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Design of a New Ice Thermal Energy Storage System

Andrew Fontaine
Union College - Schenectady, NY

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By

Andrew Stephen Fontaine

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Abstract:

Over the past 30 years, alternative energy sources and concepts have been researched and desired as current energy resources are diminishing. One such alternative energy concept is an Ice Thermal Energy Storage system (ITES). ITES systems both store and create ice that helps them serve as a cold sink that can be used to cool down buildings using only the ice in the system. This project explores a new and more complex type of ITES system that decreases the heat transfer into the system, lengthens the amount of time the ice in the system stays frozen, and lessens the amount of ice needed for cooling a building.

During the first term of this two-term project, the initial research of ITES systems was completed, a new ITES concept was designed, and initial experiments were done on the new system. The new ITES system, includes a drain and base grate that allows the melted ice surrounding the ice core to drain from the system, leaving the core surrounded by air and increasing the thermal resistance of the system. The new ITES system was compared experimentally with the traditional ITES system that does not have a drain or a base grate. The results from the experiments showed that the new ITES system was able to keep the ice core temperature at or below the freezing point three times longer than the traditional system.

During the second term of the project, further experimentation was done involving a bigger ITES system, a system with a grate base platform, and an insulated system. The results from the experiments showed that the insulated ITES system with a grate base platform and a drain was able to keep the ice at or below the freezing point two times longer than the traditional system. Solidworks thermal modeling was

also done on the new ITES system to simulate the overall system performance. Future work must be done on determining the specific materials being used in the system, as well as improving the Solidworks thermal modeling to include daily and yearly temperature patterns.

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Introduction:

The goal of this project is to design an Ice Thermal Energy Storage system or ITES system. This type of system is used as an energy source that works alongside or in place of a traditional fossil fuel burning energy source. The type of system that this project focuses on is the ITES system with the use of snow and ice as the energy source. Snow and ice from the colder months of the year is stored in a system that acts as a cold source for cooling a building during the warmer months of the year. During the warmer months of the year, the cooling pipes of a building run through the ice storage container and the snow is used to help cool the glycol running through the building cooling pipes. The cooling from the snow helps reduce the amount of electricity and fossil fuels used to traditionally cool the building.

The main goal of an ITES system is to make the cooling of buildings a more environmentally friendly process by reducing the electricity and fossil fuel consumption of yearly building cooling. With fossil fuels and other energy resources becoming more and more scarce over time, an alternative and renewable energy source that can cut down on the use of nonrenewable energy resources will be beneficial over time. This system also reduces environmental footprint as it gives a storage spot for snow so inefficient snow melting machines are not needed and neither is inefficient snow removal.

The idea of ITES systems is logical however, the traditional systems used are not a realistic energy source as the life of the ice in the systems is not long enough. This project will look to design a new ITES system that prolongs the life of the ice in these systems and makes them a more feasible energy source.

Background and Literature Review:

The idea for the storage of ice to use at a later time began in the 1800s. Frederic Tudor was the first man to "harvest ice" or store it in large quantities during the winter for use during the warmer months of the year (McRobbie). This idea spurred interest in ice as more than just frozen water and something used to cool drinks in the summertime. In recent years, this idea of ice harvesting has been applied to the world of renewable and alternative energy.

The idea of Ice Thermal Energy Storage (ITES) is to help reduce cost and resources used in the yearly cooling process of a building. The thermal energy stored in ice is used to help cool the glycol or other coolant running through the building cooling pipes for air conditioning systems. The use of ice as a cooling source helps reduce or eliminate the need for other cooling sources and resources. Instead of burning fossil fuels and using other resources, water is used as the fuel or cold source. There are primarily two types of ITES systems: an active system and a harvesting system. In an active system, ice is made during the night or during off peak electricity times and stored in the systems for use during the next day during the warmer months of the year (Rosen). In a harvesting system, snow and ice from the colder months of the year is stored in the system and used during the warmer months of the year. Most harvesting systems, once out of harvested ice and snow become active systems for the remainder of the warmer months of the year. An active system during peak and off peak electricity times can be seen in Figure 1 below.

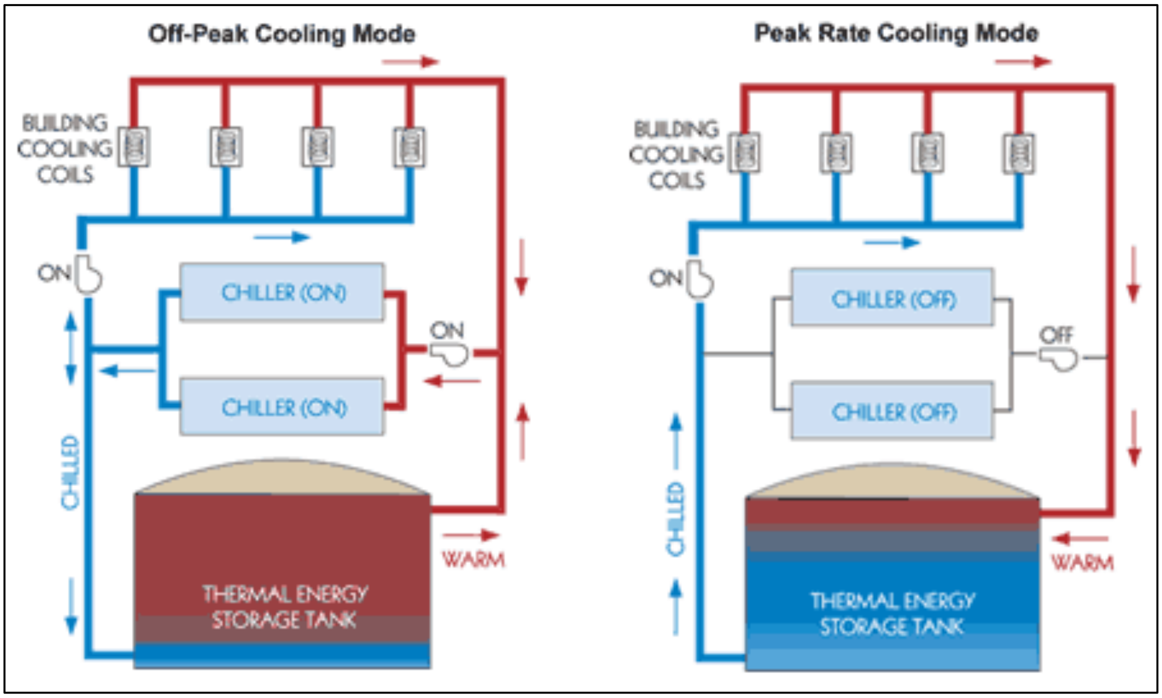

Fig.1. Active traditional ITES system during peak and off peak electricity times (Cypress, Ltd. 2016)

In order to understand how an ITES system works, all of the components that play into having an ITES system have to be considered. Some of the system properties that are looked at are the types of materials that make up each of the pieces in the system and the sizing of the system. Some of the exterior components that are looked at when having an ITES system are soil properties, geographic location, and yearly temperatures and weather patterns. All of these system and exterior properties were considered when the new ITES system was being designed.

When looking at the materials to use for the structure of the thermal energy storage tank, it was determined that a below ground level insulated tank made of concrete would allow for the best insulating properties (Heat Loss from Basement

Walls and Floors). Using Equations 1 and 2 the total heat transfer from the walls and floor of the tank can be determined.

$$\dot{Q}_{walls} = U_{wall,avg} * A_{wall} * (T_{basement} - T_{ground\ surface}) \quad \text{Equation 1}$$

$$\dot{Q}_{floor} = U_{floor} * A_{floor} * (T_{basement} - T_{ground\ surface}) \quad \text{Equation 2}$$

In Equation 1, $U_{wall,avg}$ is the average heat transfer coefficient between the walls and the ground surface and A_{wall} is the area of each wall. In Equation 2 U_{floor} is the heat transfer coefficient between the floor and the ground surface and A_{floor} is the area of the floor (Heat Loss from Basement Walls and Floors). These two equations were used to help determine what material would have the smallest amount of heat transfer, a major key to having an effective ITES system.

When looking at the external factors that affect an ITES system, the first thing to consider is geographic location. Since a harvesting ITES system relies on a change in seasons from one with snow and cold weather to one with warm weather, the locations an ITES system can be used need to be determined. In the United States, the regions where ITES systems are effective and can be implemented are the Northeast, the Great Lakes region, and parts of the Midwest (Reysa). However, non-harvesting ITES systems can be used anywhere in the United States where there is warm enough weather and cooling is needed.

Along with the general seasonal trends of locations, climate in the locations where ITES systems are being used has to be considered. The temperature, precipitation levels, and amount of sunlight are all climate factors that have a major impact on ITES systems. The air temperature in a particular region affects the ground temperature throughout that region as well. Ground temperature is directly related

to ITES systems, as the thermal energy storage tank is often underground. The ground temperature follows a similar trend to that of the air temperature. With the air temperature following a sinusoidal trend daily as well as annually, the ground temperature follows the same trend (Popiel). There is however, one distinct difference between the ground temperature and the air temperature, and that is the lag time for maximum and minimum daily and yearly temperatures in the ground compared to the air (Florides). The ground temperature maximums and minimums lag behind the maximum and minimum temperatures of the air as the ambient air temperature takes time to conduct through the soil.

Ground temperatures also vary the lag time from the air temperature as the depth changes. As the depth increases, the lag time for the maximum and minimum temperatures in the ground also increases (McIntosh). This trend is true down until about 15 meters deep. This is where the ground temperature is no longer affected by the surface air temperature and is relatively constant. At this depth and below, the ground temperature remains constant throughout the year and can be said to be equal to the average annual temperature in the region (Temperature and Thermal Properties (Basic)). A graph showing air temperatures and ground temperatures throughout the year at various depths and the lag time effect can be seen in Figure 2.

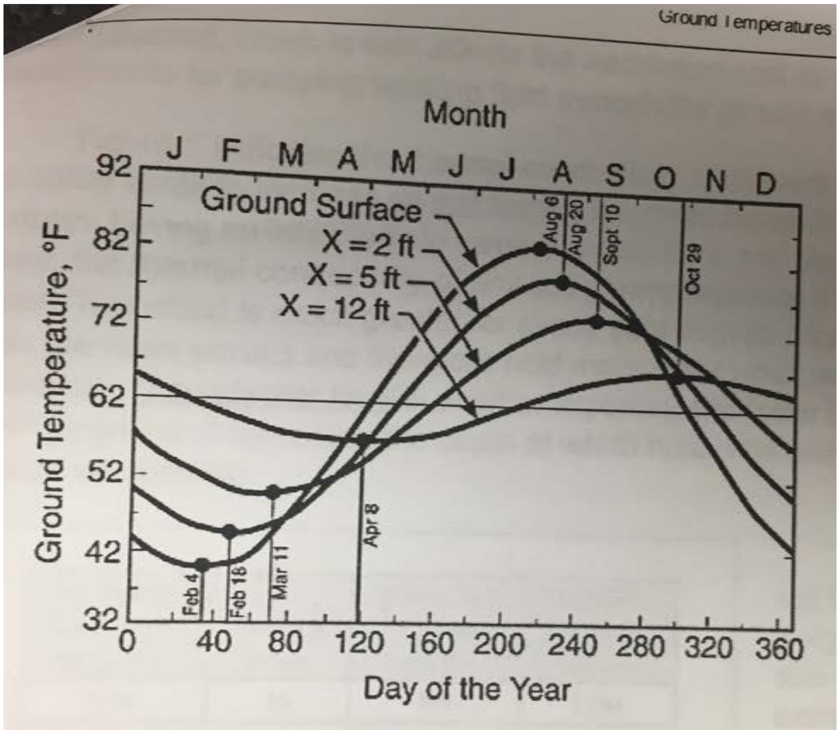

Fig.2. Temperature of air and soil based on depth to show the lag time effect.

