Design and Prototype of a Freshwater Ice Thickness Measuring Device

A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfilment of the requirements for the
Degree of Bachelor of Science

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Date:
25 April 2017

Report Submitted to:

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Abstract

In the United States, roughly 3,500 fatal drowning incidents are reported each year. A portion of which consist of cold water instances where the ice thickness of a frozen body of water is insufficient to support the weight of the individual, causing the ice underneath them to break. The proposed electromechanical design is an autonomous thermistor chain which can be used to relay the temperature profile of a body of water to an onshore receiver. The device utilizes thermistors to measure the temperature of water/ice at various depths to quantify the ice thickness of a body of freshwater. The device aims to increase ice safety by eliminating the need for on ice tests. After designing and manufacturing a thermistor chain prototype, the team created an insulated testing apparatus to simulate the freezing process of a body of freshwater such as a lake or pond. The data collected provides a representation of the accuracy of the device and serves as proof of concept.

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1.0 Introduction

In the United States, especially in the northern areas, a variety of recreational and commercial activities take place on frozen bodies of freshwater. Ice Fishing, ice-skating, snowmobiling, etc. are all dependent on the thickness of ice that formed on the surface of the water. For instance, according to the Centers for Disease Control and Prevention (CDC), ice thickness needs to be at least 4 inches thick to support the weight of a human ("CDC - BAM, Physical Activity, Fishing", 2017). This is also dependent on the type of ice. White or snow ice is half as strong as the solid "clear" ice. If the ice thickness is not known, there is a chance of breaking through.

Here in the United States (U.S.), there are roughly 3,500 annual drowning incidents, disregarding boating accidents, and including falling through ice ("Unintentional Drowning", 2017). In 2013, there were a total of 53 reported lake/river ice related deaths in the U.S. and Canada, with Canada and Wisconsin being the leading locations, each having 10 fatalities each ("Fatalities on North American Ice -2013 Season", 2013). These numbers are relatively constant year to year as in 2016 there were 41 recorded fatalities. The primary factor which caused lower numbers in 2016 was due to the short ice season as the U.S. endured a relatively mild winter ("Lake Ice - 2016 Fatalities", 2016). There is not a record of reason for falling through ice besides assuming it was due to it being too thin and failing under the weight. In addition, several accidents occurred in pairs which is most likely due to a second person venturing out onto the thin ice in order to rescue the initial person who fell through ("Unintentional Drowning", 2017).

The rate of falling through ice remains constant, with little attempt to change it. The Royal Society of Prevention of Accidents (ROSPA) advertises on signs of thin ice and survival steps if one does fall in ("Ice Safety", 2017). Additionally, there are multiple attempts on determining ice thickness in a safe way. An example is patent US4287472 A, which is an electrical approach to measure ice thickness without drilling a hole. It is dependent on the electrical resistance in ice versus the water below (U.S. Patent No. 4,287,472, 1981). The patent used to start brainstorming in this project report is another attempt on measuring ice thickness. This mechanical process operates through visual signaling to the shore when the thickness is safe enough to hold a person (U.S. Patent No. 8,299,931, 2012). The provided public information and devices are only beginning steps to reducing the fatalities due to freshwater ice thickness.

Ultimately, the purpose of this project is to manufacture an accurate way to measure ice thickness of a body of freshwater without having a person physically go onto the ice. By doing this, it will eliminate the risk involved with the unsafe "Guiney Pig" process of a person using an auger, drill, or other method of testing ice thickness. To start, the team researched ice measuring methods currently in use, either mechanical or electric, as well as processes currently under development. Once a method was chosen, the team developed a prototype to determine the accuracy of the recorded measurements in a simulated freshwater environment. The ideal design is an autonomous system which relays ice information to the user so they can adequately advertise the thickness of either the lake or pond to avoid the potential fatalities involved with venturing on to unsafe ice.

The anticipated markets for this product are aimed primarily towards a city's parks and recreation services, winter sport clubs, and the individual consumer. Parks and recreation sectors of the government can use these devices to eliminate the need for signs which arbitrarily claim that the ice thickness is unknown or to "proceed with caution." Instead, signs which display accurate listings the maximum load the ice thickness can support can be used to eliminate uncertainty. In addition, winter sport associations, such as ice fishing or snowmobiling clubs, often provide trail information or data regarding lakes. This information is often emailed to its' members on a weekly basis in an attempt to reduce the individuals from putting themselves in a potentially life-threatening situation. Closing down trails or access points as well as warning people of unsafe conditions such as when the ice has not fully formed or when thawing, will hopefully reduce the number of incidents of people falling through the ice can be mitigated and winter sport enthusiasts can enjoy the outdoors safely.

2.0 Background

Winter activities that take place on frozen bodies of freshwater are dependent on ice thickness. Ice thickness has to meet a certain depth in order to withstand the various loads involved with these activities and should be known in advance so the outdoor enthusiasts can participate safely. This section will provide information regarding ice properties, ice measuring methods, and the design components needed in order to provide accurate information to the public regarding ice thickness.

2.1 Fatality Statistics/Safety

2.1.1 Ice Related Incidents

According to the Center for Disease Control and Protection (CDC), around 3,500 fatal accidental drowning's occur annually in the United States ("Unintentional Drowning", 2017). This does not take boating related accidents into account and includes cold water instances, such as falling through ice. In a case where someone falls through the ice in the winter months, the person will immediately be surrounded by water that is well below their body temperature of 98 degrees Fahrenheit. Once in the cold water, your body's cold shock response, called the "torso reflex" will make the person want to gasp for air and hyperventilate due to our increase in heart rate (Lewis, 2017). This reflex is a primary contributor to drowning cases in cold water as the gasp for breath results in cold water filling the person's lungs. The initial shock wears off in roughly 1-3 minutes but soon the body begins to develop hypothermia (Lewis, 2017). Hypothermia is when the body is losing heat faster than it can be generated ("Hypothermia - Winter Weather", 2016). In a study done by the CDC through 2006 to 2010, there were approximately 6,600 fatalities in the U.S. due to exposure to excessive cold temperatures or hypothermia. The data is collected from submerged bodies, cold sweat, outdoor activities, or consuming alcohol and/or drugs ("Hypothermia - Winter Weather", 2016).

2.1.2 Correlation of Ice Thickness and Seasons

A few studies on lake/pond ice related fatalities were conducted in the United States. A collection of Minnesota data form 1979 to 2016 was analyzed based on the number of fatalities due to lake ice (MN DNR – Boat, & Water Safety, 2016). The data was organized into seasons, ages, mode of travel, and location. Each recorded incident was tagged with the date, county, location name, victim age, and the accident type. A winter season in Minnesota is from

November to April and during the winters of 1982-1983, there were the most deaths from lake ice, 22 fatalities (MN DNR – Boat, & Water Safety, 2016). More recently, 2010 to 2015, there were 22 deaths out of the 5 seasons, making 4.4 deaths per winter season. Additionally, 50% of the lake ice related fatalities were due to snowmobiles or ATVs, and 5% are from being on foot (MN DNR – Boat, & Water Safety, 2016).

Further data analysis was done in Wisconsin, in addition to North American as a whole. The Wisconsin Department of Natural Resources (DNR) created a report on snowmobiles incidents from 2012 to 2013 (Stark, 2013). For this report, data was collected from crash, registration, and arrests reports and was further analyzed. This year's data had 10 more fatal accidents than the previous year with a total of 20 snowmobile accidents. The DNR of Wisconsin found that 25% of these accidents occurred by the vehicles breaking through the ice (Stark, 2013). Statistics were collected from North American accident reports in 2013 on incidents where people fell through ice. There were a total of 53 fatalities and 20 of them occurred in Canada and Wisconsin ("Fatalities on North American Ice -2013 Season", 2013). The 2013 report further explained that North American ice fishing and snowmobiling were the activities leading to the incident, in addition to majority of them occurring in January (16 fatalities) ("Fatalities on North American Ice -2013 Season", 2013). The weather at the time of the fatality was also taken from the data. During the thawing season, there were 21 fatalities, making it the leading ice conditions. The following condition is nighttime with 18 fatalities ("Fatalities on North American Ice -2013 Season", 2013).

From these reports it is determined that fatalities do occur when people fall through the ice. By knowing the activity causing people to fall through the ice helped target the product to meet a specific customer. Additionally, the stage of the ice works into the design of the mechanism. Whether the ice thickness is still increasing or starting to decrease, will impact the process of determining the safe thickness.

2.2 Ice Properties

Encountering lake ice during the winter in common for people in the northern parts of the United States. Knowing safe ice thicknesses, how lake ice freezes, how it thaws, and relationships between lake ice and other material is important to for these citizens to participate in their winter season activities.

2.2.1 Load Capacity

The basic formula for determining the maximum load of a sheet of ice, also known as "Gold's Formula,' is listed in *Equation 1* (Leppäranta, 2010).

- $P = Ah^2$ (Eq. 1)

Where:

P = Load
A = Ice Strength Constant (130-230 psi)
h = Thickness of Ice Sheet

In addition to understanding the basic load capacity, a safety factor is often taken into account when determining the load capacity of freshwater ice because there are several factors which may reduce its' strength. Measuring a single space on a lake or pond does not necessarily indicate a uniform thickness. For example, wet cracks, varying thicknesses due to shaded or sunny areas, snow drifts which inhibit ice growth, gas holes, etc. can all be contributing factors to ice which is thinner than the measured result. The safety factor (S) is imposed to reduce the risk of breakthroughs due to weaker ice and is calculated using *Equation 2* (Leppäranta, 2010):

- $S = 150psi/P(h^2)$ (Eq. 2)

Where:

S = Average Body Weight Breakthrough Strength
h = Thickness of Ice Sheet (in.^{2})
P = Load (lbs)

With these factors in mind, the Massachusetts Executive Office of Energy and Environmental Affairs state that it is crucial to remain off of freshwater ice when the thickness is less than 2". Once the ice depth has increased to 4", it is thick enough to hold an average person so activities such as ice fishing would be acceptable, 5" ice is safe enough to support a snowmobile, 8"-12" for a car, and 12"-15" for a medium sized truck ("MassWildlife Ice Strength and Safety Tips", 2017). The values obtained from this study correspond to the results obtained from Minnesota's Department of Natural Resources (Leppäranta, 2010). These thicknesses are of fresh clear ice. The white, snow and slush ice is only half as strong, therefore the required thickness should be doubled. To accurately determine the exact ice thickness, the person must venture out onto the ice, use an ice chisel to chop a hole and measure by hand. Knowing the initial thickness is important prior to going onto the ice, for if it is too thin, one can fall through. Eliminating this factor by having a device to read the ice depth without applying weight to it, will improve safety on lakes and rivers.

2.2.2 Ice Growth

Bodies of freshwater lakes and ponds freeze top down, ice is less dense than water which causes it to float and the density of the liquid water is determined by its' temperature. Water is the densest at 40 degrees Fahrenheit (Ackerman, & Martin, 2010). Typically, freezing occurs along the shoreline where the water is shallow and moves inward. Professors in the Departments of Atmospheric and Oceanic Sciences department at UW Madison, Steven Ackerman and Jonathan Martin, explain how ice layers form on bodies of water. Once the atmospheric temperature drops, lakes begin to release heat and start cooling. As the water on the surface cools, it becomes more dense than the water below it, therefore it drops to the base of the lake, forcing the warmer water to the surface to begin cooling. This is a continuous cycle until the entirety of the section of the lake is around 40 degrees Fahrenheit. At this point the difference in density stops cycling the water and the surface continues to cool. When the surface water hits 32 degrees Fahrenheit, it freezes, starting the process of creating a layer of ice (Ackerman, & Martin, 2010).

Ice that forms on the top of fresh bodies of water can come in three forms. A professor at the University of Helsinki, Matti Leppäranta, wrote a book on *Freezing of Lakes and the Evolution of Ice Cover*, covering majority of the processes of surface ice on a body of water. Leppäranta mentions the types of ice that can form on a lake. Figure 1 shows a cross section of 10 inches (33 cm) of surface ice (Leppäranta, 2010). When a body of fresh water freezes, it forms primary ice, congelation ice, and snow-ice ice. Primary is when ice crystals start to join and create a thin layer, as little as a millimeter thick (Leppäranta, 2010). As the ice continues to freeze, the ice crystals align vertically in addition to there being disturbances within the formation. This leads to the ice crystals coming together randomly. This process of the ice forming into the body of water is called congelation ice (Leppäranta, 2010). The white colored ice on the upper half of the cross section is called snow-ice ice. This is dependent on the environment that the body of water is in. Snow-ice is when snow that accumulates on the surface begins to melt creating slush. This slush then freezes and forms into the sheet ice. This ice layer is not as strong as the other layers resulting in unsafe measurements (Leppäranta, 2010).

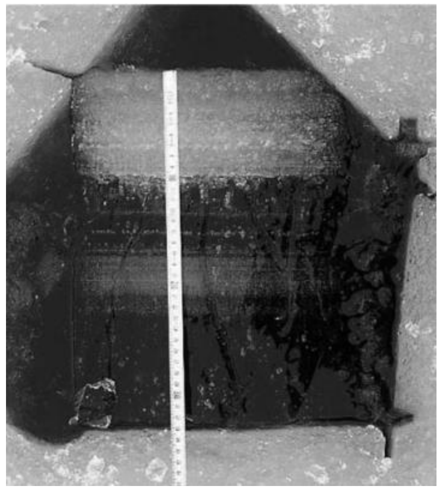


Figure 1: Cross Section of Lake Ice (Leppäranta, 2010)

There are factors that interrupt the ideal scenario of ice forming on a body of water, these are considered to be impurities. Depending on the lakes size and motion of water, there is a range in severity of impurities. For example, in larger bodies of water, there is more motion, either driven by wind or by current. This causes uneven freezing, in addition to multiple ice fractures, in comparison to static freezing on a smaller body of water (Leppäranta, 2010). Additionally, in Figure 1, large air bubbles form in the congelation ice layer, normally from released gas that was trapped in the water column or sediments (Leppäranta, 2010). These impurities can potentially decrease the strength of the ice.

In Leppäranta's text, he defines the thermodynamic process of freezing surface ice. The congelation ice layer is the main body of surface ice and it grows into the ice. The growth of this ice is dependent on the latent heat. During freezing, the latent heat is released from the bottom side of the ice and travels through the ice sheet into the atmosphere (Leppäranta, 2010). To continue increasing the thickness, the conductive heat flux through the ice sheet must be larger than the heat flux from the water to ice. With the increasing thickness of ice, there is a larger distance for the latent heat to travel causing a slower growth rate. The conduction of heat is calculated using *Equation 3*. This is by defining the freezing process on a lake to be solely in the vertical direction, disregarding horizontal variations due to the lake length being greater than a few meters.

- $\frac{\partial \rho c T}{\partial} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial \mathrm{T}}{\partial z} - Qs\right)\mathrm{t}$ (Eq. 3)

Where:

c = Specific Heat of Ice
T = Temperature
κ = Thermal Conductivity
Qs = Surface Heat Flux
z = Depth

Assuming that the heat flow through the ice equals the heat flow from the surface of the ice to the air above, or no snow cover has occurred, the following formula for the thickening of ice can be used (Ashton, 1998). *Equation 4*:

- $h = \left[\frac{2k}{\rho_i L}(T_m - T_a)t + \left(\frac{k}{H_{ia}}\right)^2\right]^{1/2} - \frac{k}{H_{ia}}$. (Eq. 4)

Where:

h = Ice Thickness
k = Thermal Conductivity
p_i = Density (Ice)
L = Latent Heat of Fusion
t = Time Since Initial Ice Formation
T_m = Freezing Point
T_a = Air Temperature
H_{ia} = Bulk Transfer Coefficient

2.2.3 Ice Decay

Knowing the process of thawing ice strongly impacts the safety of people on ice. It can be noticed that the coast of lakes and ponds melt faster than the center. The explanation of this is due to the inflow of warm water from the land's soil or streams feeding in (Ashton, 1998). This warm water hits the coastal ice and starts the melting process. The center of the lake normally melts slower than the edges due the thawing relying on heat transfer into the atmosphere from the sun (Ashton, 1998). In the progression on melting ice, once the snow that accumulated on the surface melts, the ice layer is exposed to the sun. With the ice exposed to the sun and the atmospheric temperature increasing above freezing, solar radiation begins the process of "rotting" (Ashton, 1998). Whether the ice begins melting from the top or from the bottom depends on the thermal condition (Ashton, 1998). In the duration of the winter months, there additionally is minor warming of the water beneath the ice, causing the base of the ice being weaker than the surface. This is due to solar radiation through the ice, or release of heat from the sediments at the base of the lake (Ashton, 1998).

Moriya Rufer, the Lakes Monitoring Program Coordinator for the Environmental Laboratories in Detroit Lakes, compares how the sun melts lake ice to a greenhouse. Rufer does this by the sun's ray's travel through the ice and heat the water below it. The warmed water below the ice, results in the ice begin to melt bottom up. When the ice reduces in thickness between 4 to 12 inches, it transforms into long vertical crystals, called candles (Swain, 2015). Figure 2 demonstrates ice candles. The rotting of the ice and formation of ice candles greatly reduces the ice strength to a point where it can only hold a fraction of what it used to (Ashton, 1998). These candles conduct light very well resulting in starting to melt the ice, which then has water fill in between the crystals. This results in the ice breaking apart (Ashton, 1998).

Figure 2: Ice Candles (Fatalities on North American Ice -2013 Season, 2013).

2.2.4 Freshwater Ice Temperature Profiles

After a body of water is cooled to the freezing temperature, the surface starts to freeze. Knowing the temperature of the ice in relation to the water and the air can extremely impact determining which measuring process to use. Lars Bengtsson conducted a study on lake ice on bodies of water in Sweden. The graph in Figure 3 shows the ice growth in Lulea˚, Sweden, indicating the snow height, white ice depth, and ice thickness (Bengtsson, 2012).

