protection cable. As discussed in the Design Modifications section, these simplified the design while increasing durability of components.

# Conclusions and Applications

National and international applications were explored. Considerations for using the device in other regions are discussed and case studies are provided. The similarities in environmental conditions make this area ideal for further application. The effectiveness of the design process was evaluated and projections for implementation are discussed in this section.

## Considerations

Considerations for applying this device in other areas around the world include the environment, climbing group, and snow quality. The final design can be directly applied in similar conditions or adapted for different external conditions.

Environmental qualities such as altitude of device use, air temperature, and general difference in weather should be analyzed when determining whether or not this device can be used. The components of this device have a usable temperature range, and factors such as summit altitude and air temperature will dictate whether or not the melting system could be used throughout the duration of the climb. Other weather-related factors should also be considered, such as cloud cover or altitude of the timberline. Limiting exposure to sunlight would extend the time required for the battery to charge. This means that more solar panels would be needed or climbing organizations would need to provide larger intervals between climbs to charge their batteries.

Climbing conditions like group size and trip duration are also worthwhile considerations. Larger group sizes or climbs with longer durations would require the device to be adapted. Multiples of the snow melter, solar panels, and batteries could be used or a larger tank could be manufactured. Similarly, a smaller tank could be manufactured for smaller groups or climbs with a shorter duration.

Quality of the snow is one of the most important factors in determining if this device could be used in another region. Snow is often characterized by its water-to-snow ratio, or how much water is produced from a given volume of snow. Regions with high water-to-snow ratios are ideal for this device because less snow must be collected to produce the required amount of water.

## National Applications

In addition to their Mt. Rainier climb, IMG also leads guided climbs to the summit of Mt. Whitney in California. Its summit at 14, 495 feet is about the same altitude as Mt. Rainier. On this four-day trek for six people, climbers stop at Lower Boy Scout Lake at 10, 300 feet and near Iceberg Lake at 12, 240 feet. Conditions tend to be about the same as Mt. Rainier, but the climb tends to be more challenging due to icy patches along the trail.

This design could easily be adapted to apply to climbing groups of this size and for this duration. Because there are fewer people in the climbing group, the battery and solar panel could likely stay the same. The size of the tank could even be sized down for additional portability. Additionally, Lower Boy Scout Lake, where climbers stop for their first night, is at a very similar altitude to Camp Muir.

Challenges to applying the design to this climb include greater variation in snow cover and type and use in colder temperatures. Snow cover varies significantly along the climbing trail. Some areas are covered in ice or exposed rock, limiting the regions along the trail where this device can be used. Additionally, temperatures are well below freezing as climbers approach Iceberg Lake. This nears the usable limits of the components. Replacing components with higher minimum operating temperatures would make this design applicable to IMG's Mt. Whitney climb as well.

## International Applications

Easy adaptability of this device make it a potential solution for other hiking groups in international applications. Mountain ranges in Europe have a variety of mountain with similar altitudes and climbing schedules. Differences in snow cover would require some addition adaptation of the device. In South America, year round snow cover in the Andes means resources would always be available for water production, although some larger-scale modification would be required to ensure the device functioned at higher altitudes with lower temperatures.

Switzerland and its neighboring regions, including Germany and France, offer a range of mountains that are about the same altitude as Mt. Rainier, particularly in the Pinnine Alps. Some of these mountains include Grand Combin (14, 150 ft.), Dent Blanche (14, 300 ft.) the Matterhorn (14, 700 ft.) and the Taeschhorn (14, 700 ft.). Even mountains with lower peak altitudes, like Zugspitze (9, 700 ft.) in Germany, could use this for the two-day climb required to summit its peak.

This region has a similar latitude to Mt. Rainier, making weather conditions and the open mountaineering season nearly identical. Climbers usually choose to summit mountains in this region from July to early September, and climbing with an organized group is very typical. Other climbing groups like Alpine Ascents International and Alpine Adventure Trails Tours often offer guided tours and introductory courses for novice or first-time climbers. Most of these are two or more days with small groups of people. Smaller groups or mountains with lower summits could even utilize the smaller tank discussed above.

Key factors to consider when adapting this design to be used in this region is that, despite generally having similar snow characteristics and climbing conditions, there is typically more regional cloud cover than in the Pacific Northwest. This would likely require using more solar panels to charge the battery within a 24 hour period. This can easily be accomplished using GoalZero panels, which are designed to be using in parallel to produce a quick charge time or greater power as needed.

The Andes Mountains in South America are another area of potential application of this device because of the similar environmental and climbing conditions. These regions are characterized by minimal cloud cover and persistent ground snow during climbing season. Although many of the more popular mountains have much higher elevations, some mountains like the Volcan Domuyo (15, 400 ft.), Pico El Buitre (15, 300 ft.), and Villarrica (9, 400 ft.) may be ideal.

Most of these regions are open for climbing in July through September, and guided tours are commonplace for tourists. These tours are typically two days of intense climbing to summit with several additional days before and after the climb for elevation acclimation. The two day climbing schedule is identical to that of IMG's Mt. Rainier climb, ensuring that a sufficient amount of water count be produced under similar environmental conditions.

Primary concerns when adapting this design are to ensure that components can withstand lower temperatures if used at higher altitudes. Most of the mountains in the Andes are about 20, 000 ft. in elevation and require longer climbing trips to summit. Limited cloud cover and semi-permanent ground snow would mean resources are readily available for water production. However, temperatures well below freezing could cause component failure. The heating element and pump may need to be replaced to be used at these higher elevations if temperatures are significantly lower.

## Conclusion

The application of typical engineering design processes applied well to the design and manufacture of a solar-powered snow melter for IMG. Collecting customer requirements and correlating them to engineering specifications in a House of Quality helped identify key areas of design. Developing a functional decomposition to generate potential designs assisted in the selection of a design that optimized customer and technical goals.

The prototype design was successfully used to identify failure modes and to experimentally determine the melt rate of snow for this application. Components that failed during testing were replaced for the final design. Experimental testing also yielded the approximate melt rate of snow at 2.91 μm/s (9.90 in/day). This melt rate was applied to determine that the required volume of water could be produced in less than 15 hours using the designed system.

The design will be implemented by IMG during the Spring-Summer 2014 hiking season. We look forward to continued evaluation of components and further analysis of performance of the design when in use at Camp Muir.

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