(Reysa, 4)

The makeup of the ground composition near an ITES thermal energy storage tank must also be considered, as different types of soil and soil makeups have different thermal properties. Sand and loam have the lowest thermal conductivities on average and they are both below 1 W/(m*K), while clays and silts have higher thermal conductivities between 1 and 2 W/(m*K) (Temperature and Thermal Properties (Basic)). However, these values can change drastically depending on their saturation levels. Soils and sands that are damper have higher thermal conductivities between 2 and 3 W/(m*K). Damper ground also feels a greater affect from surface air temperature as depth increases compared to average or dry ground (Reysa). To

determine ground dampness, the annual precipitation in a region must be taken into account.

Design Description:

The traditional ITES system consists of a simple storage tank that houses the either harvested or made ice. The cooling pipes from a building run through the Ice Thermal Energy Storage tank and out into the building fans to be used for cooling. A traditional system can be seen below in Figure 3.

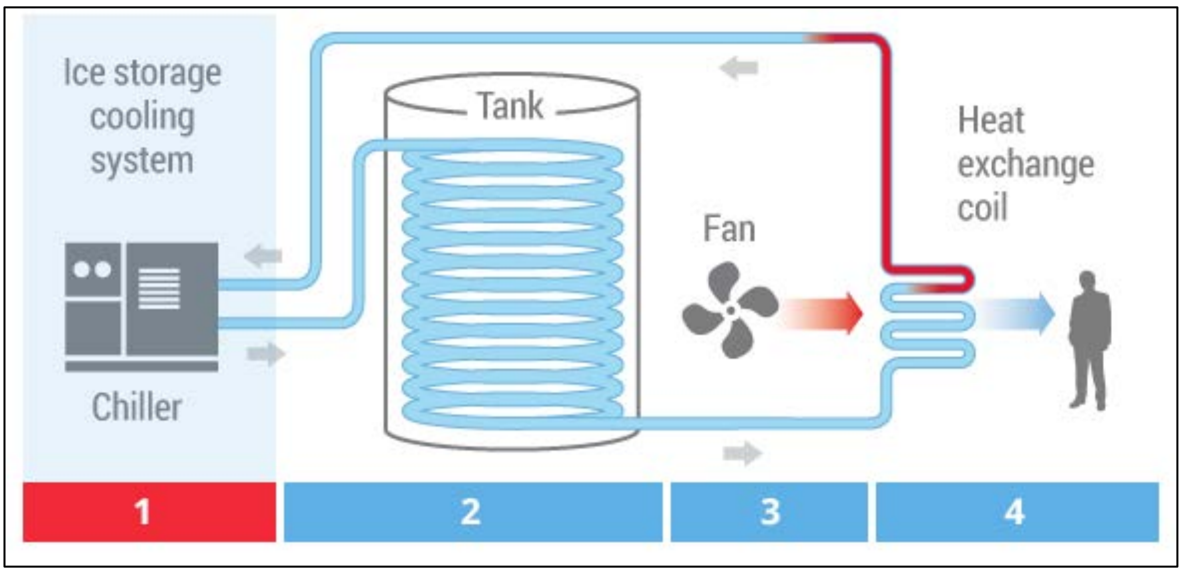

Fig. 3. Traditional ITES system with components and path of coolant through the system (Calmac 2014).

In Figure 3, the components of the system, the chiller, the energy storage tank, the building fans and the heat exchange coil can be seen. Figure 3 also shows the path that the glycol or coolant travels along from the chiller and then back into the chiller.

The traditional ITES systems, both harvesting and active, have been proven to reduce energy costs and the amount of resources needed for cooling. However, the cooling source in these systems does not have a long enough life for these systems to be used as a realistic energy source. After looking at the way in which ice melts, a new idea for an ITES system that would help prolong the life of the ice was thought of. As seen in Figure 4, a core of ice is left floating in water as the ice melts over time. Ice melts from the outside inward leaving a smaller core of ice surrounded by the already melted ice.

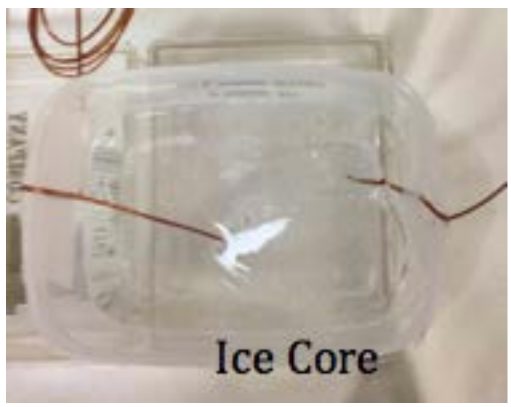

Fig.4. Ice core sitting in water after melting for a few hours.

This process of how ice melts inspired the new idea of adding a drain to the thermal energy storage tank. Adding a drain to the storage tank would allow for the snow and ice that gets melted off to leave the tank. This would leave just the snow and ice in the tank surrounded by air instead of water. The water that leaves the tank, since it had just melted, is still cold enough to be used as a cold source. This idea of using the melted ice as a cooling source inspired the idea of a precooling tank being added to the ITES system. This melting process also inspired the addition of a base

grate for the snow and ice to sit on in the storage container to reduce the heat transfer through the bottom of the container and keep the snow and ice out of the melted ice water at all times.

The advantage to having the snow and ice surrounded by air instead of water is that air has a lower thermal conductivity than water, meaning there would be less heat transfer from the air to ice than from the water to the ice. Theoretically, since air has a thermal conductivity of 0.025 W/(m*K) and water has a thermal conductivity of 0.6 W/(m*K), the ice will last longer when sitting in the storage tank surrounded by air as opposed to water.

The new design of the ITES system is seen in Figure 5. In the figure, all of the components of the new system are labeled and the path in which the coolant moves through the system is also labeled.

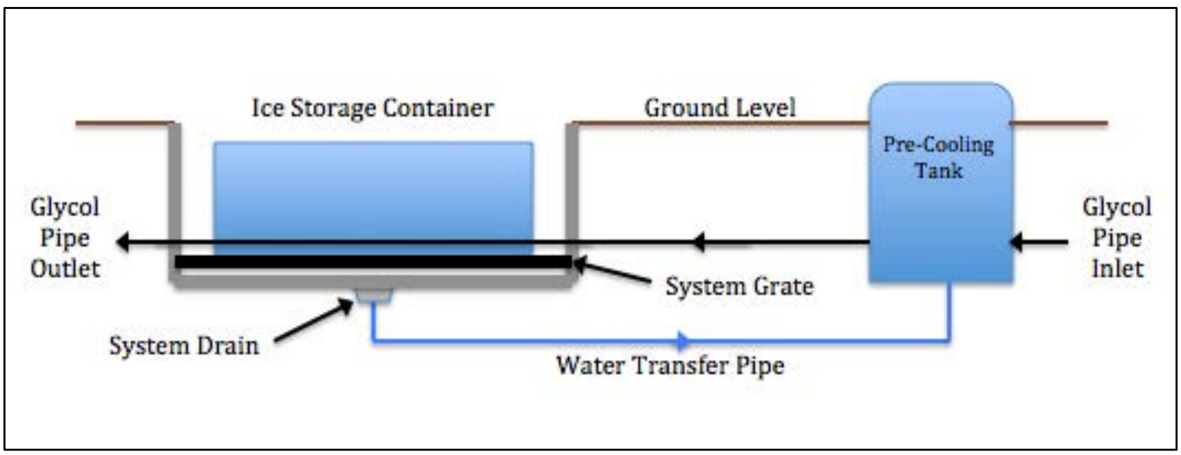

Fig.5. New ITES system with all components labeled. The path in which the coolant travels through the system is also labeled.

The new system is designed to work as either a harvesting system or an active system. The new ITES system, as a harvesting system, can work as either a direct

system or a co-cooling system. A direct system means that the system is run solely on the harvested snow and ice 24/7 until all of the snow and ice is gone, then the chillers would be used along side the active ITES system. A co-cooling system is the same thing as an active system, where the stored thermal energy would be used during the day or during peak electricity times and the chillers would be used at night or during off peak electricity times, except the snow and ice being used comes from harvesting not creating the ice over night. Once the harvested snow and ice is gone, the ITES system turns into an active system and is used in this way for the remainder of the time cooling is needed.

The new ITES system is more complex than the traditional system and has a few more components to it than the traditional system. The first piece of the new system is thermal energy storage tank. The new tank is designed to be 50x25x9 meters with 1meter thick walls. The tank is built into the ground and is made out of foundation concrete. Inside the tank, there is now a drain in the bottom and a plastic base grate 0.5 meters from the bottom of the storage container. The plastic base grate is slotted to allow the snow and ice to rest on top and the melted ice water to fall through it down to the drain. A section view of the tank is seen in Figure 6.

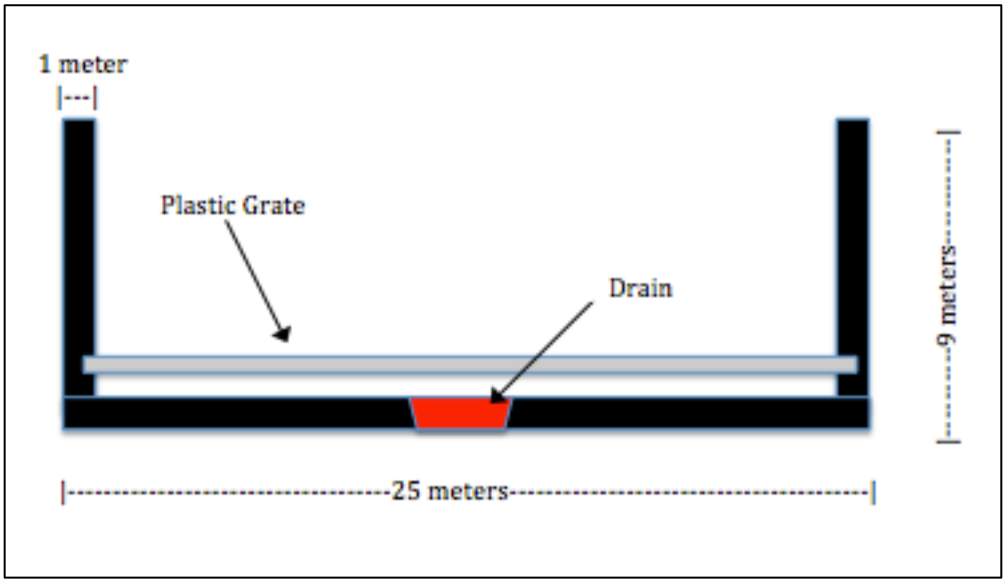

Fig.6. Section view of new Ice Thermal Energy Storage tank.

Once the water leaves the thermal storage tank, it is pumped into the next part of the ITES system, the cool water storage tank. The cool water storage tank is designed to work as a pre-cooling mechanism for the thermal energy storage tank. The building cooling pipes will run through the cool water storage tank prior to the thermal energy storage tank. The cool water storage tank will pre-cool the glycol in the building cooling pipes prior to it entering the thermal energy storage tank. This pre-cooling mechanism will help drop the temperature of the glycol entering the thermal energy storage system, thus dropping the temperature difference between the glycol and the snow and ice. The smaller temperature difference means that there will be less heat energy transferred into the snow and ice, making the snow and ice last longer. The cool water storage tank is designed to be tall and cylindrical. The tank has this shape to ensure the coldest water in the tank is at the bottom. With the height of the tank, a pressure difference between warm and cold water will be seen, making the cold water stay at the bottom of the tank and the warmer water rise to the top of the tank. The warmer water from the top of the tank will be removed and stored in a

second water storage tank and can be used to remake ice once the initial harvested ice has all melted.