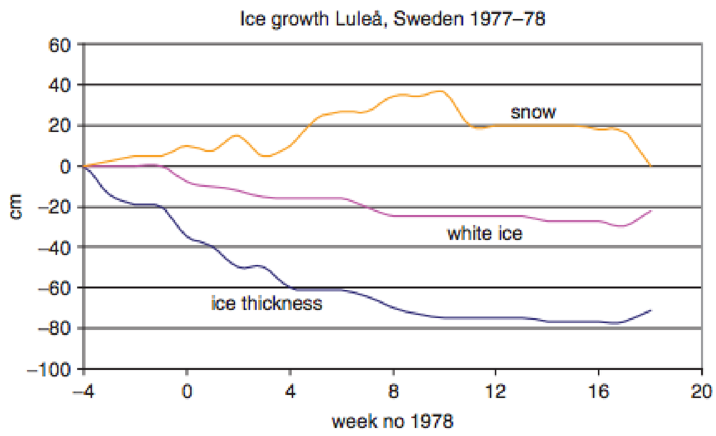


Figure 3: Ice Growth Lulea, Sweden 1977-78 (Bengtsson, 2012).

In Bengtsson's report, its states that once the lake water is completely covered in sheet ice, the ice acts as an insulator from the atmosphere. There is heat loss from the latent heat released from the growing ice and released into the cold atmosphere. There is a small heat flux from the water to the bottom surface of the ice and a large heat flux from the base of the lake. Over the year, heat is stored in the sediments of the lake and is released during the winter months ("CDC - BAM, Physical Activity, Fishing", 2017). Bengtsson explains in Figure 4 that over the course of the winter with the released heat, an ice covered lake will increase in temperature. In comparing the beginning to the end of the winter months, the overall temperature 2 meters into the body of water will remain similar, but through those months, the temperature beyond 2 meters in depth will increase.

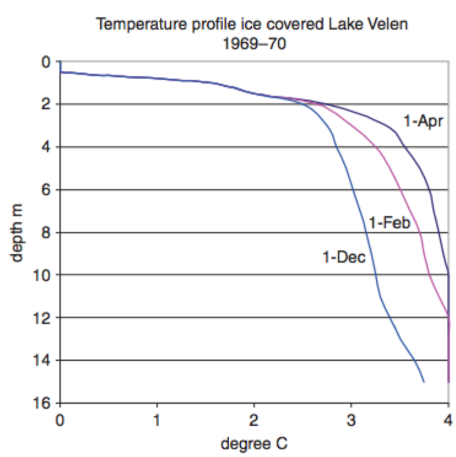


Figure 4: Temperature Profile Ice Covered Lake Velen (Bengtsson, 2012).

The report identifies the change in heat content in an ice covered lake is:

- $dH/dt = (H_{Sed} + R_{NetSol} - H_{Ice})\, A_{Surface} + H_Q$ (Eq. 5)

Where:

dH/dt = Change of Heat Content
H_{Sed} = Sediment Heat Flux
R_{NetSol} = Solar Radiation Intensity
H_{Ice} = Heat Flux from Water to Ice
$A_{Surface}$ = Surface Area
H_Q = Heat Advection

2.2.5 Convection/Mixing in Ice Covered Lakes

A circulation process of water, or convection, occurs in a fresh body of water prior, during and after the process of freezing surface water. This mixing is the result from the inlet of surrounding rivers, wind speed, underground springs, and change in water temperature. In Lars Bengtsson's report, mentioned above, research was done sharing the reasoning of the convection occurring below the ice. Thermal conditions, such as solar radiation and heat being released from base sediments start the circulation process on the water. During this convection, water velocities reach below 1mm/s. As water temperature increases it becomes less dense and as water temperature decreases it becomes more dense. Water reaches it maximum density at 4 degrees Celsius. One form of convection that occurs is when the water warms from the base sediments migrates to replace the cooler water at the surface of the water. Figure 5 is a figure demonstrating the convection process as the water beneath the ice warms through the warmth of sediment. Another form of convection occurs in late spring when solar radiation goes through the ice. At this point the density of the water reacts with the surface ice creating thawing and top mixing (Bengtsson, 2012).

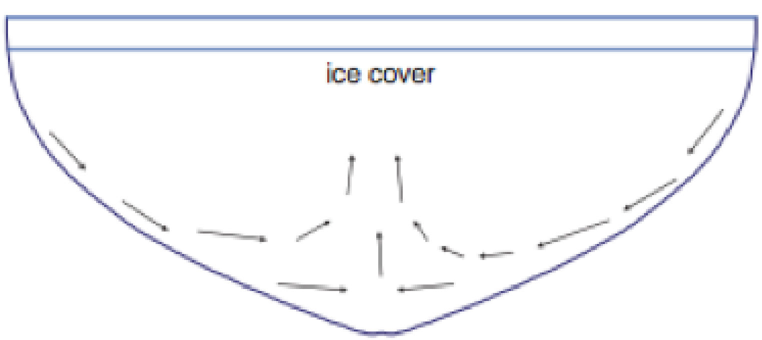


Figure 5: Demonstration of Large Lake Convective Circulation (Bengtsson, 2012)

2.3 Ice Measuring Methods

This section will explore a combination of known mechanical, temperature, and sonar based ice measuring methods. Prior to developing a device for measuring ice thickness, the team will research the various ice measuring techniques to determine which method is best suited for the current freshwater application. The chosen method will be used in the design process and for further testing to determine both accuracy and reliability.

2.3.1 Mechanical

<u>2.3.1.1 United States Patent 8299931</u>

U.S. patent 8299931 (Figure 6), Ice Safety Device, is an "inexpensive and simple operated" mechanical device that can potentially be activated to determine if the ice thickness is safe or unsafe (Eggleston, 2012). The device was initially never manufactured, yet the patented concept behind it is broad enough for design adjustments. The base design, shown in figure 6 is a floatation buoy made to be anchored onto a body of water prior to the surface freezing. The device is a pulley system supported by a floatation base (4), where a rod (22) is encased within a motionless tube (18). Tube (18) has a predetermined length of 4-6 inches (10.16-15.24 cm), which is deemed to be a safe ice thickness to hold a human. The rod (22) has a degree of freedom in the y direction and is in motion when the user wants to know the thickness. Assuming ice freezes down, the water will begin freezing around the device. With an undetermined power supply and motor, when the user desires to know the thickness, from land, the user will set off a remote signal that will trigger the device.

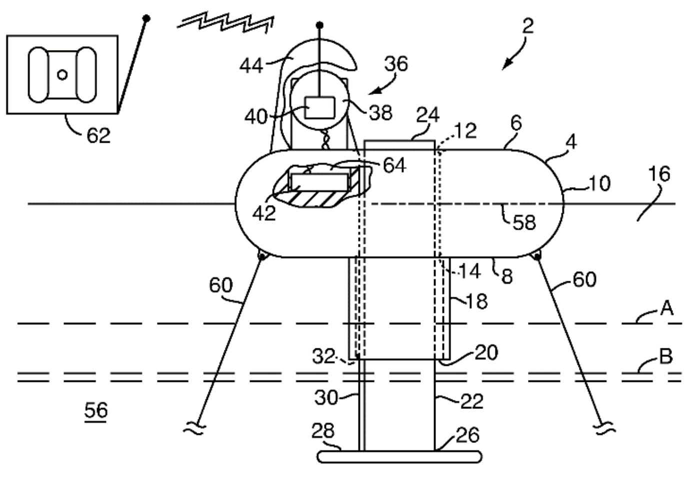


Figure 6: Patent 8299931 Ice Safety Device Base Drawing (Eggleston, 2012).

Ice is less dense than water causing it to stay on the surface of the body of water, and with the adhesive characteristic of ice to some materials, the mechanical device could potentially indicate if the ice thickness is above or below the desired depth. To know this information, the device starts in the resting position with ice forming around it. If the ice reaches a depth less than the length of the stationary tube (18), at line A, there is no binding to the rod (22). At this depth and the motor is set off, the rod (22) can move freely indicating the ice is too thin. Within time, the ice thickness reaches the depth to line B, which encases the tube (18) and rod (22). With this, the rod (22) is no longer capable of motion, resulting in signaling to the user that it is safe enough to journey on to the ice (Eggleston, 2012).

2.3.1.2 Piston Cylinder

A potential design based on the theory of a Bourdon Gauge located on a boiler, shown in Figure 7. This gauge works by using the pressure from the boiler acting on a horseshoe shaped bourdon tube. The pressure forces the tube to straighten, turning a dial. The concept of expanding with pressure was used in designing another way to measure ice thickness on a body of water.

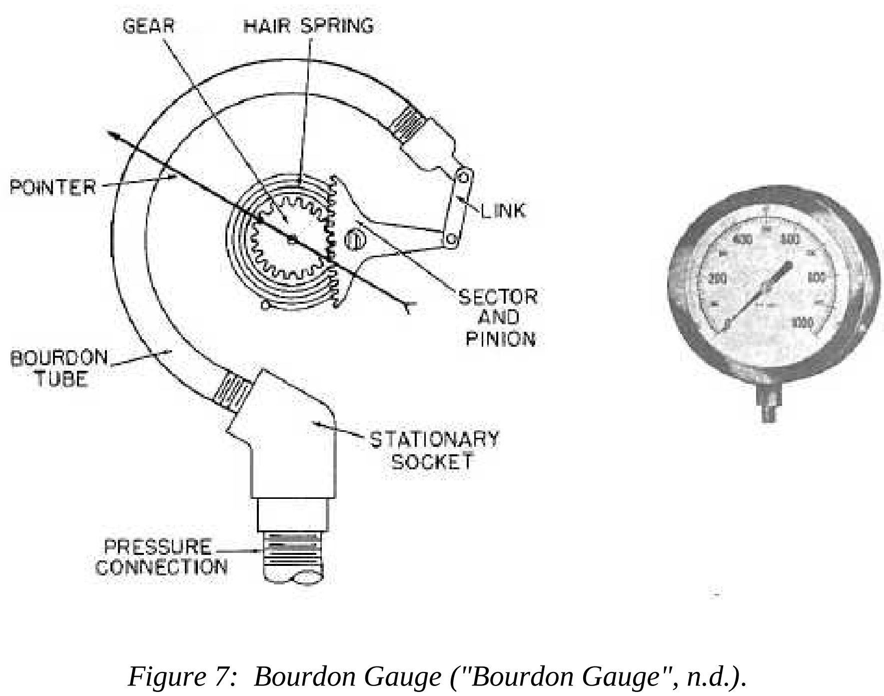


Figure 7: Bourdon Gauge ("Bourdon Gauge", n.d.).

The design consists of a main body, which is completely watertight. The device will be floating out prior to the ice freezing and is anchored in place with tethers to prevent floating around before the water freezes. The device will additionally be weighed down to counteract the buoyancy and to have the device sit with a specified depth under the surface. The shaft of the device will be filled with air and water in the specified sealed chambers of the piston cylinder assembly. The cylinders will extrude from the shaft in specified distances like small fin-like sections. Each chamber will be able to withstand extreme pressure. Within the piston cylinder assembly, there is a piston, rings, and water.

The water within the chambers replicates the surrounding fresh water and freeze at the same rate as the water around it. With this, when the surrounding water freezes, so should the water within the compartment. When this water freezes, it will expand causing the piston to move, triggering the attached mechanical device. As the surface water freezes down, the pistons will move respectively. Knowing this, it can be concluded that looking at the extruded pistons, the depth of the ice can be found.

2.3.2 Sonar

Sonar ice measuring devices are another product utilized today to create a profile of surface ice formation. The team researched sonar devices that collect ice profiles on salt bodies of water. Upward Looking Ice profiler Sonar systems (ULS), such as the Ice Profiler Sonar (IPS) are the primary source to collect keel depths, ice formation and deformation, and ice thicknesses.

ASL Environmental Sciences is a company specializing in oceanographic, acoustic, remote sensing and ice research products ("ASL Environmental Sciences", 2017). The products ASL creates are exploited on oceans today. The main system is the ASL-IPS4, which was initially designed in the Institute of Ocean Sciences in Sydney, BC but now manufactured by ASL (Birch et al., 2000). Figure 8 from a report provided by ASL, shows a demonstration of the set up and measurements made from the IPS4.

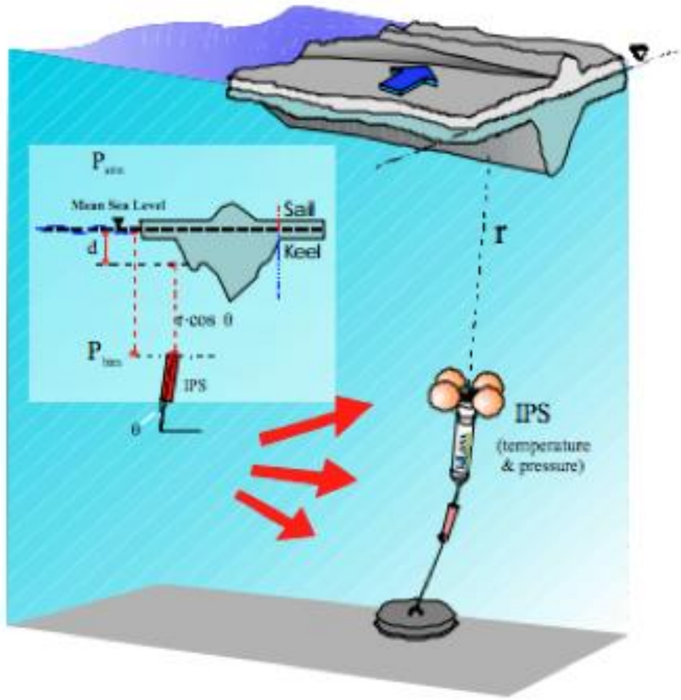


Figure 8: Representation of the Anchored IPS4 (Birch et al., 2000)

The IPS4 collects keel depth in the ice in addition to ice thickness by using a sonar system. The system records the return travel time of an acoustic pulse, sent once per second (1Hz) as it is reflected from the bottom of the ice. The pulse is sent at 420 kHz through a 1.8° beam at -3 dB. The data collected from the IPS4 is then stored within the device. From storing the memory and battery life, the product will last about 9 months in the field (Ross et al., 2016).

ASL adapted the Ice Profile Sonar (IPS) by adding additional features in enhance the collected data beyond only ice thickness. An Acoustic Doppler Current Profiler (ADCP) measures ice and water velocities by placing four acoustic beams along the bottom of the ice. When the signal is sent, the frequency of the back-scatter determine the velocity of ice growth (Birch et al., 2000). Figure 9, from the ASL testing report, shows the layout for a combined system including the IPS4 and ADCP (Ross et al., 2016). In replace of having two separate devices moored into the ice, there is now a single chain to collect ice thickness and ice velocities.

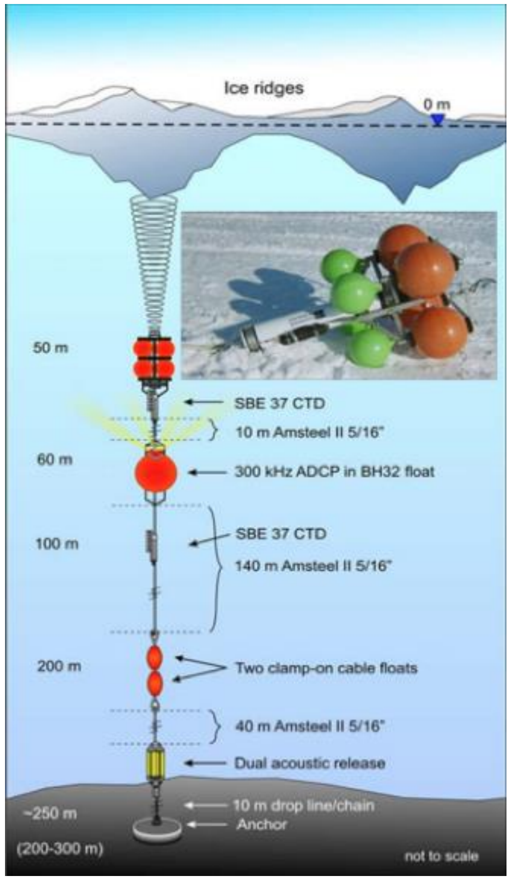


Figure 9: Deployment Arrangement of the IPS and ADCP (Ross et al., 2016).

2.3.3 Temperature

Temperature sensing devices are a viable option for both temperature measurement and control applications. For an ice measuring application, the team's research focused on the viability of NTC Thermistors and Thermocouples. Both products are available in various shapes, sizes, and materials so choosing the correct component is essential in producing an optimal system ("Temperature Sensors. Thermistors vs Thermocouples", 2017).

2.3.3.1 NTC Thermistor

NTC (negative temperature coefficient) Thermistors are temperature sensing devices composed of sintered semiconductor materials (Figure 10). These materials contain charge carriers which allow current to flow through the thermistor and relay a resistance value which is proportionate to small temperature changes ("Temperature Sensors. Thermistors vs Thermocouples", 2017).

Figure 10: NTC Thermistors ("Temperature Sensors. Thermistors vs Thermocouples", 2017)

NTC Thermistors produce high resistance at low temperatures and as temperature increases, the Thermistor’s resistance decreases. Thermistors experience large changes in resistance relative to small changes in temperature which allows for fast and accurate response times. Standard NTC Thermistors have an operating range between -50°C to 250°C (-58°F to 482°F). However, the nature of Thermistors produces a non-linear curve which limits the useful temperature span to around 100°C (212°C) ("Comparison of Thermistors, Thermocouples and RTD's", 2008). To produce a linear curve, a combination of additional electric circuitry, such as a null comparator, and computer automation will be necessary in order to provide accurate temperature measurements. For applications with small temperature spans, NTC Thermistors are to be considered a viable option due to their low cost, fast response times, and low thermal mass which will limit interference with the surround water or ice.