Analytical Design:

To understand the way in which ice melts and the way in which it behaves before, during and after a phase change from solid to liquid, an analytical model was created. Using a series of mass and heat transfer equations, the time before the ice reaches its melting point, the time during the transition of the ice to liquid water, and the time after the ice has fully melted and reaches the ambient air temperature can all be modeled. Assuming there is no heat loss to the surrounding air, the base energy balance equation, Equation 3, can be used to get Equation 4, which can be rearranged to find Equation 5. Equation 5 can then be used to model the time both before and after the ice experiences a phase change.

$$mCp\frac{dT}{dt} = Q_{in} \qquad \text{Equation 3}$$

$$mCp\frac{dT}{dt} = UA(T_\infty - T) \qquad \text{Equation 4}$$

$$T_N = T + \frac{UA}{mCp}\Delta t(T_\infty - T) \qquad \text{Equation 5}$$

In Equation 5, T_N is the new temperature being found, T is the temperature from the time step before, U is the coefficient of heat transfer, A is the surface area of the ice, m is the mass of the ice, Cp is the specific heat capacity of the ice, Δt is the time step, and T_∞ is the ambient air temperature. The only change for modeling the before and after phase change times of the ice melting is the Cp value switches to the Cp value of water after the phase change.

To model the time during the phase change from solid ice to liquid water, the mass balance equation, Equation 8, can be used. Equation 8 comes from the basic mass balance equation, Equation 6, which can be used to get equation 7, which can be rearranged to find Equation 8.

$$\frac{dm_f}{dt} h_i + mCp\frac{dT}{dt} = Q_{in} \qquad \text{Equation 6}$$

$$\frac{dm_f}{dt} h_i = U(T_\infty - T_{melt}) \qquad \text{Equation 7}$$

$$m_{fn} = m_f + \frac{UA\Delta t}{h_i}(T_\infty - T_{melt}) \qquad \text{Equation 8}$$

In Equation 8, m_{fn} is the new mass of the fluid, m_f is the mass of the fluid from the time step before, U is the coefficient of heat transfer, A is the surface area, Δt is the time step, h_i is the latent heat of fusion of water, T_∞ is the ambient air temperature, and T_{melt} is the melting temperature of the ice.

To solve for the UA term in both Equation 5 and Equation 8, when being applied to the small storage container from the experimental modeling done on the storage system, the system was treated as a thermal circuit with one-dimensional heat transfer. For the small storage container experiment, the thermal circuit resistance diagram seen in Figure 7 was used. The total system resistance was calculated using a resistance equation to find the conduction through the plastic container, as seen in Equation 9.

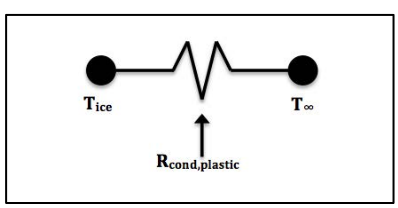

Fig.7. Thermal resistance circuit diagram for small storage container experiment.

$$R_{small\ tank} = \frac{L_{plastic}}{K_{plastic}A_{plastic}}$$ Equation 9

In Equation 9, $R_{small\ tank}$ is the total thermal resistance through the storage system, $L_{plastic}$ is the thickness of the plastic, $K_{plastic}$ is the thermal conductivity of the plastic, and $A_{plastic}$ is the average inner and outer surface area of the plastic container.

To solve for the UA term in both Equation 5 and Equation 8, when being applied to the large storage container from the experimental modeling done on the storage system, the system was treated as a thermal circuit with one-dimensional heat transfer. For the small storage container experiment, the thermal circuit resistance diagram seen in Figure 8 was used. The total system resistance was calculated using a resistance equation to find the convection through the air around the ice and the conduction through the plastic container, as seen in Equation 10.

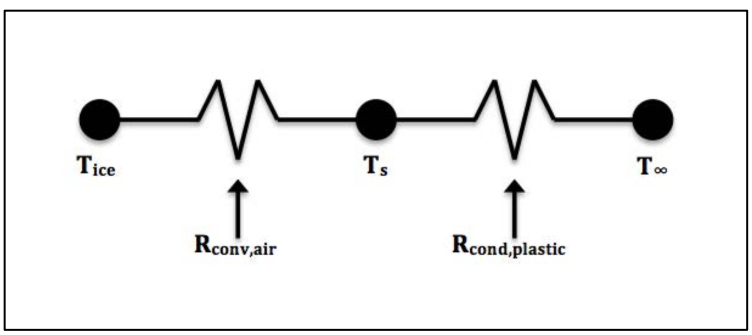

Fig.8. Thermal resistance circuit diagram for large storage container experiment.

$$R_{large\ tank} = \frac{1}{h_i A_{ice}} + \frac{L_{plastic}}{K_{plastic}A_{plastic}}$$ Equation 10

In Equation 10, $R_{large\ tank}$ is the total thermal resistance through the storage system, h_i is the convective heat transfer coefficient of the air, A_{ice} is the surface area of the ice, $L_{plastic}$ is the thickness of the plastic, $K_{plastic}$ is the thermal conductivity of the plastic, and $A_{plastic}$ is the average inner and outer surface area of the plastic container.

The $R_{small\ tank}$ value calculated using Equation 9 and the $R_{large\ tank}$ value calucalted using Equation 10 were then used in Equation 11 to find the UA value for each respective system.

$$UA = \frac{1}{R} \qquad \text{Equation 11}$$

Analytical Results:

The analytical model was applied to the small storage container experiment and the results from the analytical model and first experimental model were graphed and compared as seen in Figure 9.

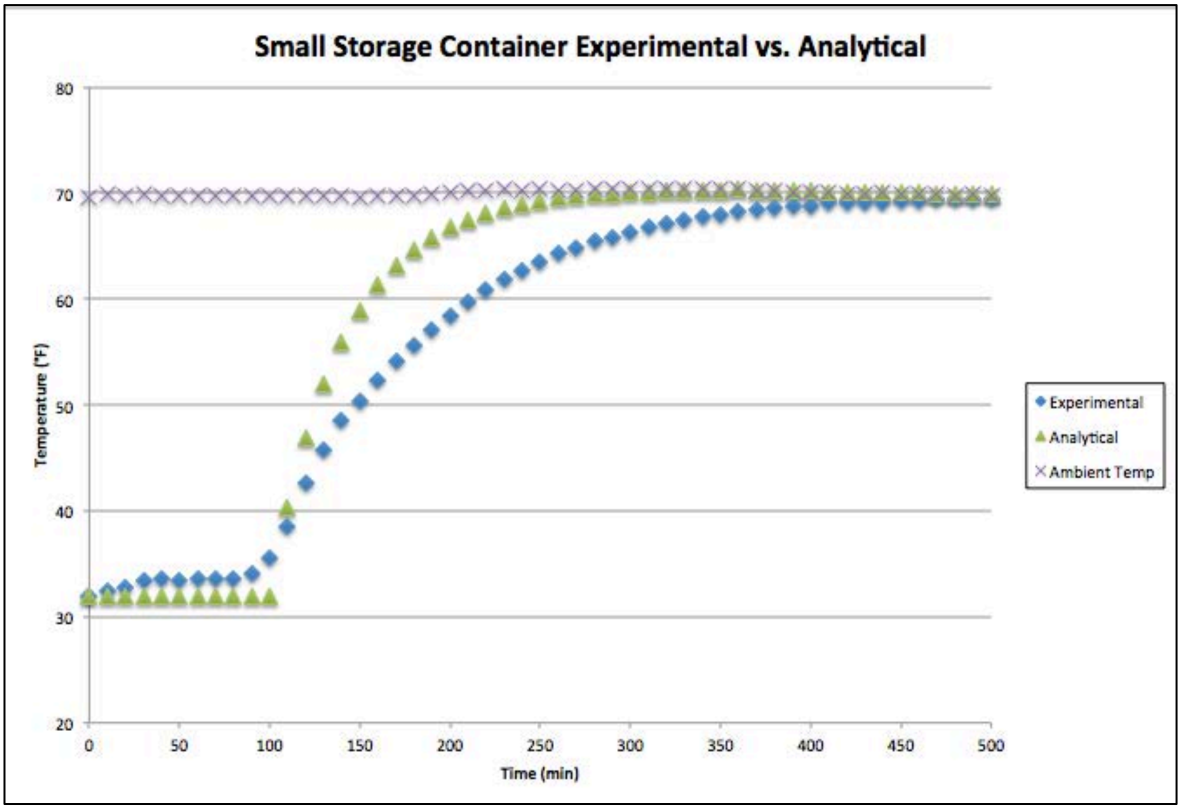

Fig.9. Small storage container experimental and analytical temperature data graphed versus time, along with the ambient air temperature graphed versus time.

The analytical model was applied to the large storage container experiment and the results from the analytical model and experimental model were graphed and compared as seen in Figure 10.

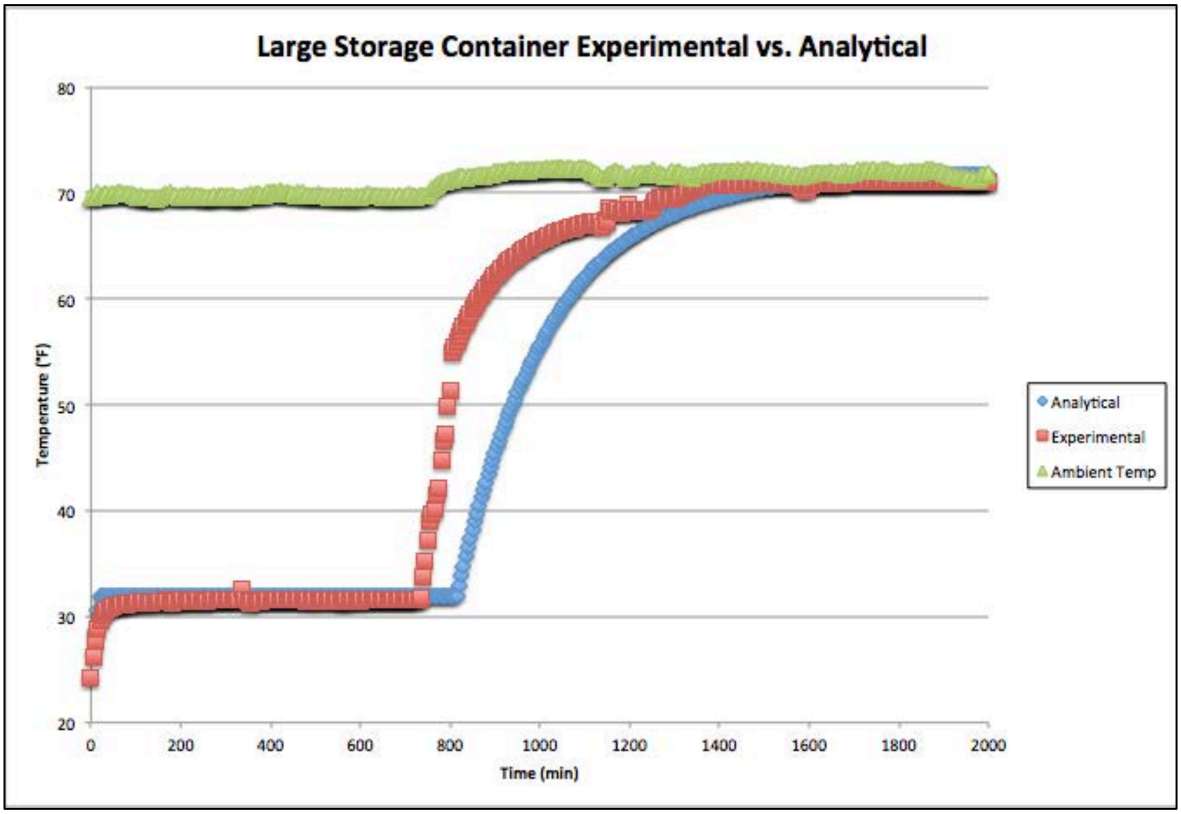

Fig.10. Large storage container experimental and analytical temperature data graphed versus time, along with the ambient air temperature graphed versus time.

Experimental Design:

The first experiment that was run was to test the idea of the drain, inspired by the way in which ice melts. Two plastic containers with dimensions 4x2x2 inches were used as the ice storage tanks. Two type K thermocouples were taped to the inside of each of the tanks. One of the thermocouples was placed near the edge of the tank 1 cm from the bottom of the tank and the other thermocouple was placed in the direct middle of the tank. The two tanks were each filled with 150 mL of water and placed in the freezer with the thermocouples attached and no lids. Once the water in

each of the two tanks was frozen, the tanks were removed from the freezer and placed on top of a plastic container as seen in Figure 11. The lids to the two tanks were added and the thermocouples were plugged into the Data Acquisition (DAQ) system.

Fig.11. Experimental setup of the two ice storage tanks. The tank with the purple lid was used as the original tank model with no drain and the tank with the pink lid was used as the new tank model with the drain.

Two additional type K thermocouples were connected to the DAQ system to record the ambient temperature around each of the two tanks. To model the drain, a small hole was drilled through the bottom of one of the tanks. Using the DAQ system, temperature data was taken at each of the 6 thermocouple locations every 10 minutes. The data from the thermocouple located in the center of the ice was graphed

against time for both the system with the drain and the system without the drain and compared.

The second experiment that was run was to test the idea of the grate on the bottom of the ice storage container. The theory behind adding a grate to the bottom of the storage container was that the ice would be completely surrounded by air, reducing the heat transfer between the bottom of the storage container and the ice. Two containers of dimensions 10x6x5 were used to freeze the ice blocks for the experiment. Two type K thermocouples were taped to the inside of each of the tanks. One of the thermocouples was placed near the edge of the tank 1 inch from the bottom of the tank and the other thermocouple was placed in the direct middle of the tank. The two tanks were each filled with 1500 mL of water and placed in the freezer with the thermocouples attached and no lids. Once the water in each of the two tanks was frozen, the tanks were removed from the freezer and the ice was removed from the freezing containers and placed in the ice storage containers.

Two plastic containers with dimensions 13x8x5 inches with full sink drains in the bottom were used as the ice storage tanks as seen in Figure 12.

Fig.12. Large ice storage container tanks used in the second, third, and fourth experimental test.

One of the ice storage tanks contained a metal grate as seen in Figure 13. The metal grate was made out of thin metal sheets with a lattice of holes in them. The four thin metal sheets used, were connected together by 0.5 inch screws and nuts along the outside of the grate. 1 inch screws were placed in each of the 4 corners of the grate and in the middle of the grate along each side to keep the grate elevated off the bottom of the tank. The constructed metal grate was 11 inches long by 5 inches wide and had a thickness of 0.03125 inches.

Fig.13. Metal grate used in the large ice storage container test.

The ice was placed on top of the metal grate in one ice storage tank and on the bottom of the other ice storage tank. The two ice storage containers, with their drains open, were each placed on top of a plastic container as seen in Figure 14. The insulation lids to the two tanks were added and the thermocouples were plugged into the Data Acquisition (DAQ) system.

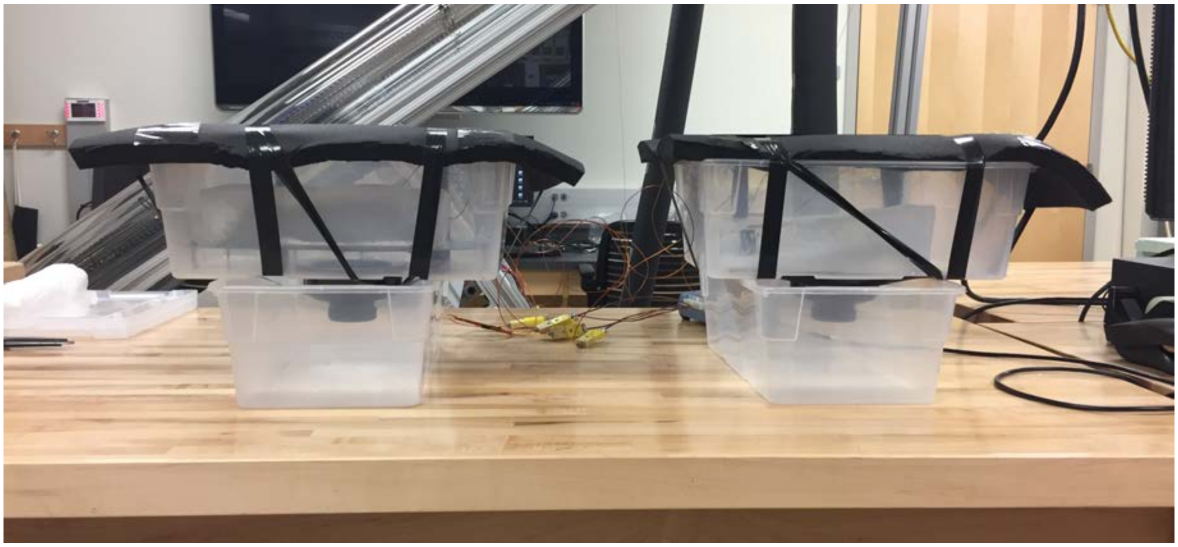

Fig.14. Experimental setup used for the large ice storage container test with the metal grate. The storage container on the left contains the metal grate with the ice block on top of it while the storage container on the right has the ice block on the bottom of the container.

An additional type K thermocouple was connected to the DAQ system to record the ambient temperature around the two tanks. Using the DAQ system, temperature data was taken at each of the 5 thermocouple locations every 5 minutes. The data from the thermocouple located in the center of the ice in each tank was graphed against time and the two systems were compared.

The third experiment that was run was the same as the second experiment run, which tested the theory of the grate on the bottom of the ice storage container. However, this time instead of a metal grate being used, a plastic grate was used. The plastic grate as seen in Figure 15 was constructed from a piece of Plexiglas that was 8 inches long by 5 inches wide, and 0.125 inches thick. The Plexiglas had 0.125 inch

diameter holes drilled into it every inch both length-wise and width-wise. The Plexiglas then had a 1 inch screw drilled into each corner to keep it off the bottom of the ice storage container.

Fig.15. Plastic grate used in experimental modeling of ITES storage container.

The two ice freezing containers, containing the two placed thermocouples, were filled with 1500 mL of water and put in the freezer. Once the water in each of the two tanks was frozen, the tanks were removed from the freezer and the ice was removed from the freezing containers and placed in the ice storage containers. The ice was placed on top of the plastic grate in one ice storage tank and on the bottom of the other ice storage tank. The two ice storage containers, with their drains open, were each placed on top of a plastic container as seen in Figure 16. The insulation lids to the two tanks were added and the thermocouples were plugged into the Data Acquisition (DAQ) system.

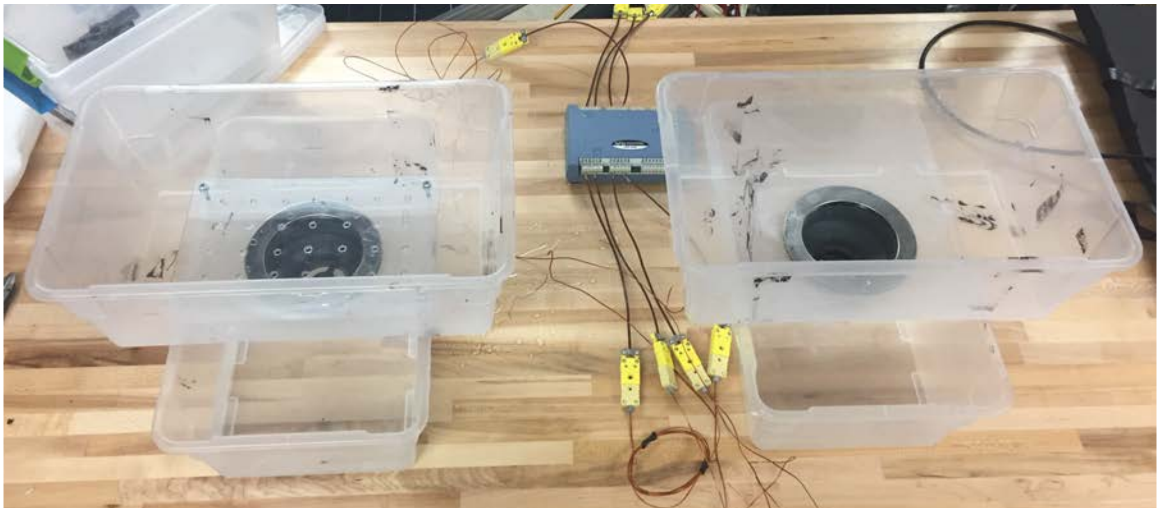

Fig.16. The two ice storage containers with both of their drains open. The storage container on the left contains the plastic grate in the bottom.

An additional type K thermocouple was connected to the DAQ system to record the ambient temperature around the two tanks. Using the DAQ system, temperature data was taken at each of the 5 thermocouple locations every 5 minutes. The data from the thermocouple located in the center of the ice in each tank was graphed against time and the two systems were compared.

The final experiment that was run was to compare the new ITES storage tank with the drain, grate, and insulation to the traditional ITES storage tank with no drain, no grate, and no insulation. In this experiment, the large ice storage containers, with the sink drains in the bottom, were used. To model the new ITES system, one of the tanks had its drain open, the plastic grate on the bottom, and the storage container was wrapped in 1 inch thick insulation as seen in Figure 17. To model the traditional ITES system, the other storage container had its drain closed, no grate, and no insulation.

Fig.17. Final ITES storage container with a drain, a plastic base grate, and 1 inch thick insulation around the sides, top, and bottom of the container.

The two ice freezing containers, containing the two placed thermocouples, were filled with 1500 mL of water and put in the freezer. Once the water in each of the two tanks was frozen, the tanks were removed from the freezer and the ice was removed from the freezing containers and placed in the ice storage containers. The ice was placed on top of the plastic grate in the new ITES ice storage tank and on the bottom of the traditional ITES ice storage tank. The two ice storage containers were each placed on top of a plastic container as seen in Figure 18. The insulation lids to the two tanks were added and the thermocouples were plugged into the Data Acquisition (DAQ) system.