2.3.3.2 Thermocouple

A Thermocouple is an electrical device composed of two dissimilar conducting metals that connect to a single point ("Temperature Sensors. Thermistors vs Thermocouples", 2017). Thermocouple’s consists a measuring junction (hot) and a reference junction (cold) which maintain different temperatures and produce a low thermo-electric voltage which can be converted into temperature. Commonly used Thermocouples, such as the K-Type Thermocouple, operate over a broad range of temperatures ranging from -200°C to 1250°C (-328°F to 2282°F). Ultimately, the two major limitations of Thermocouples are the reduced accuracy as a result of large temperature ranges and that they are prone to calibration drift after extended use. Table 1 offers a comparison between commonly used NTC Thermistors and Thermocouples which the team will used to analyze a temperature based measuring method.

	Temperature Range	Stability (Temperature Drift)	Accuracy Range	Response Time	Linearity
NTC Thermistor	- Wide Variety of Applications - (-50°C to 250°C)	(0.2°C to 0.02°C)/yr	0.05°C to 0.20°C	0.12s - 10.0s	- Non-Linear-Output Requires Linearization
Thermocouple	- Lack Accuracy at Low Temps. - Good in Extreme Temp. Applications - (-200°C to 1250°C)	(1°C to 2°C)/yr	± 5°C	0.2s - 10.0s	- Non-Linear-Requires Conversion

Table 2: NTC Thermistor vs. Thermocouple

2.3.4 Research Summary

This extensive research performed covered the background for the team to reach the final goal for designing and building a device that measures the thickness of ice on a body of water. With about annually 3,500 accidental drowning incidents in the United States ("Unintentional Drowning", 2017) and 50% of the lake ice related fatalities in one state are due to snowmobiles ("Fatalities on North American Ice -2013 Season", 2013)., the team began looking into ice properties and other ice measuring methods that address the safety issue.

The ice properties for surface ice on a fresh body of water are critical to create a safe device. The team knowing that the load capacity to hold an average person to be 4 inches, 5 inches to safely support a snowmobile, and 8 to 12 inches for a car, will assist in the placement of the thermistors in final design (MassWildlife Ice Strength and Safety Tips", 2017). As shown in Figure 1, there are three different types of ice that can form each with different strengths. Primary ice, congelation ice, and snow-ice ice can each be picked up on the thermistors therefore need to be considered when creating a safety factor for the product (Leppäranta, 2010). With the a fresh body of water completely covered in ice, the ice acts as an insulator with heat loss from latent heat being released from the growing ice ("CDC - BAM, Physical Activity, Fishing", 2017). An additional small heat flux from the undersurface of the ice occurs and a large heat flux from the warm sediments at the base of the body of water ("CDC - BAM, Physical Activity, Fishing", 2017). Through radiation and warm sediments water temperature will increase and from cool atmospheric temperature and the underside of ice water temperature will decrease. As water temperature increases it becomes less dense and as water temperature decreases it becomes more dense, with the maximum density at 4 degrees Celsius (Leppäranta, 2010]. When the atmospheric temperature increases, thawing strongly impacts the safety of people on ice. Once the snow on the surface melts, the lake ice is exposed to the sun creating a greenhouse effect. This causes the solar radiation to heat the water below the ice causing ice to melt underneath the ice in addition to on top of it, causing unsafe conditions (Ashton, 1990).

There are a few devices available today addressing the issue of thin ice. The measuring methods consist of mechanical, sonar, and temperature approaches. The first mechanical method is a patented method using a remotely motorized pulley system shown in Figure 5 (Eggleston, 2012). This device is an anchored buoy system that signals to the user on land when the ice is unsafe, but does not notify when the ice is safe. Another mechanical device is a theoretical piston cylinder product. This device is a series of small piston cylinder systems with water within the chamber. The series is projected down into the water from a flotation. As the ice freezes down it also freezes the water in the chamber, signaling the thickness of the ice. Sonar is another method that's used in studies today. Ice Profiler Sonar (IPS) the primary device used, shown in Figure 9. The product measures ice thickness and keel depths by recording the return travel time of an acoustic pulse, sent once per second (1Hz) as it is reflected from the bottom of the ice.

The difference in temperature of ice and the water below was utilized when researching the viability of NTC Thermistors and Thermocouples. NTC (negative temperature coefficient) Thermistors, shown in Figure 6, are devices composed of sintered semiconductor materials that produce high resistance at low temperature. Therefore, as the temperature increase, the resistance decreases. The NYC thermistors have fast and accurate responses in the temperature range between -50°C to 250°C (-58°F to 482°F) ("Comparision of Thermistors, Thermocouples and RTD's", 2008). For the team's final design this is a highly considerable measurement option due to low cost, fast response times, and low thermal mass. Thermocouples are another temperature measuring device. It is an electrical device composed of two dissimilar conducting metals that connect to a single point ("Temperature Sensors. Thermistors vs Thermocouples", 2017). A hot and cold junction produce a low thermoelectric voltage which creates a readable temperature. Thermocouples operate in a temperature range of ranging from -200°C to 1250°C (-328°F to 2282°F). The comparison of thermocouples and thermistors can be found in Table 1.

3.0 Design Specifications

This section will discuss the various requirements which influenced the team's decisions in the design process. The design is to be an autonomous device that can wirelessly communicate ice measurement data to the user. The flotation frame must withstand the forces of freezing surface water, while supporting the weight of the components. The thermistor chain must read accurate temperatures to create a reliable temperature profile of the surface ice. The device's electric components must efficiently operate in the freezing environment, in addition to having a lifespan long enough to complete its task. Listed below are expanded design specifications for this measuring device.

Frame Specifications:

- Durable buoy flotation with large sub buoyancy
- Water proof compartments for water sensitive components
- Framework is nonconductive material (PVC)
- Framework is water tight to protect thermistor wiring

Thermistor and Circuitry Specifications:

- Standard NTC thermistors operating between -50°C and 150°C with accuracy of ±0.20°C
- Microcontroller sorts temperature information from the thermistors used
    - The Arduino UNO R3 equipped with six analog input pins for the thermistors
- Arduino software and code converts the thermistor resistance values for each thermistor to temperature values.
- Power supply's lifespan up to the first full freeze.
    - Rechargeable battery functions in freezing environment conditions
- Wireless communication to website and/or cellular message

4.0 Preliminary Design Components

The goal of this project is to design and manufacture an autonomous electromechanical device to measure freshwater ice thickness through the use of a thermistor chain. This section will cover the various design components necessary to meet this goal and the reasoning behind the selection of each component. The team utilized a variety of tools in selecting the components to be used such as decision matrices and tables which weighed the pros and cons of the available products. In addition, the material composition was driving factor in each component selection due to the harsh environmental conditions the product will face.

4.1 NTC Thermistor

As stated in the background section, NTC thermistors are temperature sensing devices composed of sintered semiconductor materials. After careful research and working with a U.S. Sensor Corp. application engineer, the team determined that a custom NTC thermistor probe would best suit the design assembly (Appendix A). With such a wide variety of available products, the team thermistor selection was based on the following five properties which were believed to be crucial to optimizing the desired temperature readings:

4.1.1 Temperature Range

The first consideration when choosing a temperature sensor should be the operating range. Standard NTC thermistors operate efficiently between -50°C and 150°C. Other Thermistors, such as products with glass-encapsulated housings, operate at higher temperatures rated for up to 250°C. Since the thermistor will primarily be operating in cold winter conditions, high temperature readings are not necessary. Therefore the maximum operating temperature for the NTC thermistor is 105°C while the minimum temperature remains at -50°C ("5 Thermistor Sensor Considerations When Selecting An NTC Thermistor", n.d.).

4.1.2 Accuracy

The NTC thermistors will be operating in cold weather conditions and the primary temperatures the team will seek to record are at 0°C or freezing temperatures. The selected thermistor has an accuracy rating of ±0.20°C between -2°C to 3°C. This will provide accuracy at the desired temperature range while reducing cost by not requiring high accuracy readings at temperatures outside of the desired range ("5 Thermistor Sensor Considerations When Selecting An NTC Thermistor", n.d.).

4.1.3 Stability

Stability is an important characteristic for thermistors in long-term applications. The materials and construction of the thermistor can affect the rate at which temperature sensors "drift" over time or the rate which the accuracy of their readings drops. For example, according to Ametherm, "An epoxy-coated NTC thermistor can change by 0.2°C per year while a hermetically sealed one changes by only 0.02°C per year" ("5 Thermistor Sensor Considerations When Selecting An NTC Thermistor", n.d.). Though the thermistors used in this application will only be needed for a single season at a time, the team sought to prevent the need for replacing thermistors on a yearly basis by purchasing thermistor probes with air-tight housings.

4.1.4 Packaging

Packaging requirements are typically dictated by the environment the thermistor will operate in. Since the thermistors will initially be completely submerged in water, the thermistor element will be potted in a 300 Series Stainless Steel housing which is both moisture resistant and will prevent rust accumulation.

4.2 Microcontroller Board

After selecting an NTC thermistor, the next primary component in creating an autonomous ice measuring device is selecting a microcontroller board. A microcontroller is essentially a small computer on a single integrated circuit which contains processing cores (CPUs) along with memory and programmable input/outputs. The microcontroller will allow the team to retrieve and sort temperature information from the multiple thermistors used in the application. When selecting a microcontroller board, the primary features the team was concerned with where the amount of analog inputs, digital input/output pins, and shield compatibility.

The quantity of analog input pins is crucial because they dictate the amount of thermistors the design can support. Analog inputs vary from digital input/output pins because analog inputs provide varying numbers while digital input/output (I/O) pins essentially provide a yes or no response. In other terms, digital input/output pins provide a 0 or 1 with nothing in between while analog input pins can relay a 0 or 1 with everything in between ("Digital Pins vs. Analog Pins.", 2009). Digital I/O pins are useful for servo motors or switches because they are either in an “ON” or “OFF” state but cannot be programmed to relay a voltage from the thermistors which the team will ultimately convert to a temperature.

The shield compatibility component is also crucial because it provides the team with further design freedom. For example, companies such as Arduino provide “shields” or additional components that can be added to their products for enhanced features such as Wi-Fi compatibility, the ability to communicate wirelessly up to distances of 300ft (outdoors) as well as additional analog or digital pins ("Arduino Shields", n.d.).

4.2.1 Arduino

The Arduino UNO R3 was ultimately selected as the microcontroller board to be used in the design. However, due to the available resources, the SparkFun RedBoard was used in the preliminary design and prototyping stage (Figure 11). The SparkFun RedBoard is programmed with Arduino and shares the majority of the features which the Arduino UNO R3 provides.

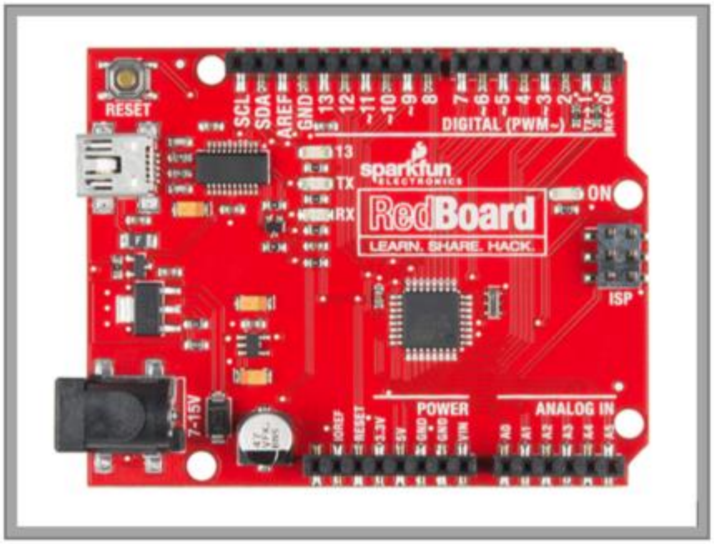


Figure 11: SparkFun RedBoard (SparkFun, 2017)

The RedBoard can be easily programmed over a USB Mini-B cable using the Arduino IDE (SparkFun, 2017) and the uploaded code will be used to sort and retrieve temperature values from the thermistor chain used in the design. The six analog input pins will support six individual thermistors. In addition, though the SparkFun RedBoard does not share the Arduino brand, it is still compatible with both the Arduino software and products such as shields. The remaining RedBoard features are listed below (SparkFun, 2017):

- ATmega328 Microcontroller with Optiboot (UNO) Bootloader
- USB Programming Facilitated by the Ubiquitous FTDI FT231X
- Input Voltage – 7-15V
- 0-5V Outputs with 3.3V Compatible Inputs
- 14 Digital I/O Pins (6 PWM Outputs)
- 6 Analog Inputs
- ISP Header
- 32k Flash Memory
- 16MHz Clock Speed
- All SMD Construction
- R3 Shield Compatible

4.3 Circuitry

The electric circuitry component of the design is used in conjunction with the microcontroller board and individual thermistors. The temperature value relayed from the thermistors is based on the measured resistance. Since microcontrollers do not have a built in resistance-meter, a voltage reader is needed (Ada, 2012). This is commonly referred to as an analog-digital converter. The circuitry is based upon the microcontroller board features as well as the 10 kΩ NTC thermistor referred to in the previous sections.

4.3.1 Wiring Diagram

Thermistors are resistive devices so an excitation source must be supplied to the thermistor and then read across the terminals ("Temperature Measurements with Thermistors", 2015). The application of measuring ice requires a high rate of accuracy so a voltage divider is used in conjunction with the NTC thermistor. A voltage divider is a simple circuit in which the return voltage is a fraction of the original by aligning two resistors in series. Since the NTC thermistor is essentially a 10 kΩ resistor, a second 10 kΩ resistor is connected in series to the thermistor. The measured voltage is in between the two resistor components and is relayed to one of the six analog inputs on the RedBoard. Figure 12 represents the simplified wiring diagram for a single thermistor ("Temperature Measurements with Thermistors", 2015).

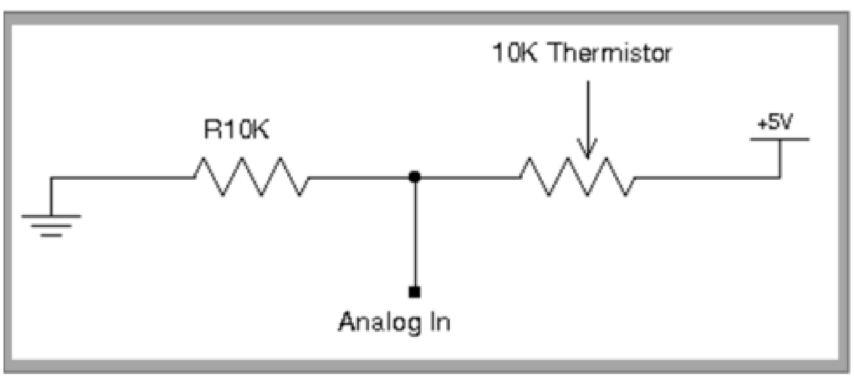


Figure 12: Wiring Diagram ("Thermistor", 2017)

4.3.2 Thermistor Circuitry

The physical circuitry for six individual thermistors can be seen in Figure 13. The circuit begins by sending a voltage to the positive terminal of the breadboard which then travels to the positive end of a 10 kΩ resistor (blue wires). The combination of the 10 kΩ resistor and the 10 kΩ thermistor act as a voltage divider and the resulting current is sent to one of the six analog outputs (green wires) located on the Arduino board. The last component of the circuit was to simply ground the opposing end of the thermistor as shown in the yellow wires. The circuit design was then duplicated for the remaining 5 thermistors.

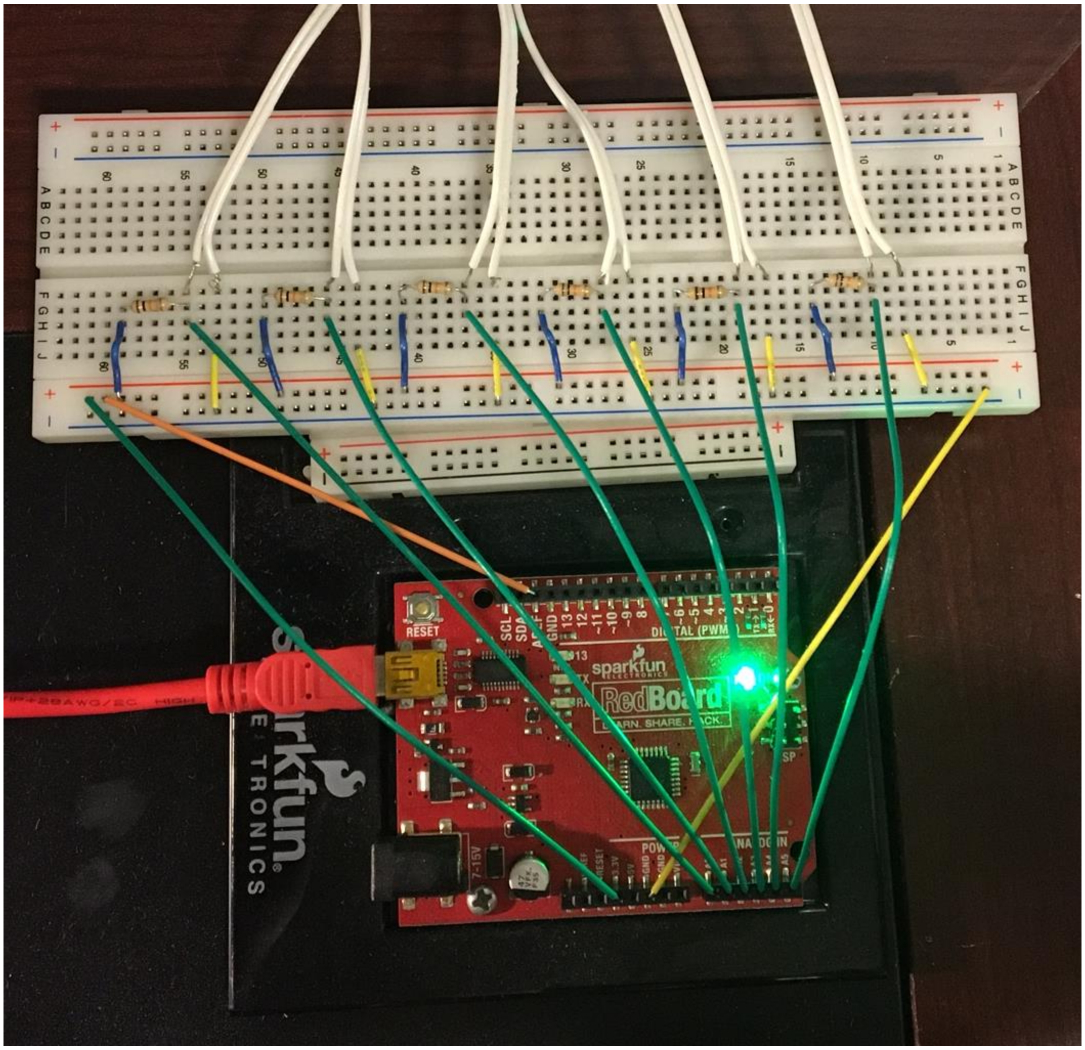


Figure 13: Thermistor Circuitry

4.4 Software

The section explains the Arduino software and source code used to convert the thermistor resistance values to temperature values. The primary equations used to retrieve a temperature value from an NTC thermistor are the Beta Value Equation (*Equation 6*) and Steinhart-Hart Equation (*Equation 7*). The beta value coefficient was provided from the manufacturer of the NTC thermistor used in this design so the team chose to use the Beta Value Equation in the following calculations.