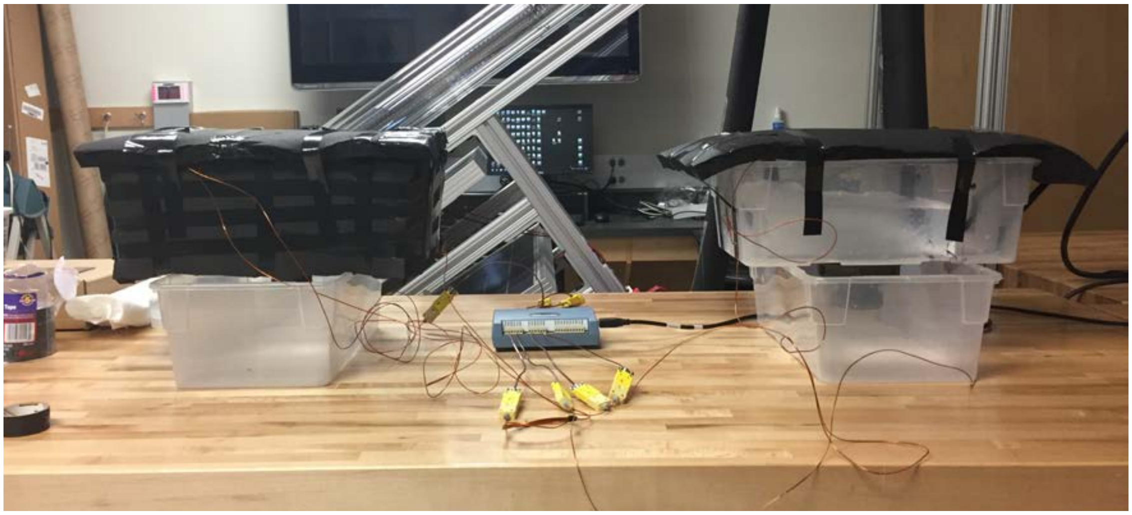

Fig.18. Experimental setup used to test the new ITES storage container and the traditional ITES storage container. The new ITES storage container with the drain, plastic grate, and insulation can be seen on the left and the traditional ITES storage system with no drain, grate or insulation can be seen on the right.

An additional type K thermocouple was connected to the DAQ system to record the ambient temperature around the two tanks. Using the DAQ system, temperature data was taken at each of the 5 thermocouple locations every 5 minutes. The data from the thermocouple located in the center of the ice in each tank was graphed against time and the new and traditional ITES storage systems were compared.

Experimental Results:

The results from the first tabletop experiment consisting of the two small ice storage tanks, one with the drain and one without the drain, can be seen in Figure 19.

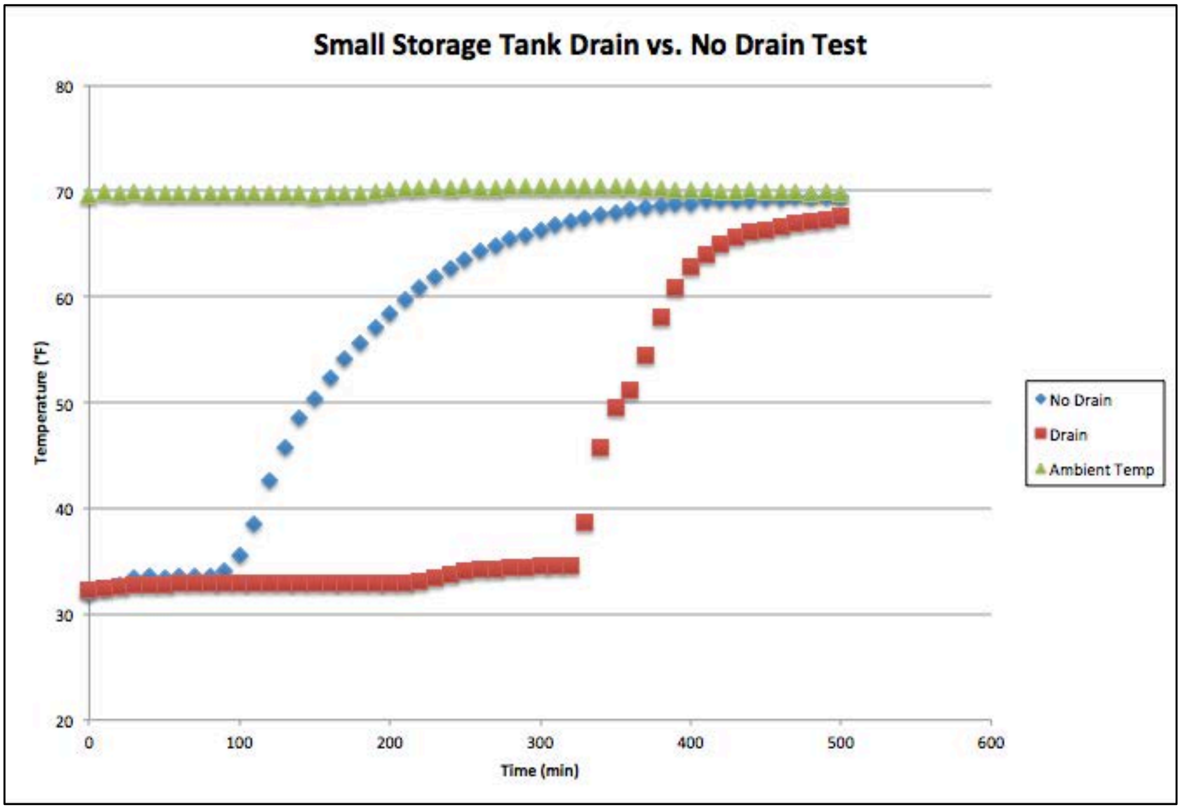

Fig.19. Temperature versus time graph for the small two tank experiment, one with a drain and one without a drain. The temperature data is from the thermocouple located at the center of each of the tanks. The temperature at this location in each of the tanks is graphed versus time. The ambient temperature around the two tanks is also graphed versus time.

The results from the second tabletop experiment consisting of the two large ice storage tanks to test the affect of the metal grate on the ice melt time can be found

in Figure 20. For this experiment, both tanks had their drains open, and one of the tanks contained a metal grate on the bottom of the tank.

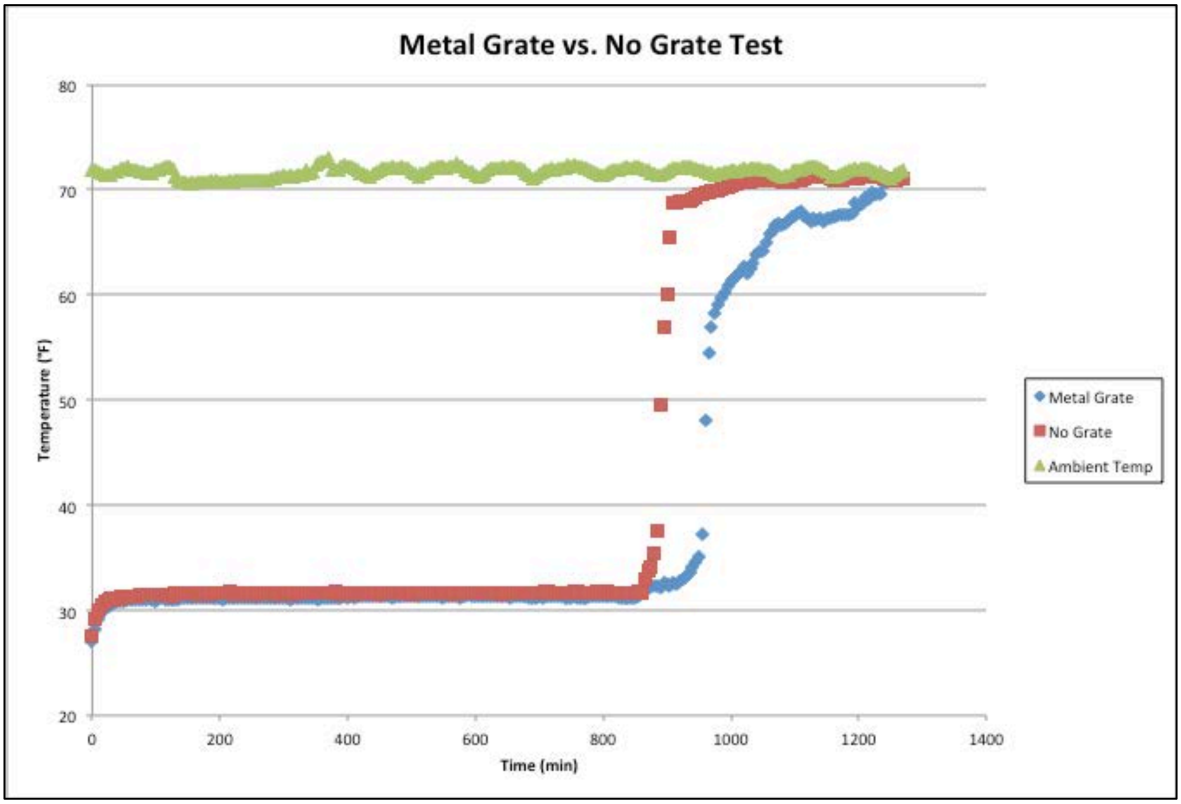

Fig.20. Temperature versus time graph for the large two tank experiment, one with a metal grate in the bottom of the tank and one without a grate. The temperature data is from the thermocouple located at the center of each of the tanks. The temperature at this location in each of the tanks is graphed versus time. The ambient temperature around the two tanks is also graphed versus time.

The results from the third tabletop experiment consisting of the two large ice storage tanks to test the affect of the plastic grate on the ice melt time can be found in Figure 21. For this experiment, both tanks had their drains open, and one of the tanks contained a plastic grate on the bottom of the tank.

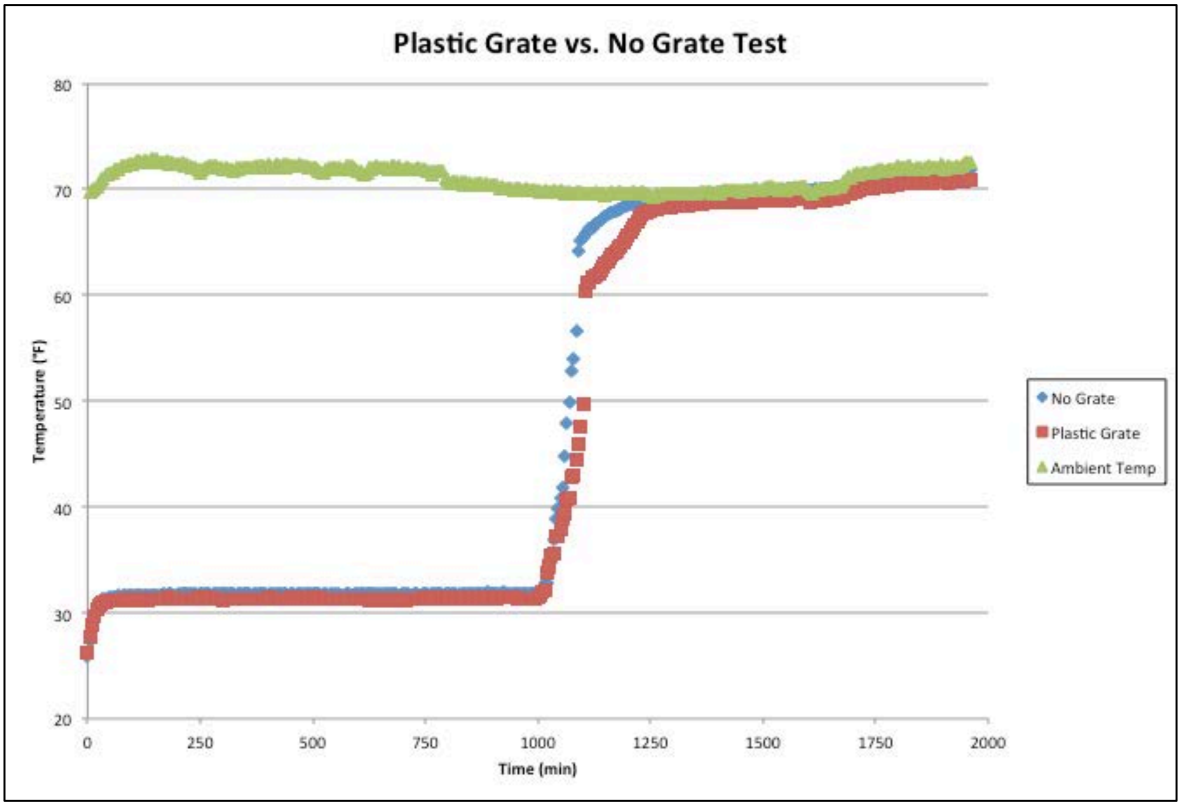

Fig.21. Temperature versus time graph for the large two tank experiment, one with a plastic grate in the bottom of the tank and one without a grate. The temperature data is from the thermocouple located at the center of each of the tanks. The temperature at this location in each of the tanks is graphed versus time. The ambient temperature around the two tanks is also graphed versus time.