- $1/T = (1/T_0) + (1/B)\ln(R/R_0)$ (Eq. 6)

Where:

T = Temperature (K)
T_0 = 25 degrees Celsius (298.15 K)
B = Beta Value Coefficient of Thermistor
R_0 = Resistance at Room Temperature (Ω)
R = Resistance Measured (Ω)

- $1/T = A + (B)\ln(R) + C(\ln(R))^3$ (Eq. 7)

Where:

T = Temperature (K)
R = Resistance (Ω)
A, B, & C = Steinhart-Hart Coefficient

Using either the Beta Value Equation or the Steinhart-Hart Equation in conjunction with the thermistor chain and wiring will result in a temperature value that can be used to create a lake profile. Figure 14 provides an example of how the Beta Value Equation can be programmed into the Arduino software to produce a temperature value. The Arduino software also provides the team with a tool to manipulate the readings obtained from the thermistor chains to produce graphs and ultimately provide an ice thickness value to the user.

```
//Calculate temperature using the Beta Factor equation
float temperatura0 = 0;
temperatura0 = media0 / TERMISTORNOMINAL;      // (R/Ro)
temperatura0 = log(temperatura0); // ln(R/Ro)
temperatura0 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura0 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura0 = 1.0 / temperatura0;                 // Invert the value
temperatura0 -= 273.15;                         // Convert it to Celsius
```

Figure 14: Beta Value Equation

4.5 Power Supply

In order to create an autonomous ice measuring device, a power supply is needed to provide the required input voltage of the microcontroller board and circuitry.

4.5.1 Battery

Due to the harsh weather conditions the device will be subjected to, the team decided to pursue precharged Nickel-Metal Hydride (NiMH) batteries as the power source. These long-term use batteries offer the ability to be recharged if necessary which is crucial to ensuring that the device is powered until the ice is frozen to the point where it is safe for someone to walk on. This time period could potentially last as long as 2-3 months depending upon when the device is set. With this in mind, pre-charged NiMH batteries are capable of experiencing 150-500 charging cycles which may help combat the cold climate which will drain the batteries faster than the anticipated rate in normal working conditions (Wood, 2016). The self-discharge rate, in ideal conditions, is roughly 10-20% every 6 months. Once the energy capacity of the battery drops to 30-50% is peak capacity, the battery could then be recharged for further use through the use of solar cell panel which could be mounted to the device's frame. The best uses for NiMH batteries are in high-drain devices such as GPS receivers which makes the batteries compatible for the Arduino use. The output voltage of NiMH batteries is roughly 1.2V so an array of batteries arranged in series or parallel will be necessary to ensure the Arduino and subsequent circuitry receives the required power (Wood, 2016).

4.5.2 Photovoltaic

Photovoltaic (PV) energy is produced from the direct conversion of sunlight into electricity at the atomic level (Knier, 2002). This process is known as the photovoltaic effect. Solar panels operate based on light energy, not heat, which makes this renewable energy source a viable power supply candidate because the cold outside temperature will not affect PV efficiency. In fact, solar panels tend to perform better in cold temperatures as opposed to hot temperatures ("Winter Solar Panel Performance and Maintenance", 2017).

PV cells generally produce a relatively small amount of electricity so multiple cells are linked to form a PV module. An array, or combination of modules (Figure 15), can then be constructed by wiring multiple modules in both series and parallel to produces the required voltage or current of the load (Knier, 2002). For the final design, a PV array, as seen in Figure

15, could be mounted on top of the flotation device and wired to NiMH batteries. This would allow the batteries to be recharged during the day and ensure that the device is continuously powered throughout the winter.

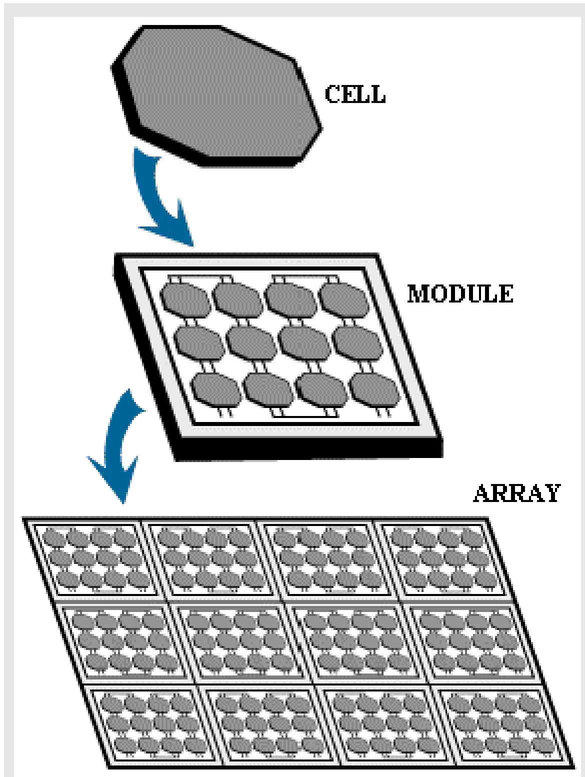


Figure 15: PV Array Composition (Knier, 2002.)

4.6 Flotation

4.6.1 Flotation Type

This section will explore the various commercial flotation products. The reason for focusing on commercial floatation products as opposed to the standard recreational products, such as a Type IV Ring Buoy or Polyform Twin Eye Buoys (Figure 16), is due to the differences in external/internal composition and sub buoyancy parameters ("Barrier Floats", 2017). Typically, recreation products are composed of marine grade vinyl and filled with air to add buoyancy. The product is intended to be used as a temporary mooring or a “fender” buoy which could act as a buffer to prevent damage between the vessel and a dock. TYPE IV Ring Buoys have the desired internal composition, urethane foam, which does not drastically expand or contract with varying temperatures such as air. However, the sub buoyancy standard of a TYPE IV is 16.5 lbs (Witkiewicz & Zieliński, 2006), as regulated by the USCG and State Law Enforcement agencies, which limits the use of additional components such as a power supply, motor, or framework.

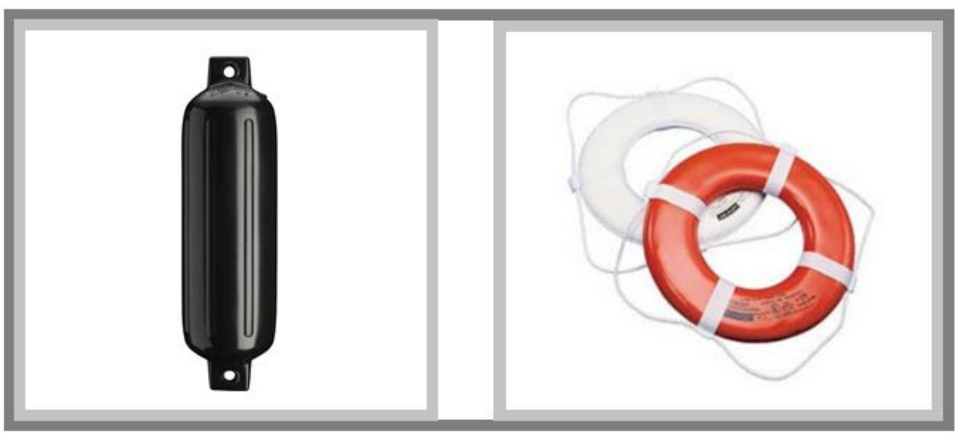


Figure 16: Polyform Twin Eye Buoy & Type IV Ring Buoy

The commercial buoy product market can be divided into four main categories (Table 2). Can buoys and regulatory buoys are similar in being able self-right themselves when anchored. However, the buoy need to maintain a proportional center of mass after the addition of the mechanical components of the ice measuring device which could potentially make the buoy unbalanced. If the buoy were to freeze at a severe angle, the measuring results would be skewed and provide false readings. Mooring buoys provide a sufficient sub-buoyancy at a relatively low weight but once again, a center of mass would be difficult to achieve due to the shape of the buoy. Ultimately the barrier float proved to be the most viable option within these four groups.

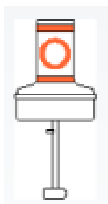
	Product Specifications				
	Float Style	**Traditional Usage**	**Features**	**Sub Buoyancy (lbs.)**	**Net Weight (lbs.)**
Barrier Floats		- Barrier floats are attached in a series to restrict boating traffic or swimmers from specific danger areas	- External compositon: polyethylene Shell - Internal composition: urethane foam - Shatterproof: will not crack, chip, peel, or rust - Colors: international orange or white - One piece construction - A-type: steel rod through center w/ eye nuts - B-type: plastic or steel pipe thru foat	33 - 1,600 lbs.	3 -116 lbs.
Can Buoys		- Channel Marker - Standard cans widely used by the U.S. Army Corps of Engineers	- External composition: ABS Shell - Internal composition: urethane foam - Self-right without tack	N/a	N/a
Mooring Buoys		- Moor ships from drifting to problematic areas	- External compositon: polyethylene Shell - Internal composition: urethane foam - Steel rod through center	30-240 lbs.	3-36 lbs.
Regulatory Buoys		- Approved and universally used by local, state and federal agencies to ensure water safety. - Ideal for private applications.	- External composition: ABS Shell - Internal composition: urethane foam - Self-right without tack - Stainless steel anchoring eye (saltwater applicaton)	30-84 lbs.	24-49 lbs.

Table 2: Commercial Floatation Product Comparison

Barrier buoys are typically linked in chains and connected to can anchored can buoys. This creates a barrier use to prevent boating traffic from entering a certain area. To properly execute this purpose, barrier buoys have a large sub-buoyancy in comparison to its net weight which is sufficient to support any additional equipment for this ice measuring device. The sub-buoyancy, in combination with the cylindrical geometric shape, provides a strong base to build upon. The following barrier floats products will be analyzed to determine the best suited model for a prototype base, Table 3:

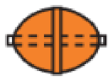
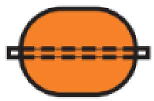
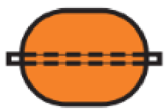
	Rolyan Barrier Float Comparison					
	Float Style	**Diameter & Lenth (in.)**	**Description**	**Sub Buoyancy (lbs.)**	**Net Weight (lbs.)**	**Cost ($)**
B1130BO		12" x 13"	- 1/2" sch. 40 PVC pipe thru float.	33 lbs.	4 lbs.	$44.00
B1318BO		13" x 18"	- 1/2" sch. 40 PVC pipe thru float.	55 lbs.	10 lbs.	$70.00
B1830BO		18" x 30:"	- 1" sch. 40 galvanized steel pipe thru float.	200 lbs.	25 lbs.	$129.00
B1848BO		18" x 48"	- 1" sch. 40 galvanized steel pipe thru float.	~ 325 lbs.	45 lbs.	$189.00

Table 3: Rolyan Barrier Float Comparison ("Barrier Floats", 2017)

The product specification which is crucial to the success of the prototype is the model volume relative to its sub buoyancy rating. The primary material which affects sub buoyancy is the volume of urethane foam which can be placed within the polyethylene shell. Depending upon the power source, framework, and additional mechanical measuring components, the prototype must be able to support an estimated 100-200 lbs. In addition to the sub buoyancy rating, the product dimensions in terms of length relative to diameter must be taken in consideration. Maintaining an steady center of mass on a moving surface, such as the unfrozen body of water, is vital to ensure the measuring component remains perpendicular the plane being measured. If the float's center of mass varies easily due to wind or water current, the data collected could be comprised. Essentially, buoys will have be connected in series or parallel to create a dependable center of mass and the number of buoys needed to achieve this is affected by the product's dimensions. Therefore, based on product dimensions and sub buoyancy, model B1318BO and B1848BO will be further analyzed.

4.7 Frame

This section will expand upon the buoys from the previous section to determine the necessary layout structure to achieve a sufficient sub buoyancy rating and center of mass.

4.7.1 Design 1: B1318BO

Product Specifications:

- Outer Diameter: 13in.
- Length: 18in.
- Sub-Buoyancy: 55lbs.
- Net Weight: 10lbs.
- External Comp: Polyethylene Shell
- Internal Comp: Urethane Foam
- One Piece Construction
- 1/2” Sch. 40 PVC Pipe Thru Center

Due to the ratio of length/diameter, additional buoys will need to be connected in series, as well as in parallel. The ½” sch. 40 PVC pipe which runs through the center of the buoy provides a useful conduit for additional PVC framework ("Sch 40 PVC Reducer Bushing Flush Style", n.d.). For example, a ½” to 1” sch. 40 PVC pipe reducer bushing can be used to step the ½” PVC to a thicker 1” PVC pipe. The additional thickness will increase the stability of the prototype and allow the base to support additional static loads. The required PVC pipe diameter will be determined in later stages of the design process and will account for the total frame load. A B1318BO concept assembly using 1” PVC pipe (Figure 17) has been created and will serve as the first proposed float and framework design.

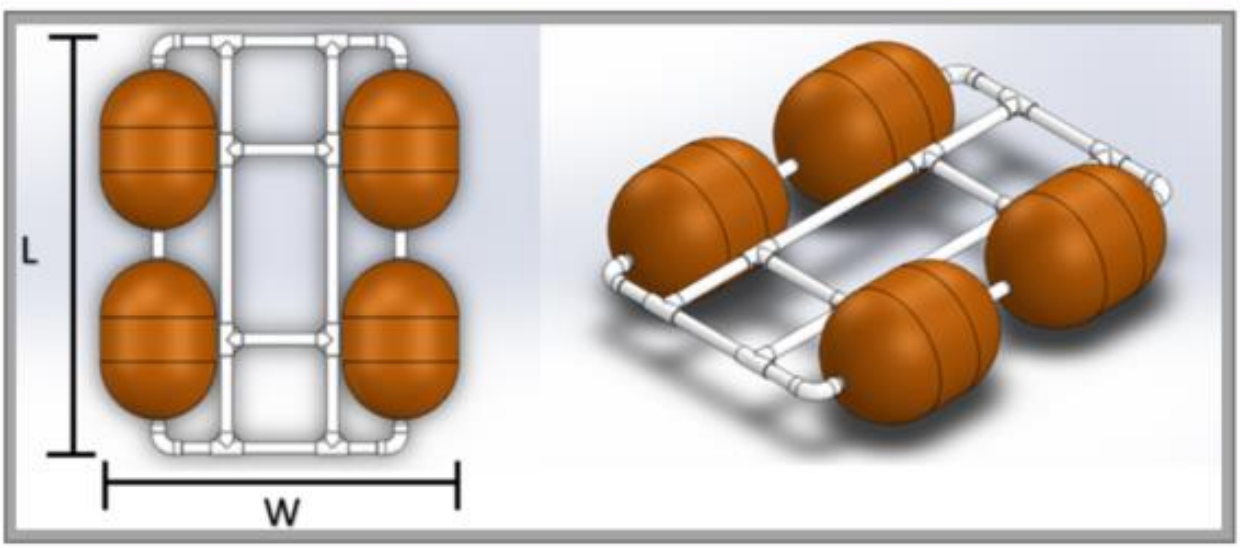


Figure 17: Top & Isometric View of B1318BO Frame Assembly

The preliminary framework design consists of four B1318BO floats connected by l” sch. 40 PVC pipe ("Sch 40 PVC Reducer Bushing Flush Style", n.d.). The floats provide the structure with a combined sub buoyancy of roughly 220 lbs. which exceeds the estimated requirement. The total length (l) and width (w) dimensions of this assembly are roughly 48” x 40” and the height is simply the outer diameter of the tube, 13”.