The results from the final tabletop experiment, testing the new ITES storage container against the traditional ITES storage container can be found in Figure 22. For this experiment, the new ITES storage container had its drain open, the plastic grate in the bottom, and was wrapped in 1 inch of insulation on all sides while the traditional system had its drain closed, no grate on the bottom and no insulation.

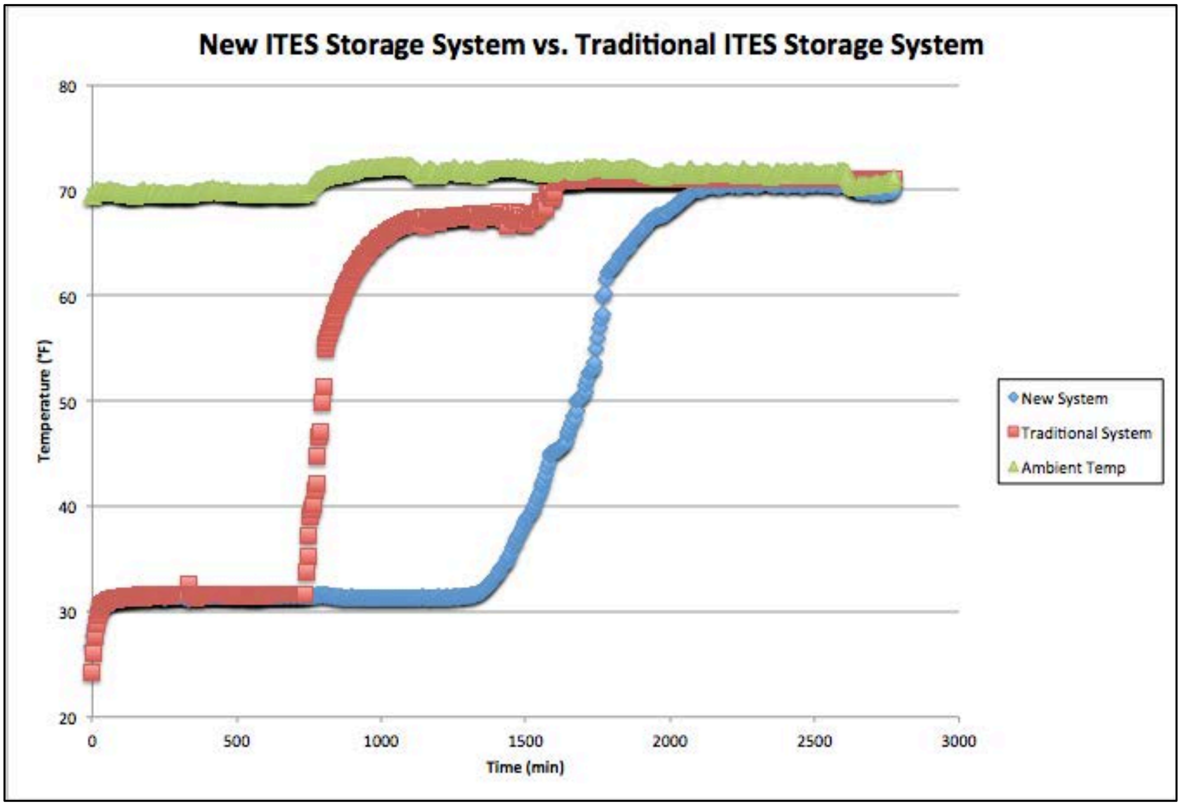

Fig.22. Temperature versus time graph for the large two tank experiment, comparing the new ITES storage system and the traditional ITES storage system. The temperature data is from the thermocouple located at the center of each of the tanks. The temperature at this location in each of the tanks is graphed versus time. The ambient temperature around the two tanks is also graphed versus time.

Solidworks Modeling Design:

To model the full scale ITES system, a Solidworks model was designed and a transient thermal study was run to model the system performance over time. To construct the model, four individual Solidworks parts were created and then an assembly was constructed from the parts. Once the assembly was complete, thermal boundary conditions were applied to the model and the thermal study was run.

The first part of the model that was created was the soil. The soil was created as the exterior boundary that would hold the ITES storage container. The soil component was modeled as a rectangular block that was 70 m long, 45 m wide, and 12 m deep. In the center of the soil, a rectangular block of dimensions 50 m long by 25 m wide by 10 m deep was cut out to hold the ITES storage container component. The Solidworks material properties of soil were applied to the soil component. A picture of the dimensioned Solidworks soil component can be found in Figure 23.

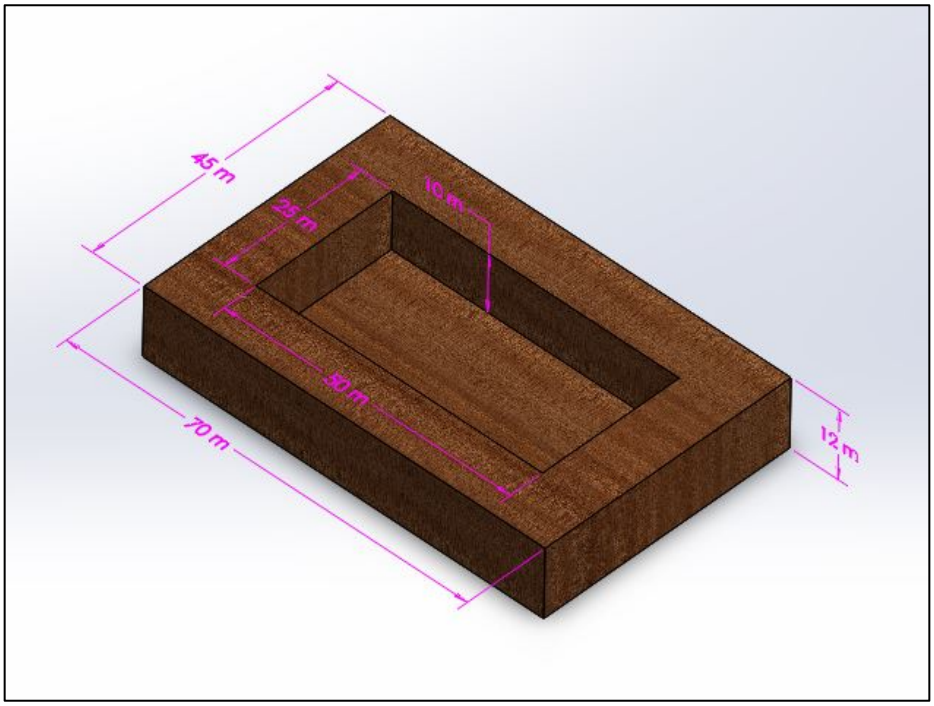

Fig.23. Dimensioned Solidworks soil component used in the assembly for the transient thermal study.

The second part of the model that was created was the ITES storage container. The storage container component was modeled as a rectangular block that was 50 m long, 25 m wide, and 10 m deep. The storage container also had a uniform wall and bottom thickness of 1 m. In the center of the storage container, a rectangular block of dimensions 48 m long by 23 m wide by 9 m deep was cut out to hold the air layer component. The Solidworks material properties of concrete were applied to the storage container component. A picture of the dimensioned Solidworks ITES storage container can be found in Figure 24.

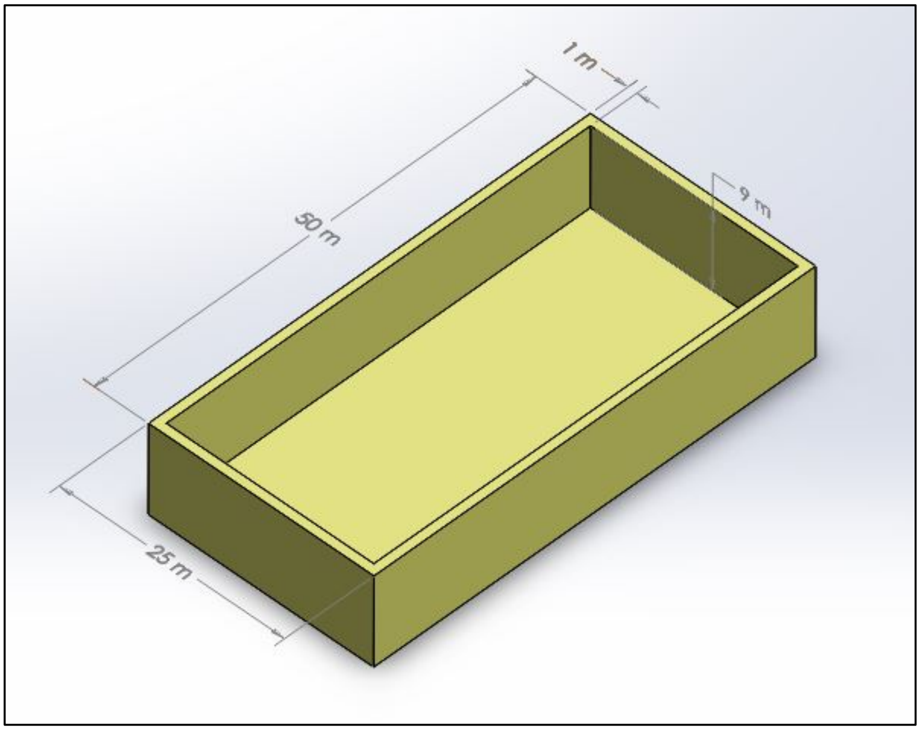

Fig.24. Dimensioned Solidworks ITES storage container component used in the assembly for the transient thermal study.

The third part of the model that was created was the air layer that is inside the ITES storage container around the ice block. The air layer component was modeled as a rectangular block that was 48 m long, 23 m wide, and 9 m deep. The air layer also had a uniform wall and bottom thickness of 1 m. In the center of the air layer component, a rectangular block of dimensions 46 m long by 21 m wide by 8 m deep was cut out to hold the ice block component. The Solidworks material properties of air were applied to the air layer component. A picture of the dimensioned Solidworks air layer component can be found in Figure 25.