4.7.2 Design 2: B1848BO

Product Specifications:

- Outer Diameter: 18in.
- Length: 48in.
- Sub-Buoyancy: 325lbs.
- Net Weight: 45lbs.
- External Comp: Polyethylene Shell
- Internal Comp: Urethane Foam
- One Piece Construction
- 1” Sch. 40 Galv. Steel Pipe Thru Center

Here, the ratio between length and diameter is far larger than B1318BO and will therefore not require any additional units to be linked in series. Instead, an additional buoy will be connected in parallel which will provide a sufficient base in terms of sub buoyancy and weight distribution. The 1” sch. 40 galvanized steel pipe which runs through the center of the buoy will be used a framework component. Steel and PVC components are compatible, however, this connection will require an adhesive which creates a high strength bond for this application. A B1318BO concept assembly using 1” PVC pipe (Figure 18) has been created and will serve as the second proposed float and framework design.

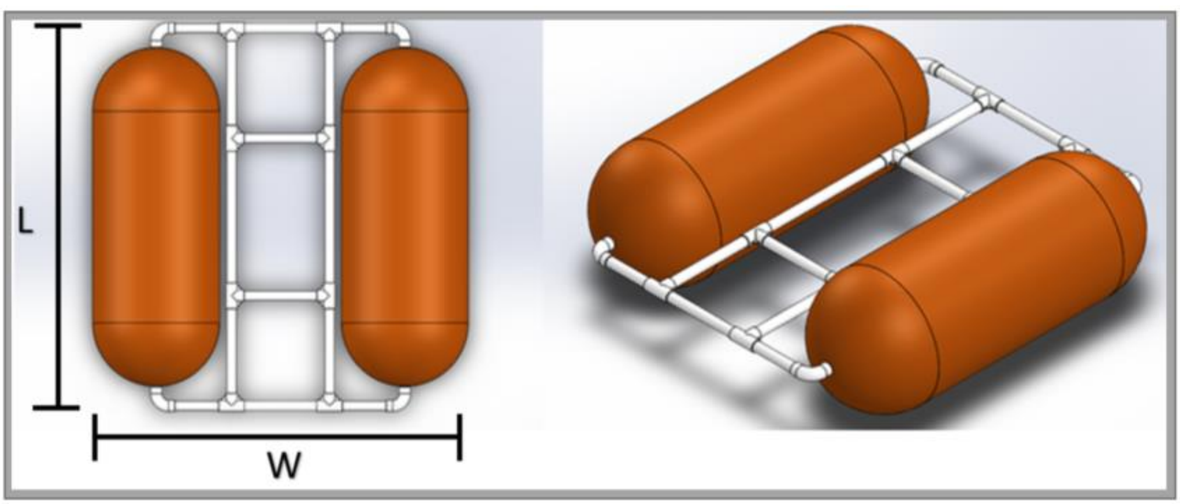


Figure 18: Top & Isometric View of B1848BO Frame Assembly

The preliminary framework design consists of four B1848BO floats connected by l" sch. 40 PVC pipe. To total length (l) and width (w) of this design is 54" by 54" respectively with an 18" height. The use of two B1848BO floats is necessary to ensure stability, however, this also produces a sub buoyancy of roughly 650 lbs. which is far more than this prototype is anticipated to handle. Future adjustments to this design are dependent on the power source. For example, if a lead-acid battery is determined to be the most effective power supply, it could potentially be housed within the buoy. The hollow PVC pipe frame could also serve as an insulated track to run any wiring to the load (Figure 19).

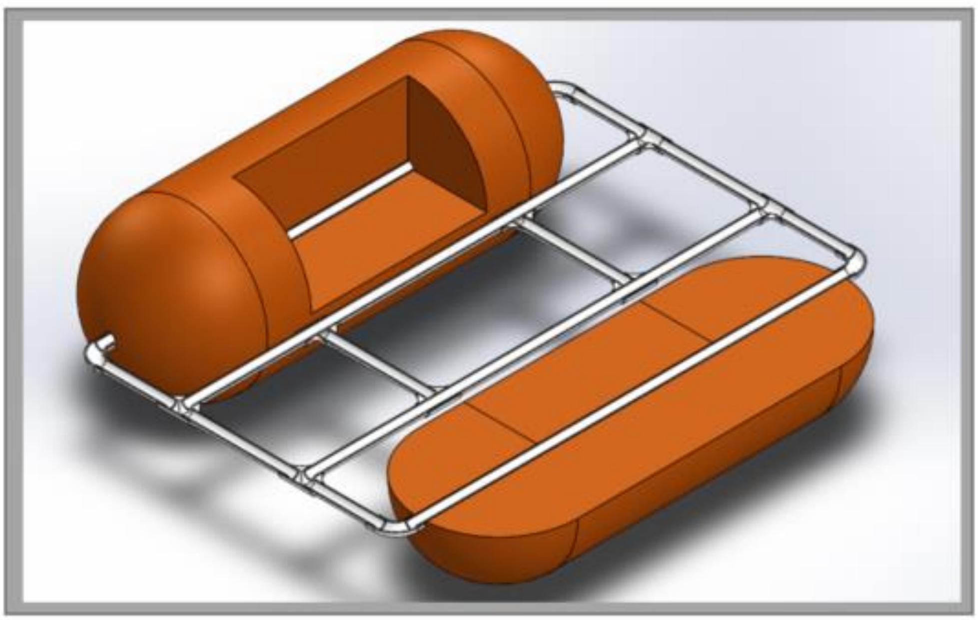


Figure 19: Isometric View of Cutaway Frame Assembly

Cutting away a section of the buoy provides a section for the power source to be seated within the design. The sub buoyancy is far greater than what is estimated to be required for the design. Structural stresses or strains that the prototype will experience will have to be analyzed to ensure the design is mechanically sound. In addition, the section view of Figure 19 clearly shows the area within the PVC frame which could be used to keep any wire or electrical components insulated from the harsh weather conditions.

5.0 Proof of Concept

The end goal for this device is to have an autonomous buoy capable of sending information regarding the temperature profile of a body of water wirelessly to an onshore receiver. Prior to building a prototype which complies with the design specifications previously listed, the team set out to test the design decision to use a thermistor chain to gather temperatures at different depths and form a temperature profile. The experiment was designed to confirm our ideas about temperature profile correlating with ice thickness and to test the tolerance of our ice thickness estimates. The timing of the project did not allow the team to put a thermistor chain directly in to a body of fresh water before ice formation began. The experiment was instead conducted in a transparent 32 gallon barrel. The bottom of the reservoir was insulated using layers of foam board and the sides were insulated using blow-in insulation. The thermistor chain frame was placed on top of the barrel with the thermistor chain extending into the water in the barrel. The full setup can be seen in Figure 20, Figure 21, and Figure 22.

Figure 20: Isometric View of Test Apparatus (No Cover)

Figure 21: Top View of Test Apparatus

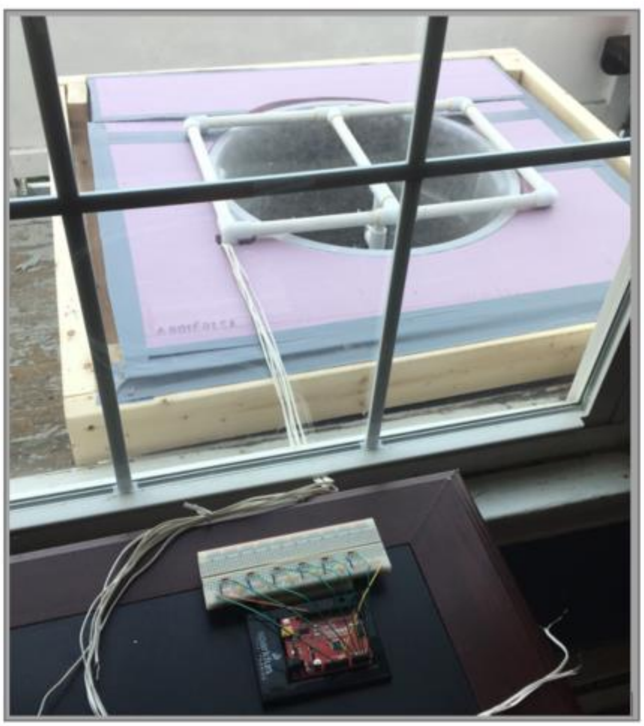


Figure 22: View from Testing Location

5.1 Thermistor Chain

The thermistor chain used for this experiment consists of six thermistors separated into two arrays of three thermistors. The thermistors in each array are spaced 3 inches apart and the two arrays are spaced 9 inches apart. The first thermistor was 0.375 inches from the surface of the water. Figure 23 shows the assembly thermistor chain which was placed inside of the 32 gallon bucket. The spacing of the thermistors is designed to provide a larger range for the temperature profile. The cluster closest to the surface of the water is meant to provide data as the ice is freezing, whereas the lower cluster of thermistors provides information regarding the state of the ice after it is already formed. The thought process behind this is that during ice formation, the ice will theoretically form at each depth as the corresponding thermistor reads 0 degrees Celsius. After the ice is frozen, the temperature in the water will fluctuate as well as the temperature of the ice that is already formed, which can spike above 0 degrees Celsius while remaining ice. The team wanted to gather some data at a depth below what we thought the ice would ever reach; the data from the deeper thermistors may be useful during the middle winter months as well as during the ice thawing stage.

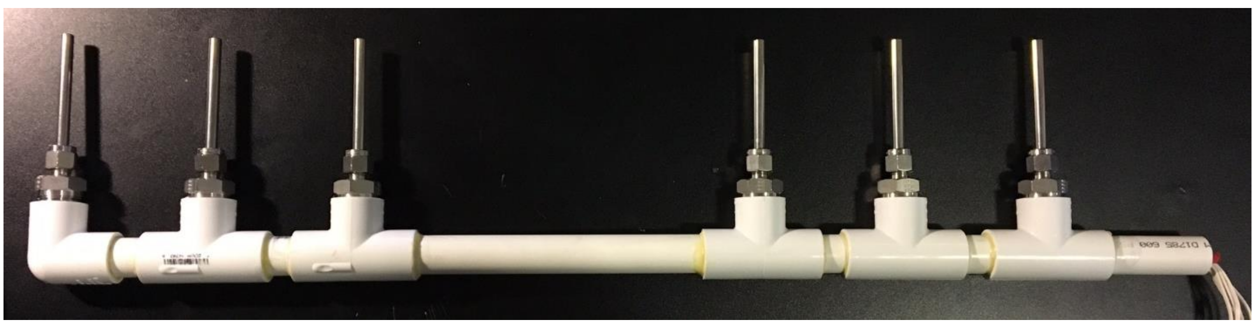


Figure 23: Thermistor Chain Assembly

Since the thermistor chain is constantly submerged in water and there are electrical components running through the frame, every opening and joint in the chain must be watertight. Construction began from the bottom thermistor and was carried out upward from there. This allowed for easier handling of the thermistor leads as they were fed up through the thermistor chain to the top of the frame. The frame was made of PVC piping. The actual chain of thermistors consisted of t-joints, which the thermistors were fed through to have access to the water, and straight pipes that connected the thermistor locations together. Each thermistor was fed from the inside of the frame through a swage-lok to ensure a watertight seal. The swage-lok crimps down on the metal of the thermistor until it creates a seal with the metal of the thermistor (Figure 24).

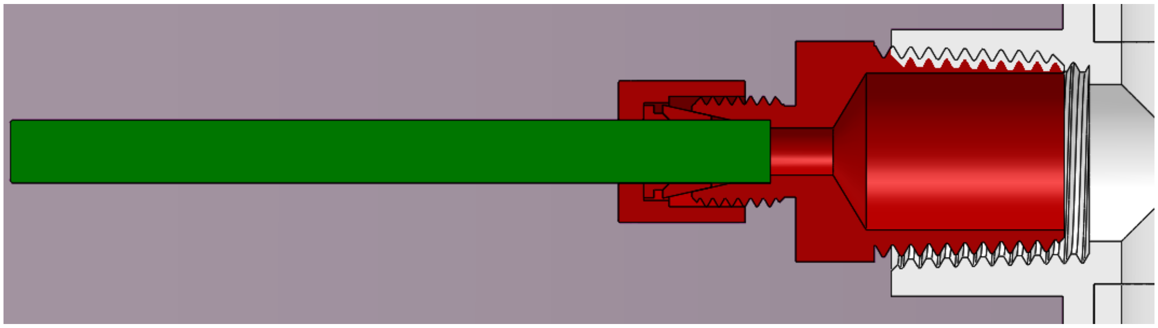


Figure 24: CAD Model of Swage-Lok and Thermistor

5.2 Lake Simulation

Due to the time constraints of the project, the use of a fresh water lake or pond was simply not possible. To properly test what we thought to be true about the temperature profile of a body of water and how it could predict the thickness of the ice it was necessary to construct a water reservoir that could mimic the freezing that takes place in a large body of water.

In a body of water, ice formation always begins at the surface and propagates downward. A bucket like the one we used alone would not have worked because conduction and convection through the side walls and base of the tank would have skewed the temperature profile. In addition, ice formation in an uninsulated tank would not be solely from the surface of the water, but would also take place on the inside walls of the tank. To account for this, the group constructed a square-based structure out of wood to place the tank in. The walls and base of the structure consisted of foam board insulation covered in plastic wrap. Between the outside of the tank and the inside of the structure wall was then filled with blow in insulation to try to mitigate as much conduction through the tank walls as possible (Figures 20 and 21).

5.3 Arduino Code

This section will provide a walkthrough of the Arduino code used to gather information regarding the ice temperature profile within the test apparatus. The full code can be referenced in Appendix B.

The code begins by defining all known variables and integers. In this case, analog pins 0-5 are defined as PINOTERMISTOR0 A0 through PINOTERMISTOR5 A5 for the six respective analog pins. The nominal thermistor value of the10 kΩ thermistor is further defined as 10,000 and temperature value at that resistance is 25 which serves as the comparison to which the retrieved resistance values will be compared to. In addition, the number of samples collected is listed as 5 which means that the output resistance value or reading obtained from each thermistor per second is the average of 5 values. The Beta Value Coefficient obtained from the product sheet is also listed in conjunction with the true resistor values. The team used an Ohm Meter to obtain to the true resistance value of each 10 kΩ resistor that was used in the circuitry to improve the accuracy of each reading.

The Void Setup section of the code was used to sort the data obtained from the thermistors. Each time a test is run, an excel spreadsheet is programmed to list a time and thermistor heading for each thermistor. With this in place, whenever a reading is recorded, the value goes to its' respective heading to help sort the information.

The Void Loop portion of the data is where the bulk of the coding takes place. It is at this point that the team created the Beta Value Equation code so that the system would run the equation for each thermistor in regards to the resistance value the thermistor reads in conjunction with the Beta Value listed earlier. The " while statement" listed in the beginning serves as a time stamp where the code will continue to run as long as the code has not been running for more than 60 seconds. As long as the 60 seconds has not transpired the code will continue to run the Beta Value Equation for each thermistor and export the value through an excel spreadsheet plug-in to its' respective heading. The "delay (1000) portion of the code results in running the equation once every second and recording a temperature value in degrees Celsius. After the code had finished the team then opened the spreadsheet to which the data had been transferred to, averaged the 60 values retrieved from the test, and graphed each thermistor value to obtain an ice thickness measurement. With a theoretical value in place the team then drilled a hole in the ice to get a physical measurement which served as a comparison of how accurate the test was.

6.0 Results & Analysis

In this section, the results of the test setup are introduced and analyzed based on their accuracy in estimating an ice thickness. The information obtained from the test experiment will provide the team with a threshold or rating of how accurate the thermistor chain was in determining ice thickness. For example, if the team finds that the ice depth reads 2 inches but the physical measurement results in the true ice thickness being 2 ½ inches thick, then the team would claim that the accuracy of the thermistor chain is within ± ½ in for that measurement. Therefore, the onshore user would not declare that the ice is safe for a single person to walk until the thermistor reading results in a thickness greater than 4 inches plus the uncertainty of the measurement, as stated in the background section.

The test was carried out over a two week period during the months of February and March with temperatures ranging from 5 to 35 degrees Fahrenheit. At the beginning of the testing period, the device experienced the lower end of the temperature range mentioned above and ice was strictly in the formation stage as the temperature rarely rose above freezing. Towards the end of the testing period temperatures hovered at or above the freezing mark, giving us a glimpse into the behavior of ice during the thawing stage. The results from the data during the freezing stage are listed in Appendix C while the results from the thawing stage which were taken roughly a week apart are listed in Appendix D.

While the ice was in the process of freezing, the temperature profile obtained through the thermistor chain resulted in measurements that were far more accurate than originally anticipated (Appendix C). The data sets in Appendix C all display a continuous growth of ice. The estimates during this stage were based on where the graph of the temperature intersected the Thermistor Depth or x-axis (where the temperature is equal to zero). The temperature-distance curve created from the recorded temperature measurements and the depth of the thermistors below the water were used to obtain a theoretical ice measurement which was then compared to physical ice measurement. This was done by simply drilling a hole into the ice and measuring the true depth. The data sets which were collected in combination with a physical measurement resulted with an uncertainty between 0.125 inches to 0.375 inches. Therefore, in the ice formation stage of the experiment, the team determined that the tentative uncertainty of the thermistor chain was ± 0.375 inches. Figure 25 provides an example of two data sets which recorded ice depths ranging from 2.375 inches to 3.25 inches.

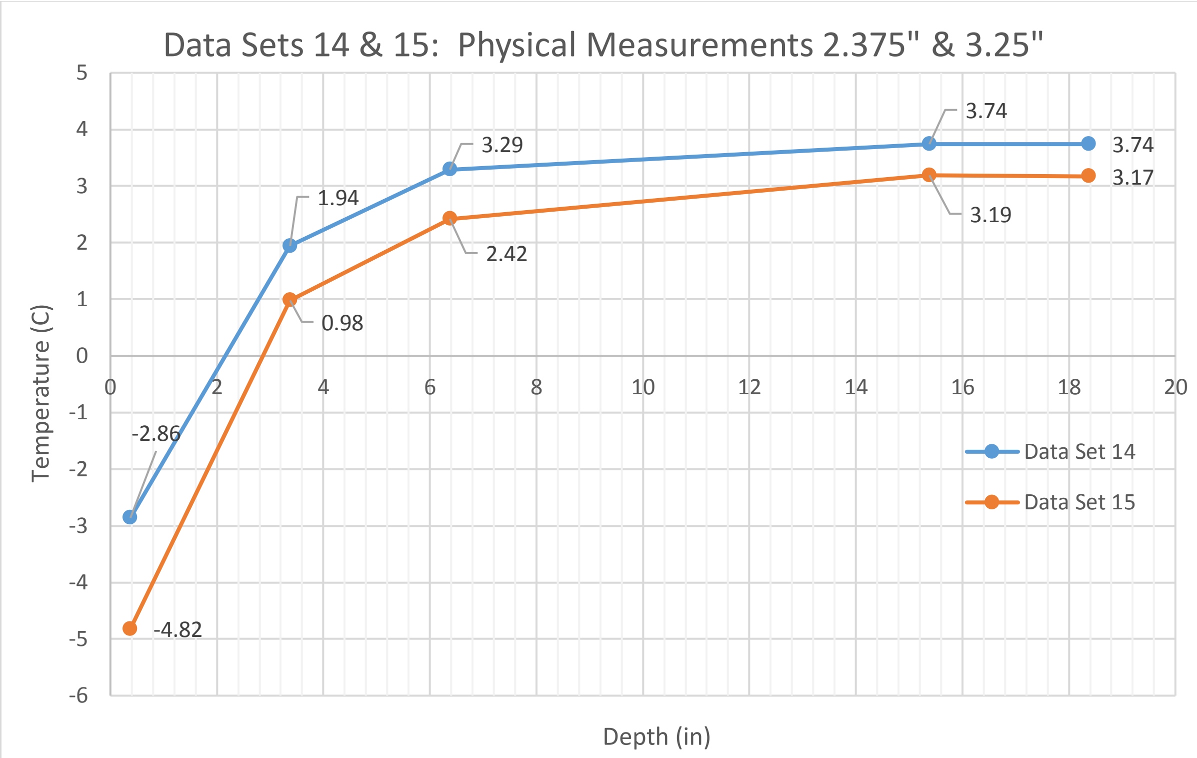


Figure 25: Data Sets 14 & 15

Initially, the team’s research aimed to observe the profile under the ice. This is due to the fact that water is a very unique liquid in that it experiences a decrease in density below 39.2 degrees Fahrenheit as it forms into its solid state, hence ice floating on top of water. Other than making the ice float, this also causes a temperature inversion below the surface of the ice. Warmer fluid would rise to the surface in most other fluids, but in water it sinks to the bottom and allows us to measure a temperature profile. The "warm water" in this case is around 34 degrees Fahrenheit. Heat transfer is then by conduction through the inversion layer because natural convection no longer occurs in the layer of water below 39.2 degrees. The resulting temperature profile will be nearly linear with position below the ice. Tracing this profile back to the 32 degrees Fahrenheit (0 degrees Celsius) intercept will approximate the location of the ice. However, due to the construction of test apparatus, the density inversion which the group had anticipated was complicated because the insulation at the bottom of the 32 gallon barrel was insufficient and resulted in a greater amount of heat loss from the bottom than was originally anticipated, this may have allowed for unintended natural convection to occur as cooler water rose to the surface. The temperature readings of the bottom thermistor array were much lower than would exist in a natural body of water. Therefore, the team determined that omitting the sixth and sometimes fifth thermistor values from the graphs was necessary in order to produce the linear temperature profile which normally occurs directly under the ice. This method resulted in fairly accurate numbers from just our readings in the immediate vicinity of the ice/water boundary by using linear interpolation and observing where the graph intersected 32 degrees Fahrenheit (0 degrees Celsius). The graphs can once again be seen in data sets 8 through 17 in Appendix C.

The team also determined that accurate ice thickness measurements were typically a result of a temperature difference between two thermistors such that one was slightly below freezing while the other was slightly above. This occurred throughout the ice formation stage and provided a strong indication that the ice thickness was somewhere between those two thermistor depths. The uncertainty, as stated earlier, was determined through physical measurements which continuously proved the team's estimate. In addition, the group determined that a more condensed thermistor array at the top 4 inches, of which is deemed to be safe enough for a single person to walk on, would yield greater certainty as more thermistors would be frozen at the top layer. Furthermore, if you have two thermistors below the water and both measure below 32 degrees Fahrenheit (0 degrees Celsius), the ice depth was as thick as the distance between the thermistors. If the bottom thermistor in a pair of two were to be placed four inches below the surface of the water, the uncertainty of the temperature profile would be less significant once that thermistor reads below 32 degrees Fahrenheit (0 degrees Celsius). At this point the ice thickness could be estimated as 4 inches. This would ultimately increase the reliability of the thermistor measurements during the ice formation stage.

Towards the beginning of March, the thawing stage began to occur due to warmer weather where temperatures were above or close to 32 degrees Fahrenheit (0 degrees Celsius). During the thawing stage of ice, there was less of a concrete correlation between the temperature of the ice/water and the thickness of the ice. Data sets 18-19 can be seen in Appendix C and resulted less accurate readings. This could be due to a number of different factors. For example, thermistors which were still covered by ice were reading above 32 degrees Fahrenheit (0 degrees

Celsius) during days where the ambient temperature was closer to the freezing temperature. This ruled out the method for estimating thickness that was used during the freezing stage because none of the temperatures would read below 32 degrees Fahrenheit (0 degrees Celsius). This was in part due to the fact that the ice was not completely frozen and instead was mixture of water and ice. After testing the ice thickness in data set 19 (Appendix D) the team proceeded to drill a hole into the ice to obtain a physical measurement. As the team drilled down into the barrel, a slushy mixture poured out of the drill site before the team had even reached the bottom surface. This did not occur during the freezing stage or in the data sets collected in Appendix C. When the team performed physical measurements during the freezing stage, only ice crystals were removed and water did not emerge until the ice had completely broken through. This indicated that the ice was no longer solid and the team concluded that when ice measurements reach this thawing stage of haphazard temperature readings, it is safer to remain off of the ice.

7.0 Conclusion & Future Recommendations

The final goal of this project was to make an autonomous buoy capable of wirelessly sending information to an onshore location in regards to the thickness of lake ice. After creating a prototype and testing rig to have a proof of concept, the next step the team envisions would be to adapt this product to be tested on a fresh body of water and perform an extensive market study for potential target customers. The frame, electrical, and internal coding needs to evolve in order for the product to become an independent system.

Ultimately, the information obtained from the group's testing apparatus proved that though using a thermistor chain to determine ice thickness is a plausible method, there is still some uncertainty. The accuracy of the thermistor measurements could be increased by having additional thermistors placed at the top of the array, at depths between 4-6 inches, and fewer thermistors at the deeper end of the thermistor chain. Temperature readings between two thermistors in which one was below freezing temperatures and one was slightly above provided accurate readings, but smaller distances between them would decrease uncertainty. In addition, further testing in natural bodies of water would helpful in determining the amount of thermistors needed and their relative uncertainty which has an impact on the cost of the product.

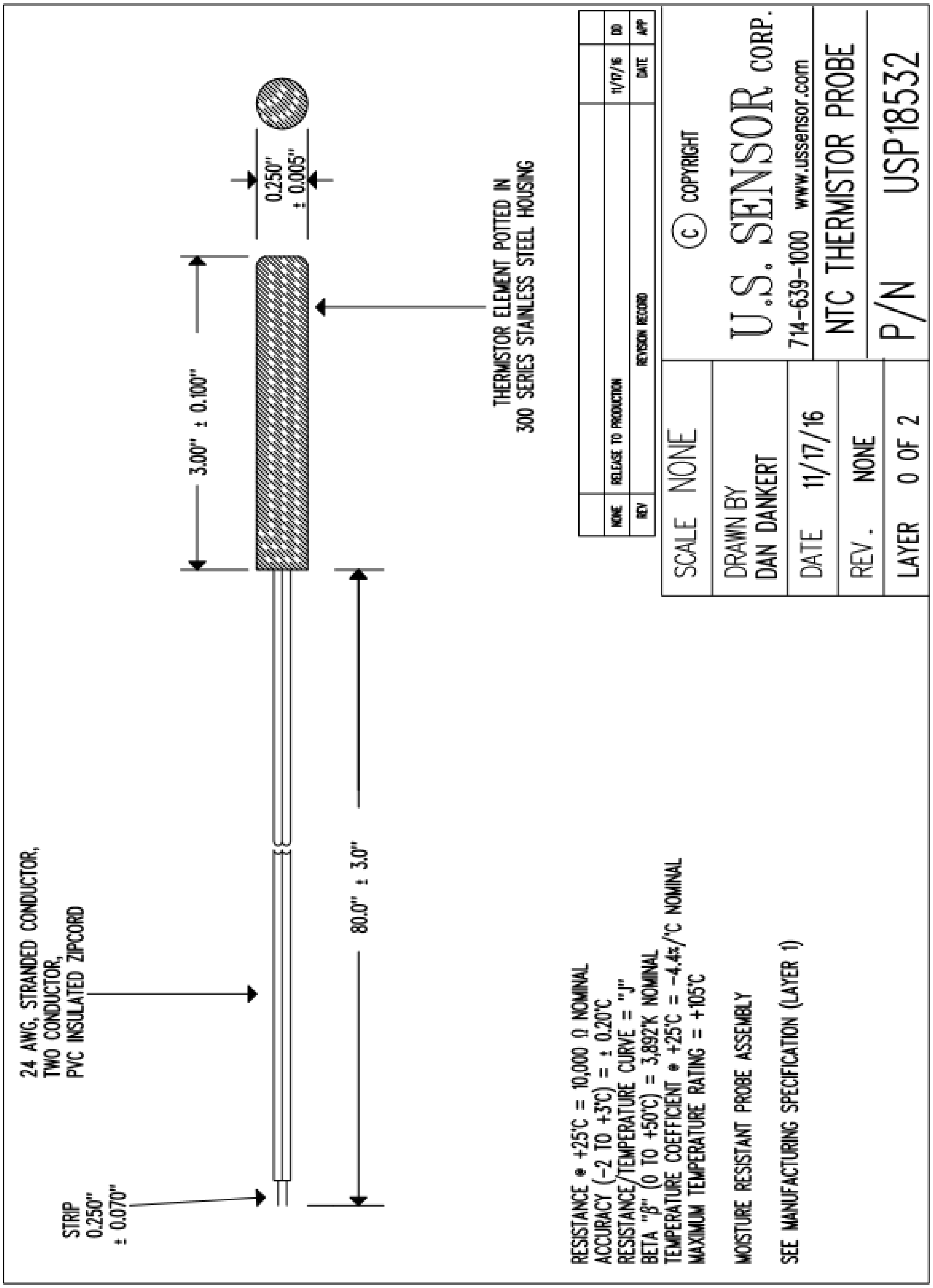
The research behind the potential frame was conducted in section 4.7. Due to budgeting, the team was unable to move ahead in creating the flotation frame. Therefore, moving forward, the team continues to recommend having a water tight frame, utilizing swage-loks to safely display each thermistor. To improve, additional tubing to support a selected buoy array, shown in Figure 17 or Figure 18 in section 4.7, will allow the product to hold the device at the surface of the water. The future frame and buoys are capable of being watertight and safely supporting all components of the device.

To have the device be completely autonomous, the team recommends extensive research into potential power supplies, such as the ones mentioned in Section 4.5. Main factors that should be considered are environmental freezing temperatures, life spans, and voltage drop when selecting the ideal battery. Potential batteries could be rechargeable by the use of a solar panel or other renewable energy sources.

The selected power supply would run the device to read the ice thickness. The team finds that including further Arduino coding and wireless communication will create a user friendly product. Ideally, the team recommends the output of the product to be a cellular text message, utilizing a smart phone application, or posting on a company's website. With further knowledge in coding, the team recommends directly sharing the profile of the surface ice and pairing the shared diagram with what the thickness can support.

The recommended design of this product is targeted towards commercial use, such as Parks and Recreations, snowmobiling companies, and other organizations using lake ice. Due to the size of the device and cost, the team is refraining from marketing it towards personal use. By installing a few measuring devices along the surface of a larger lake, the organization will be able to collect readings of the ice thickness throughout the body of water and potentially create an ice thickness map to communicate to the user when and where it is safe enough to withstand recreational use.

Appendix A: NTC Thermistor Probe



Appendix B: Arduino Code

```
// Pin that the thermistor is connected to
#define PINOTERMISTOR0 A0
#define PINOTERMISTOR1 A1
#define PINOTERMISTOR2 A2
#define PINOTERMISTOR3 A3
#define PINOTERMISTOR4 A4
#define PINOTERMISTOR5 A5

// Nominal temperature value for the thermistor
#define TERMISTORNOMINAL 10000

// Nominal temperature depicted on the datasheet
#define TEMPERATURENOMINAL 25

// Number of samples
#define NUMAMOSTRAS 5

// Beta value for our thermistor
#define BCOEFFICIENT 3892

// Value of the series resistor
#define SERIESRESISTOR0 9910
#define SERIESRESISTOR1 9980
#define SERIESRESISTOR2 9910
#define SERIESRESISTOR3 9910
#define SERIESRESISTOR4 9860
#define SERIESRESISTOR5 9990

int amostra0[NUMAMOSTRAS];
int amostra1[NUMAMOSTRAS];
int amostra2[NUMAMOSTRAS];
int amostra3[NUMAMOSTRAS];
int amostra4[NUMAMOSTRAS];
int amostra5[NUMAMOSTRAS];
int i;

void setup(void) {
Serial.begin(9600);
analogReference(EXTERNAL);
//Serial.println("CLEARDATA");
Serial.println("LABEL, Time, Thermistor 0, Thermistor 1, Thermistor 2, Thermistor 3, Thermistor 4, Thermistor 5");
//Serial.println("RESETTIMER"); // resets timer to 0
}
```

```
void loop(void) {
float media0;
float media1;
float media2;
float media3;
float media4;
float media5;

//if(millis() > 10000){
while (millis()<60000){
  for (i=0; i< NUMAMOSTRAS; i++) {
  amostra0[i] = analogRead(PINOTERMISTOR0);
  amostra1[i] = analogRead(PINOTERMISTOR1);
  amostra2[i] = analogRead(PINOTERMISTOR2);
  amostra3[i] = analogRead(PINOTERMISTOR3);
  amostra4[i] = analogRead(PINOTERMISTOR4);
  amostra5[i] = analogRead(PINOTERMISTOR5);
  delay(10);
  }


media0 = 0;
media1 = 0;
media2 = 0;
media3 = 0;
media4 = 0;
media5 = 0;
for (i=0; i< NUMAMOSTRAS; i++) {
media0 += amostra0[i];
media1 += amostra1[i];
media2 += amostra2[i];
media3 += amostra3[i];
media4 += amostra4[i];
media5 += amostra5[i];
}
media0 /= NUMAMOSTRAS;
media1 /= NUMAMOSTRAS;
media2 /= NUMAMOSTRAS;
media3 /= NUMAMOSTRAS;
media4 /= NUMAMOSTRAS;
media5 /= NUMAMOSTRAS;
// Convert the thermal stress value to resistance
media0 = 1023 / media0 - 1;
media0 = SERIESRESISTOR0 / media0;

media1 = 1023 / media1 - 1;
media1 = SERIESRESISTOR1 / media1;

media2 = 1023 / media2 - 1;
media2 = SERIESRESISTOR2 / media2;

media3 = 1023 / media3 - 1;
media3 = SERIESRESISTOR3 / media3;

media4 = 1023 / media4 - 1;
media4 = SERIESRESISTOR4 / media4;

media5 = 1023 / media5 - 1;
media5 = SERIESRESISTOR5 / media5;
```

```
//Calculate temperature using the Beta Factor equation
float temperatura0 = 0;
temperatura0 = media0 / TERMISTORNOMINAL;     // (R/Ro)
temperatura0 = log(temperatura0); // ln(R/Ro)
temperatura0 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura0 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura0 = 1.0 / temperatura0;                 // Invert the value
temperatura0 -= 273.15;                         // Convert it to Celsius

//Calculate temperature using the Beta Factor equation
float temperatura1 = 0;
temperatura1 = media1 / TERMISTORNOMINAL;     // (R/Ro)
temperatura1 = log(temperatura1); // ln(R/Ro)
temperatura1 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura1 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura1 = 1.0 / temperatura1;                 // Invert the value
temperatura1 -= 273.15;                         // Convert it to Celsius

//Calculate temperature using the Beta Factor equation
float temperatura2 = 0;
temperatura2 = media2 / TERMISTORNOMINAL;     // (R/Ro)
temperatura2 = log(temperatura2); // ln(R/Ro)
temperatura2 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura2 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura2 = 1.0 / temperatura2;                 // Invert the value
temperatura2 -= 273.15;                         // Convert it to Celsius

//Calculate temperature using the Beta Factor equation
float temperatura3 = 0;
temperatura3 = media3 / TERMISTORNOMINAL;     // (R/Ro)
temperatura3 = log(temperatura3); // ln(R/Ro)
temperatura3 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura3 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura3 = 1.0 / temperatura3;                 // Invert the value
temperatura3 -= 273.15;                         // Convert it to Celsius

//Calculate temperature using the Beta Factor equation
float temperatura4 = 0;
temperatura4 = media4 / TERMISTORNOMINAL;     // (R/Ro)
temperatura4 = log(temperatura4); // ln(R/Ro)
temperatura4 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura4 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura4 = 1.0 / temperatura4;                 // Invert the value
temperatura4 -= 273.15;                         // Convert it to Celsius

//Calculate temperature using the Beta Factor equation
float temperatura5 = 0;
temperatura5 = media5 / TERMISTORNOMINAL;     // (R/Ro)
temperatura5 = log(temperatura5); // ln(R/Ro)
temperatura5 /= BCOEFFICIENT;                   // 1/B * ln(R/Ro)
temperatura5 += 1.0 / (TEMPERATURENOMINAL + 273.15); // + (1/To)
temperatura5 = 1.0 / temperatura5;                 // Invert the value
temperatura5 -= 273.15;                         // Convert it to Celsius
```