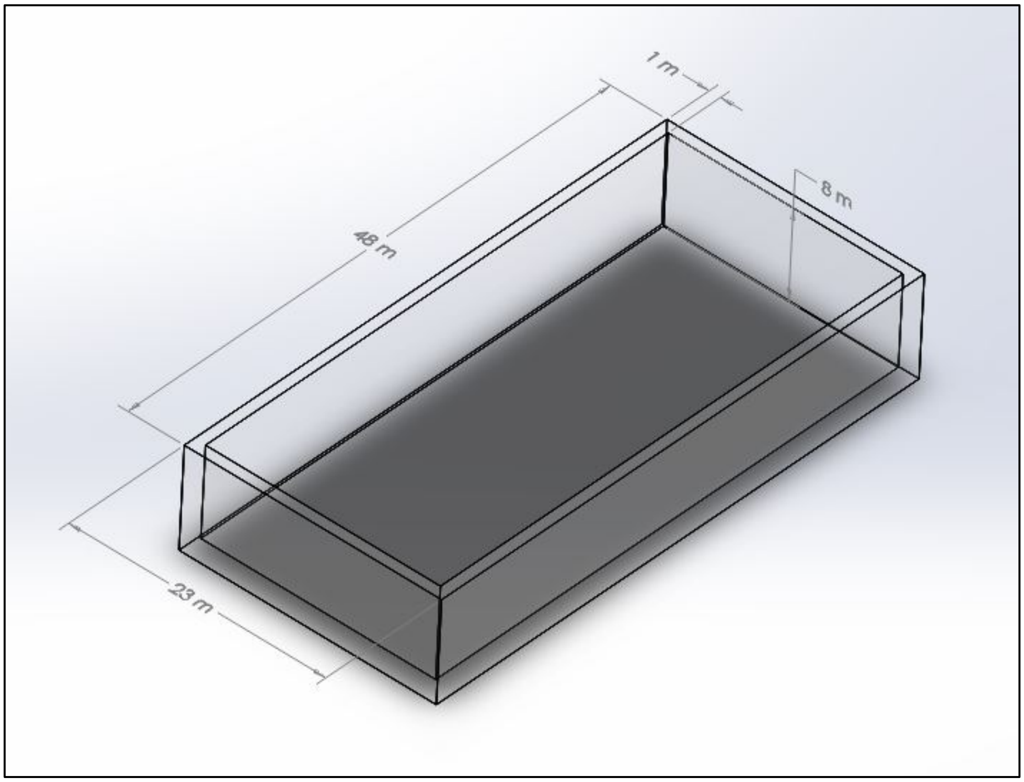

Fig.25. Dimensioned Solidworks air layer component used in the assembly for the transient thermal study.

The fourth part of the model that was created was the ice block component that is inside the ITES storage container and the air layer. The ice block component was modeled as a rectangular block that was 46 m long, 21 m wide, and 8 m high. The Solidworks material properties of water were applied to the ice block component. A picture of the dimensioned Solidworks ice block component can be found in Figure 26.

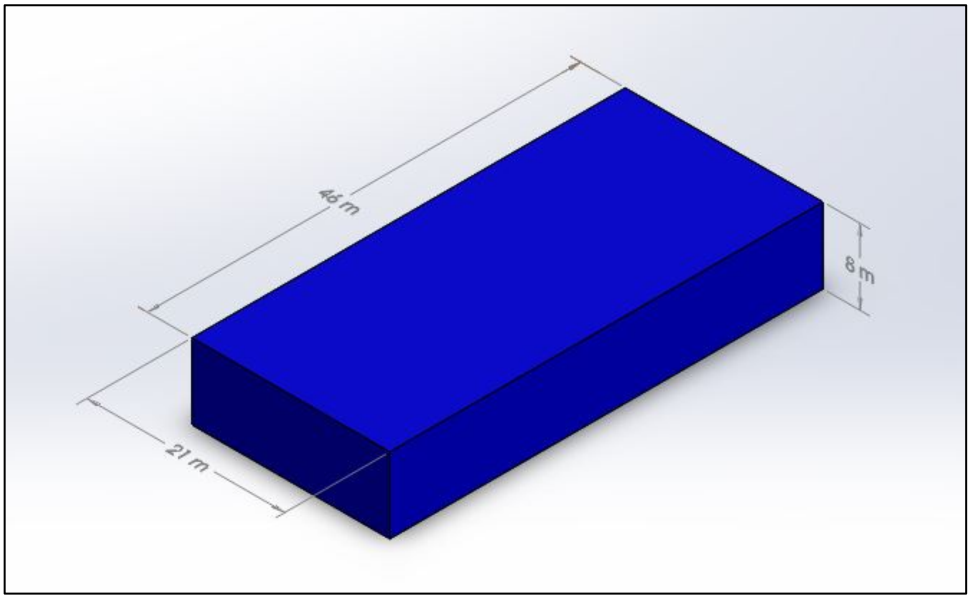

Fig.26. Dimensioned Solidworks ice block component used in the assembly for the transient thermal study.

The last part of the model that was created was the ITES storage container top. The storage container top was modeled as a rectangular block that was 50 m long, 25 m wide, and 0.5 m thick. The Solidworks material properties of concrete were applied to the storage container top. A picture of the dimensioned Solidworks ITES storage container top can be found in Figure 27.

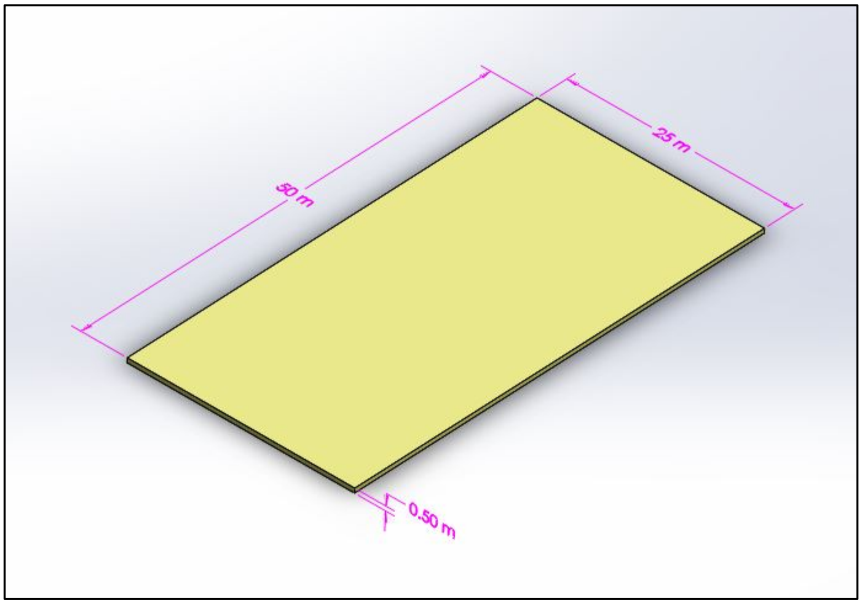

Fig.27. Dimensioned Solidworks ITES storage container top used in the assembly for the transient thermal study.

Once all of the ITES storage container system components were constructed, and assembly of the 5 parts was created. An isometric view of the entire assembled system can be found in Figure 28 and a section view of the assembled system can be found in Figure 29.

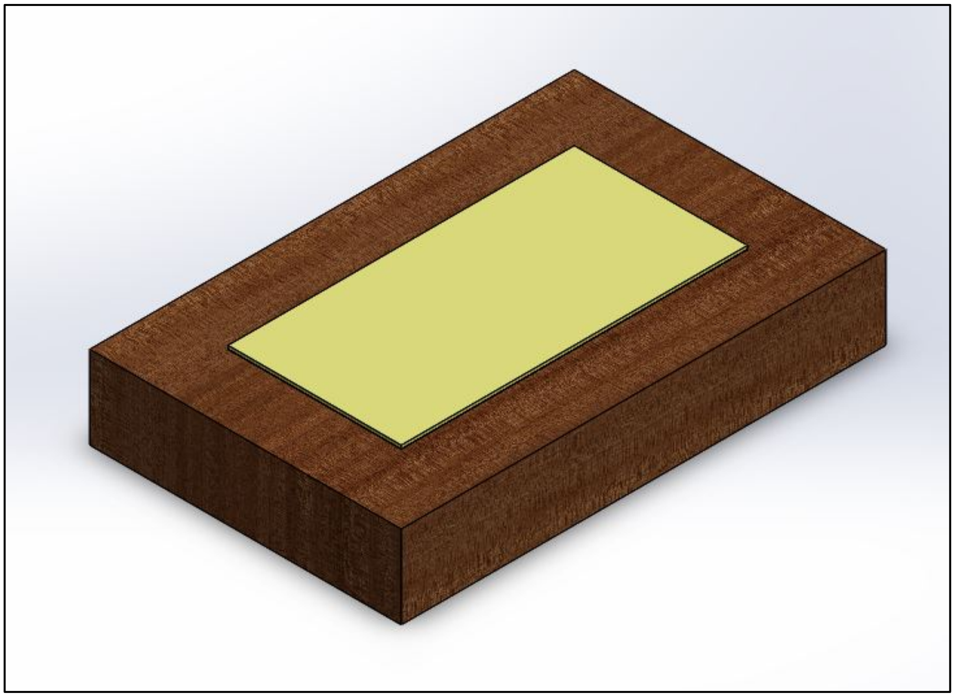

Fig.28. Isometric view of entire ITES storage container system Solidworks assembly used in the system transient thermal study.

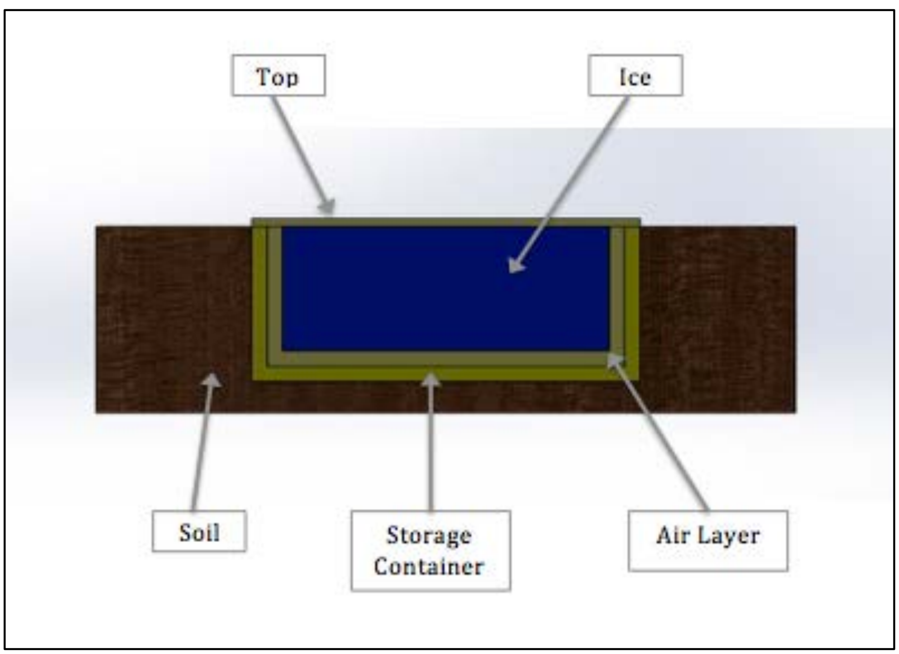

Fig.29. Section view of entire ITES storage container system Solidworks assembly used in the system transient thermal study.

Once the assembly of the ITES storage container system was complete, thermal boundary conditions were applied to each component. A constant temperature of 72°F was applied to exterior surfaces of the soil component, including the top and bottom surfaces. The top of the storage container was also given a constant temperature of 72°F. The ice block component, the surrounding air layer component, and the storage container component were given an initial temperature of 32°F. Contact resistances and boundary conditions were also applied to all of the components. A convection boundary condition was also applied to the air layer component to account for the convection from the inner wall of the storage container through the air layer to the exterior surface of the ice block. A fine mesh was selected for all of the thermal studies to yield the most accurate results. Four transient thermal studies were run on the assembled system using the thermal boundary conditions listed above and each study was run for a different time duration. The results from the various thermal studies run were then analyzed to determine the ITES system performance over time.