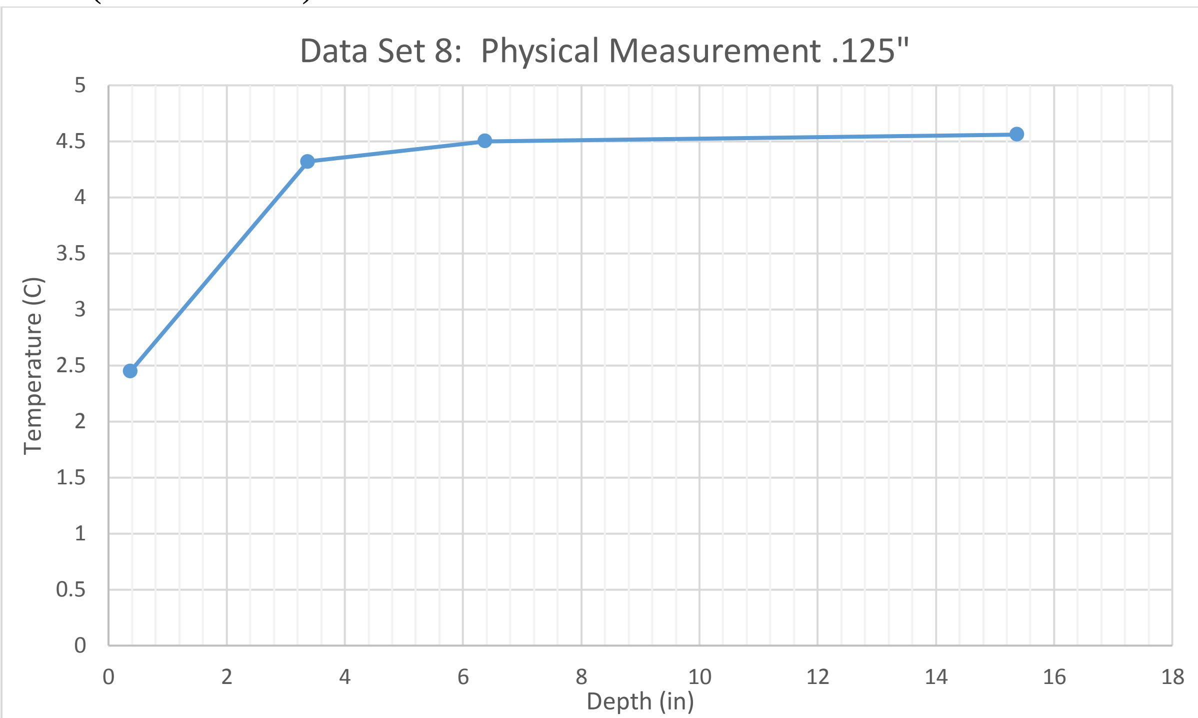
```
Serial.print("DATA,TIME,");
Serial.print(temperatura0);
Serial.print(",");
Serial.print(temperatura1);
Serial.print(",");
Serial.print(temperatura2);
Serial.print(",");
Serial.print(temperatura3);
Serial.print(",");
Serial.print(temperatura4);
Serial.print(",");
Serial.println(temperatura5);

delay(1000);
}
//} else{
//}
}
```

Appendix C: Ice Formation Stage

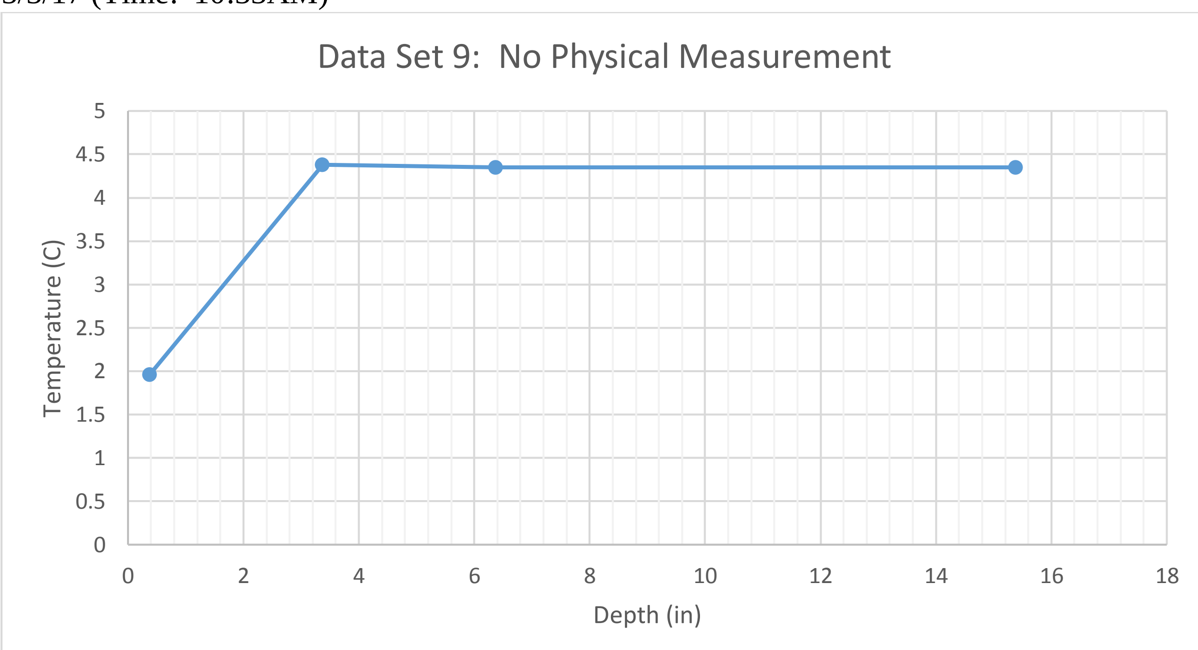
Data Set 8:

Ambient Temp = 22 F
3/3/17 (Time: 7:01AM)



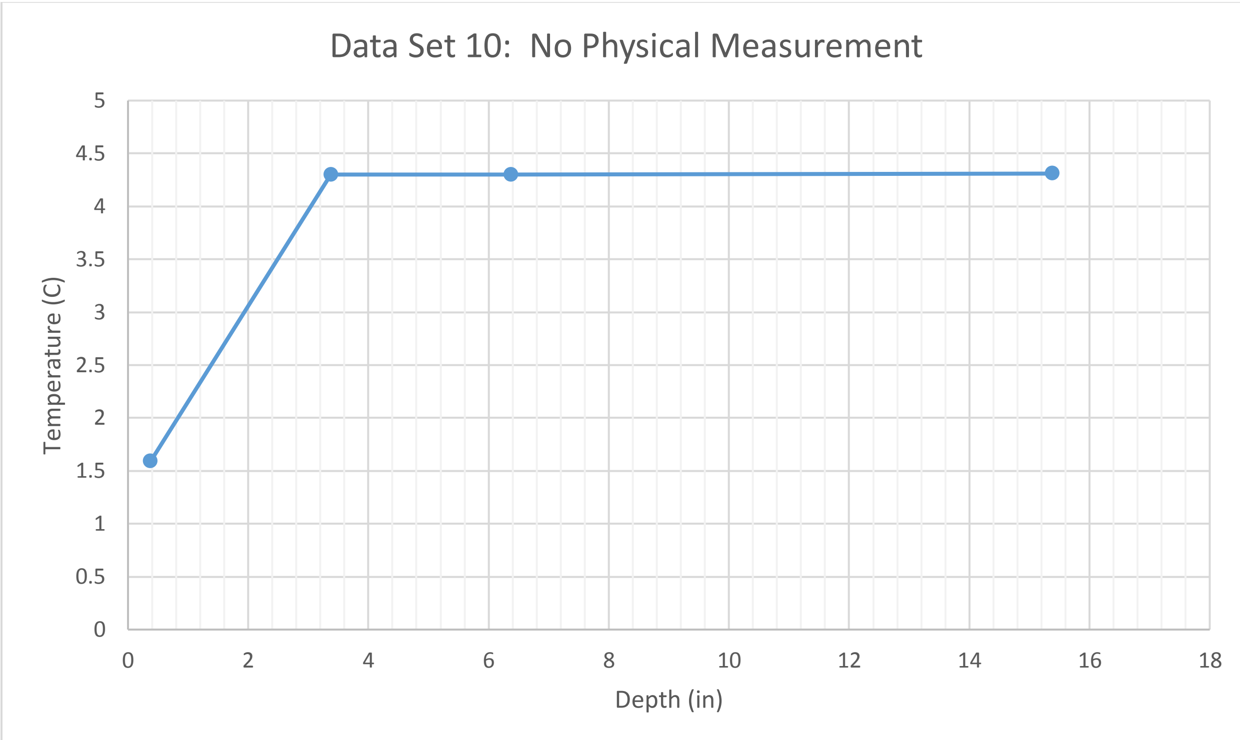
Data Set 9:

Ambient Temp = 28 F
3/3/17 (Time: 10:33AM)



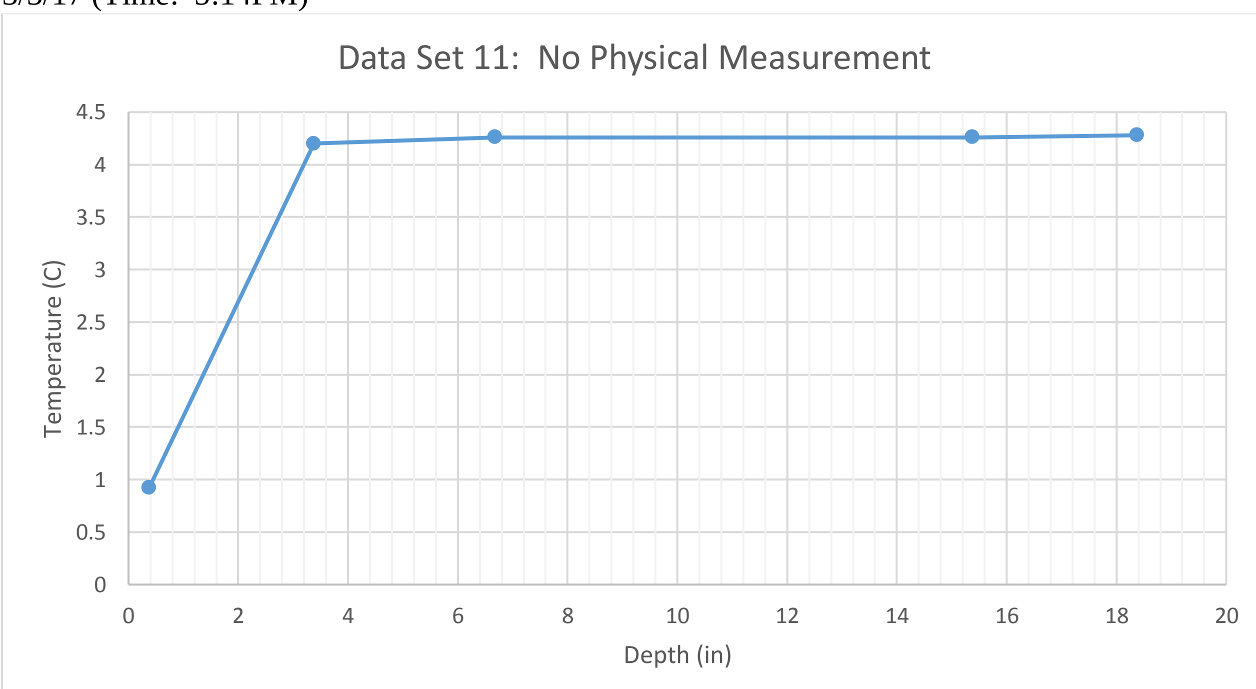
Data Set 10:

Ambient Temp = 30 F
3/3/17 (Time: 11:40AM)



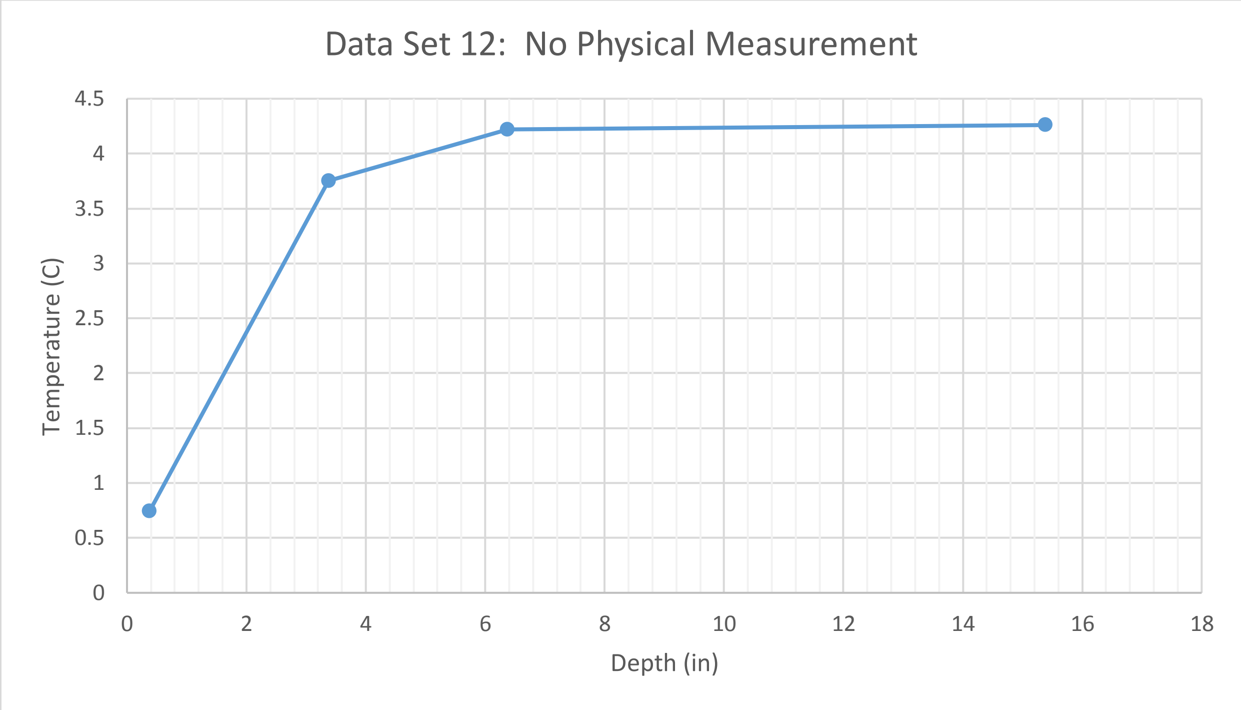
Data Set 11:

Ambient Temp = 32 F
3/3/17 (Time: 5:14PM)



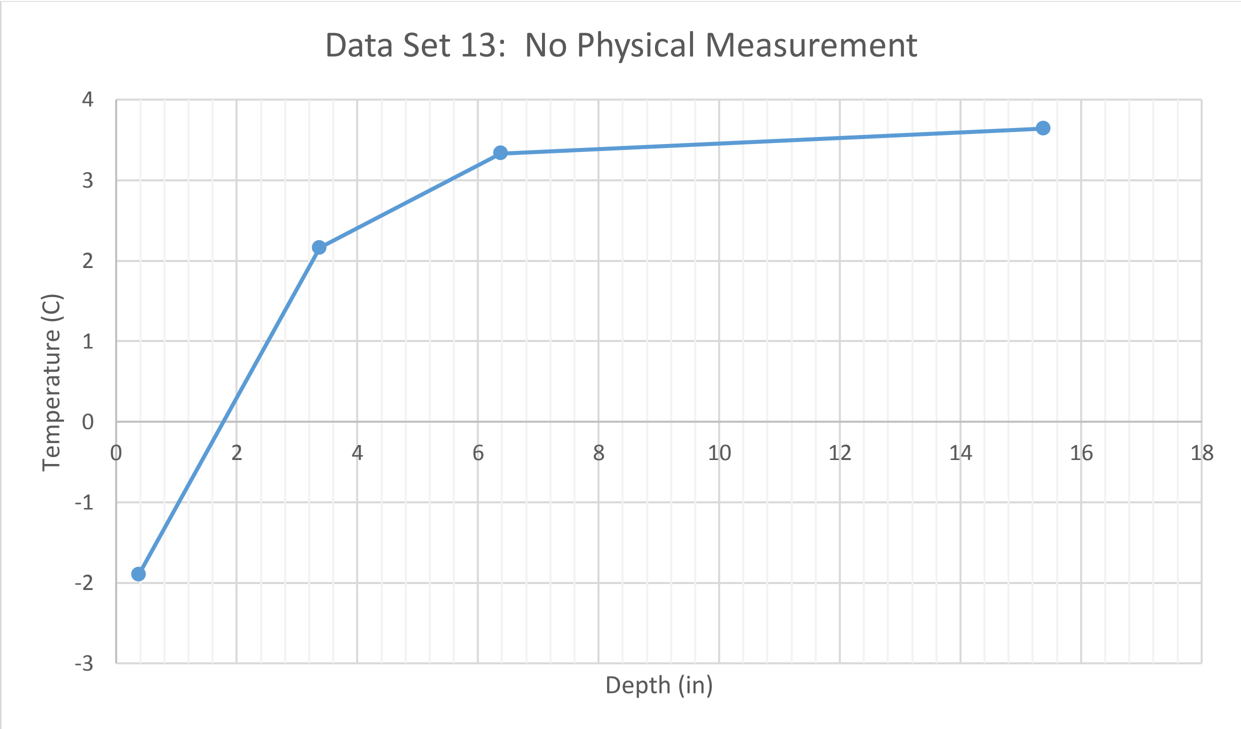
Data Set 12:

Ambient Temp = 29 F
3/3/17 (Time: 6:51PM)



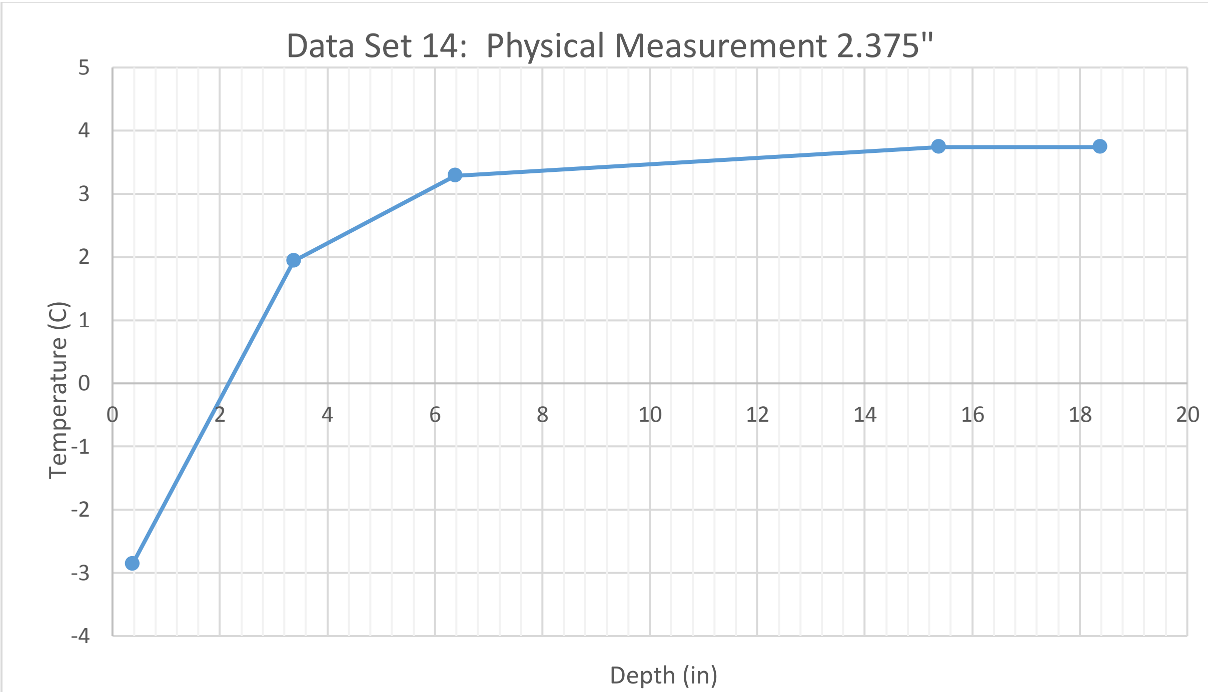
Data Set 13:

Ambient Temp = 15 F
3/4/17 (Time: 9:39AM)



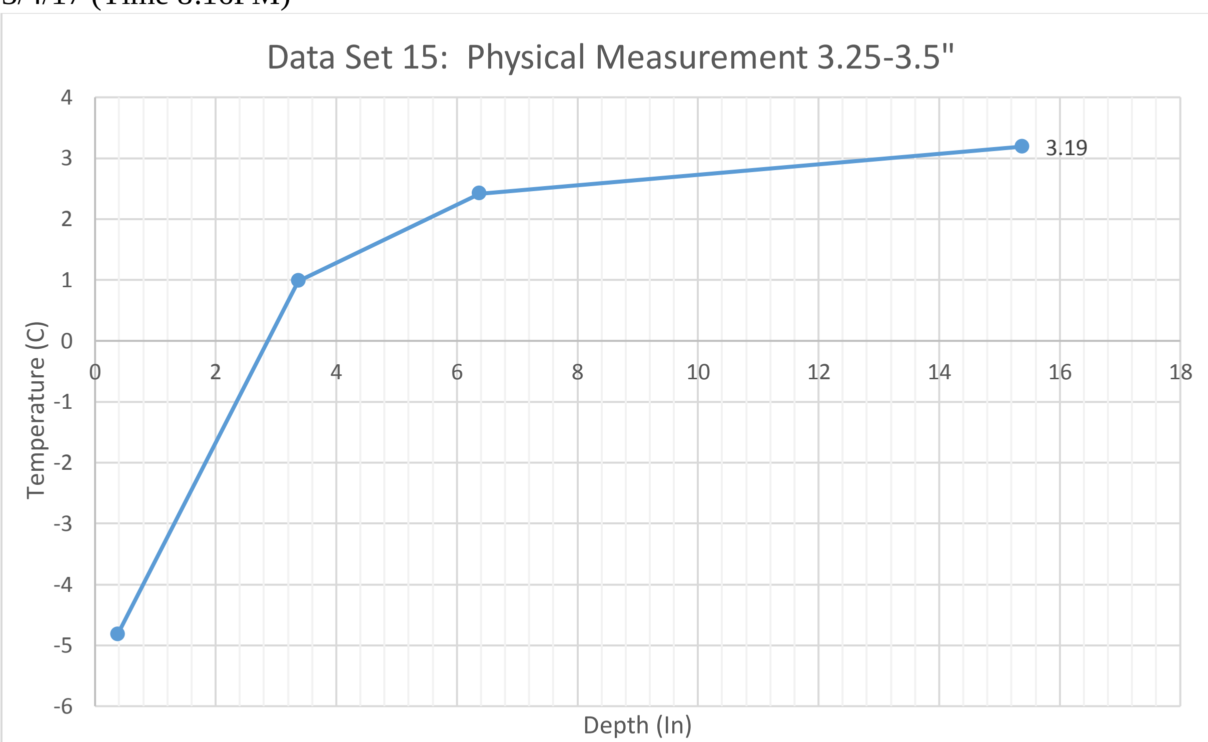
Data Set 14:

Ambient Temp = 19 F
3/4/17 (Time: 2:55PM)



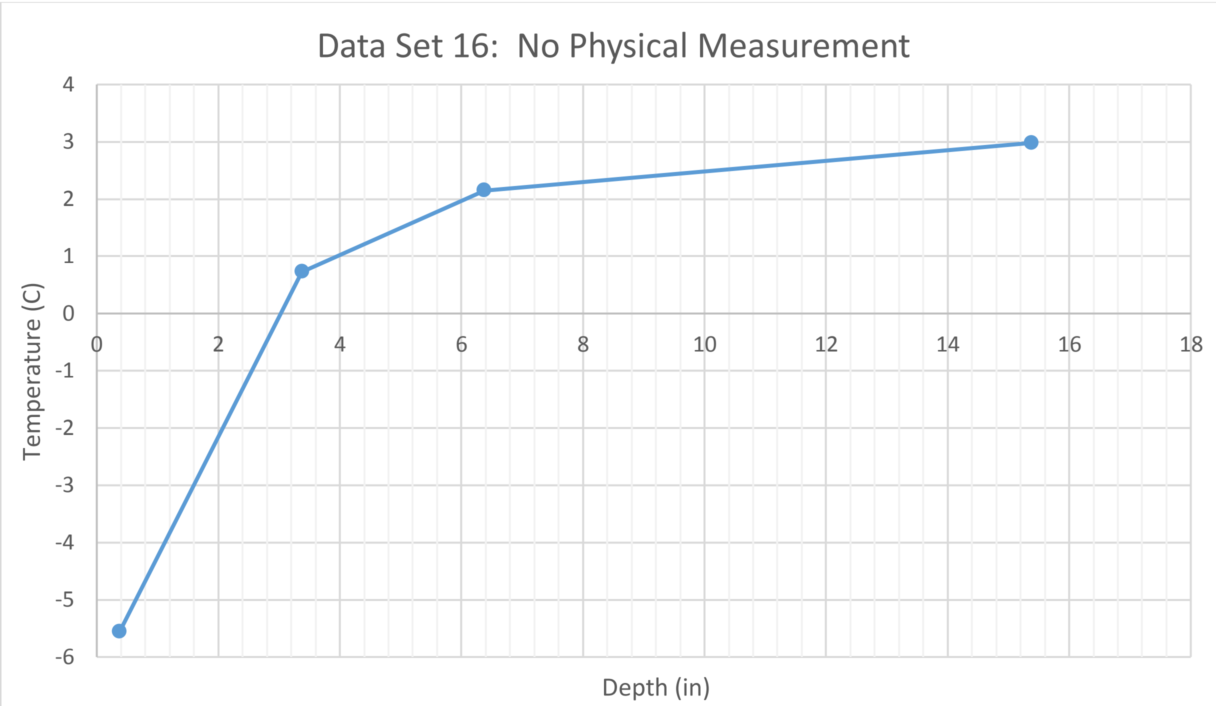
Data Set 15:

Ambient Temp = 12 F
3/4/17 (Time 8:16PM)



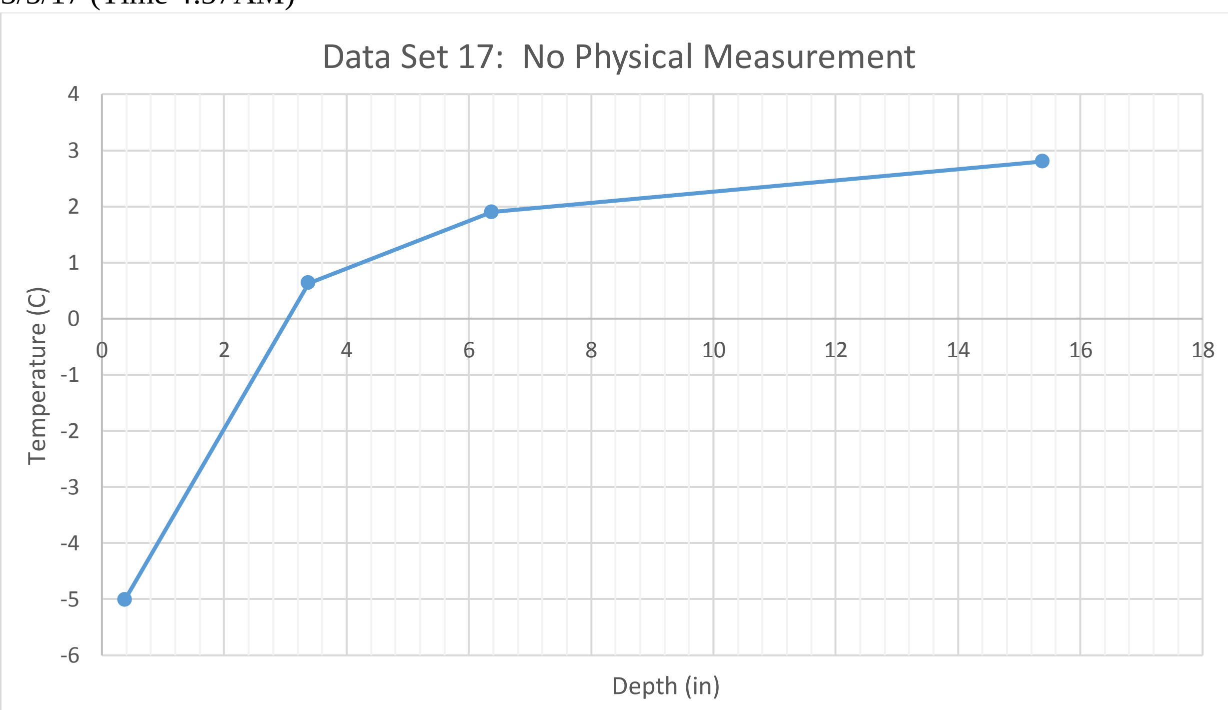
Data Set 16:

Ambient Temp = 7 F
3/5/17 (Time 2:37AM)



Data Set 17:

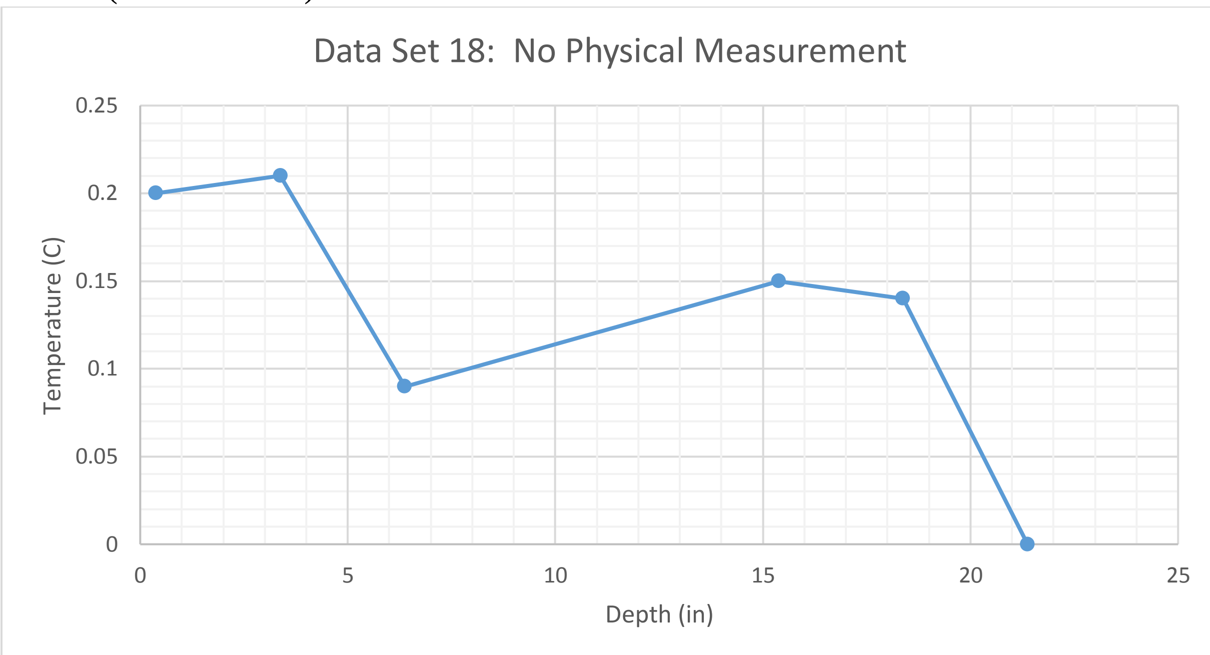
Ambient Temp = 7 F
3/5/17 (Time 4:57AM)



Appendix D: Ice Thawing Stage

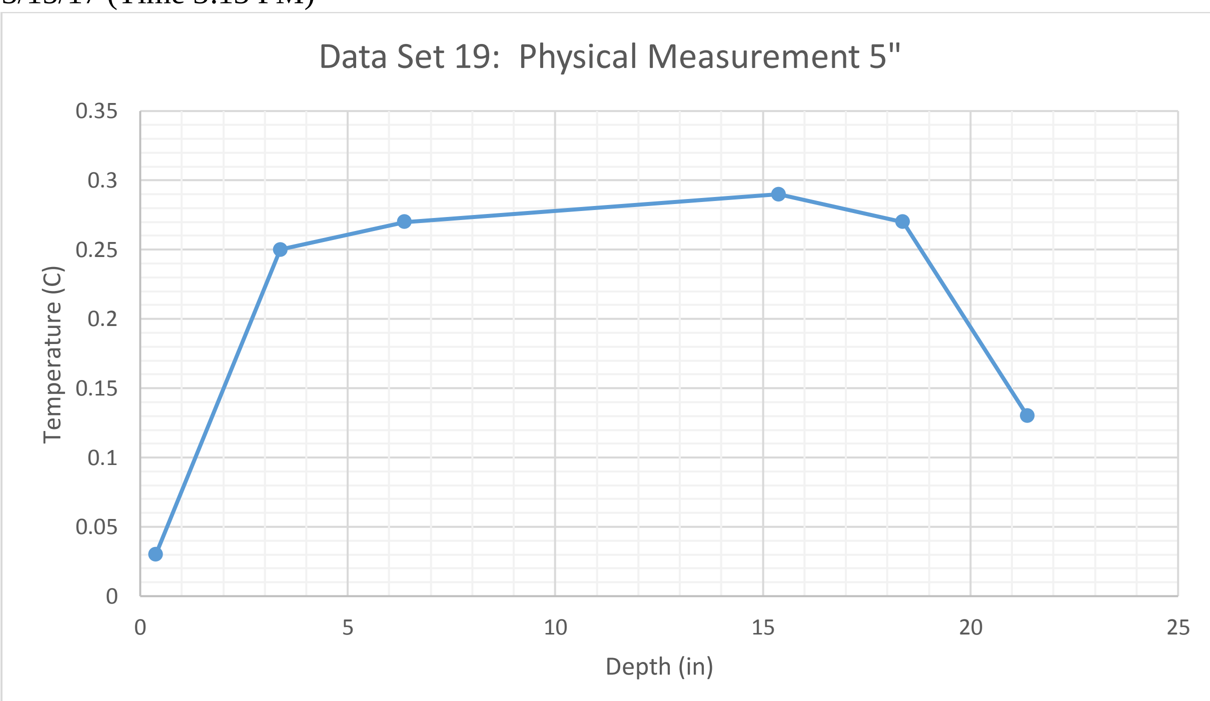
Data Set 18:

Ambient Temp = 32 F
3/13/17 (Time 8:18 PM)



Data Set 19:

Ambient Temp = 34 F
3/15/17 (Time 3:13 PM)



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