Solidworks Modeling Results:

For the first Solidworks transient thermal study, the total time duration was one day and the time steps were taken every hour. A sectioned view of the ITES system showing the temperature results after one day can be seen in Figure 30. Temperature probes in various parts of the system can also be seen in the figure.

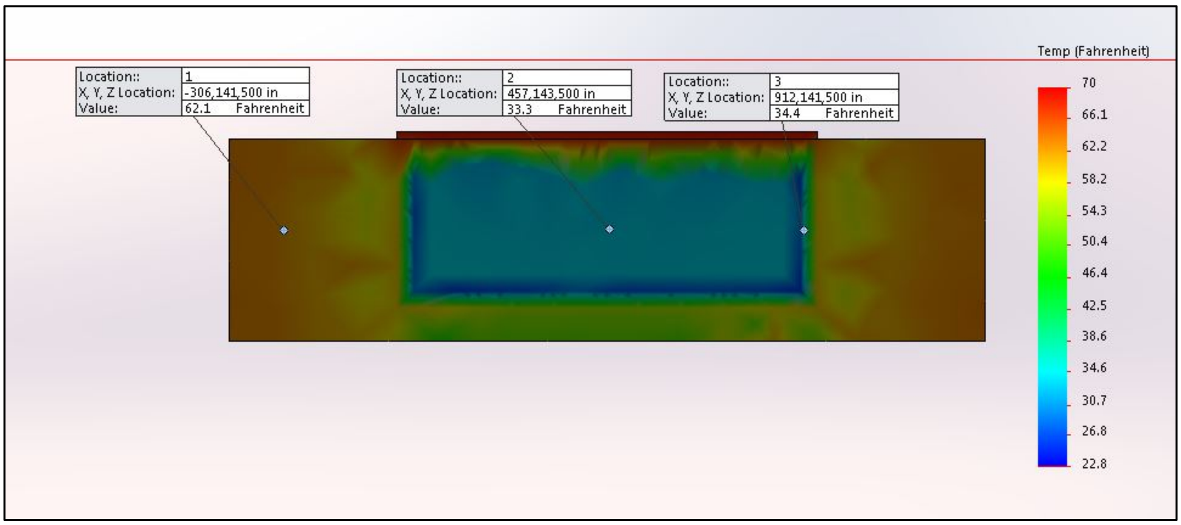

Fig.30. Temperature gradient of sectioned view of Solidworks transient thermal study of full scale ITES system after one day. In the figure, temperature probes in the soil layer, ice block, and air layer are shown with their respective temperatures.

For the second Solidworks transient thermal study, the total time duration was one week and the time steps were taken every 6 hours. A sectioned view of the ITES system showing the temperature results after one week can be seen in Figure 31. Temperature probes in various parts of the system can also be seen in the figure.

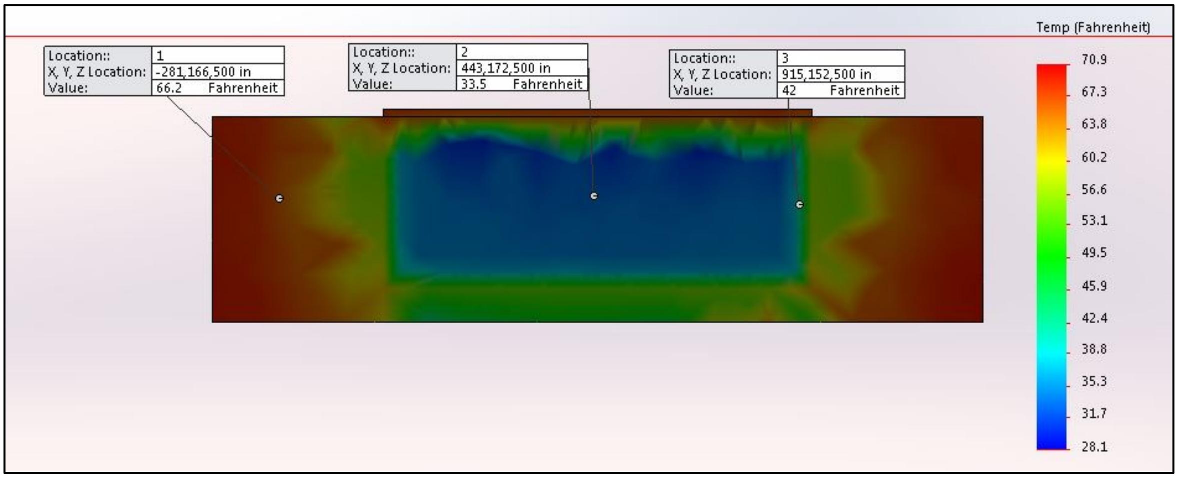

Fig.31. Temperature gradient of sectioned view of Solidworks transient thermal study of full scale ITES system after one week. In the figure, temperature probes in the soil layer, ice block, and air layer are shown with their respective temperatures.

For the third Solidworks transient thermal study, the total time duration was one month (30 days) and the time steps were taken every day. A sectioned view of the ITES system showing the temperature results after one month can be seen in Figure 32. Temperature probes in various parts of the system can also be seen in the figure.

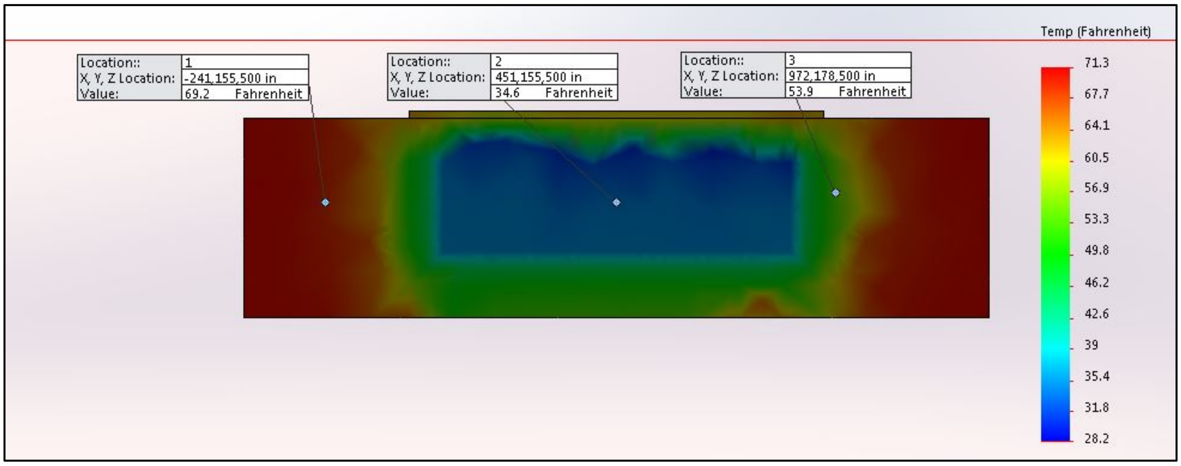

Fig.32. Temperature gradient of sectioned view of Solidworks transient thermal study of full scale ITES system after one month (30 days). In the figure, temperature probes in the soil layer, ice block, and air layer are shown with their respective temperatures.

For the fourth Solidworks transient thermal study, the total time duration was three months (90 days) and the time steps were taken every 3 days. A sectioned view of the ITES system showing the temperature results after three months can be seen in Figure 33. Temperature probes in various parts of the system can also be seen in the figure.

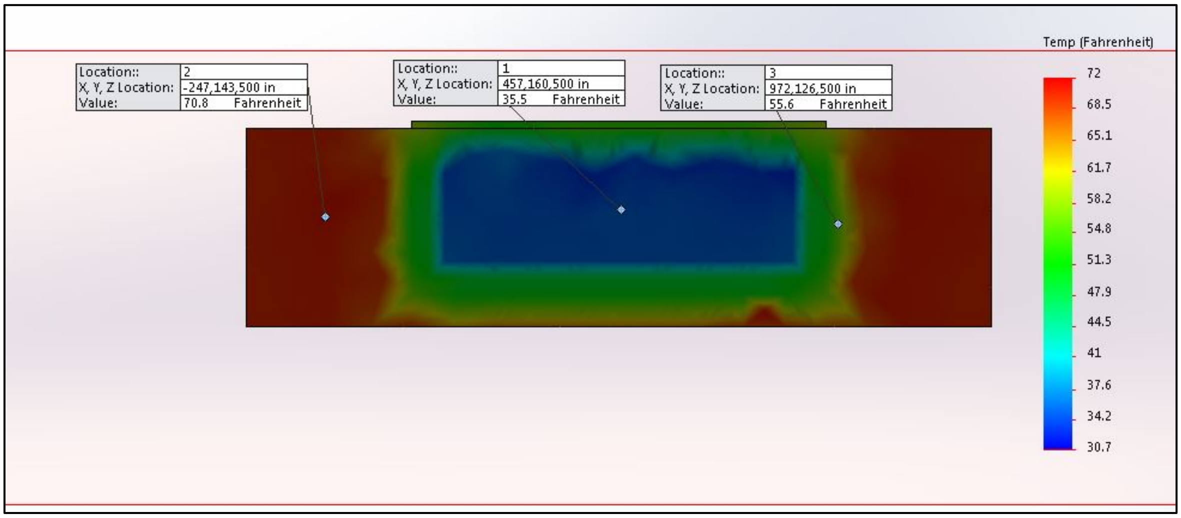

Fig.33. Temperature gradient of sectioned view of Solidworks transient thermal study of full scale ITES system after three months (90 days). In the figure, temperature probes in the soil layer, ice block, and air layer are shown with their respective temperatures.

Discussion:

Analytical Modeling Discussion:

Using the three part analytical model to predict the melt time of the ice was seen to align with the actual melting histories of the ice block used in the initial experimental test. Figure 9 shows the temperature data from the analytical model and experimental model from the first experimental test graphed together versus time. In this analytical and experimental model, the melting history of a 150mL block of ice was predicted. The results show that the analytical and experimental model match during the first stage of the ice melting process: below 32°F to 32°F. During the second stage of the ice melting process, when the ice is at a constant temperature of 32°F, the experimental model does not stay constant at 32°F. The experimental model gradually rises in temperature from about 32°F to 34°F during the first 100 minutes. Around the 100 minute mark, both the analytical and experimental models enter the third stage of the ice melting process, where the melted ice, which is now water, heats up to the ambient air temperature. The experimental model does follow a similar curve to the analytical model during this stage of the melting process but it is less accelerated at the beginning of the process. This slower acceleration at the beginning of the process caused the experimental model to take more time to reach the ambient air temperature.

The difference between the analytical and experimental models during this initial test could have been due to inaccuracies in the measurement of how much water was used in the test. Also, the thermal resistance that was calculated in the

analytical model could have been inaccurate as both average surface areas of the materials and a generic thermal conductivity of plastic were used.

Using the three part analytical model to predict the melt time of the ice was seen to align with the actual melting histories of the ice block used in the final experimental test. Figure 10 shows the temperature data from the analytical model and experimental model from the final experimental test graphed together versus time. In this analytical and experimental model, the melting history of a 1500mL block of ice was predicted. The results show that the analytical and experimental model match during the first stage of the ice melting process: below 32°F to 32°F. During the second stage of the ice melting process, when the ice is at a constant temperature of 32°F, the experimental model does not stay constant at 32°F as long as the analytical model does. The experimental model enters the third stage of the melting process about 100 minutes before the analytical model does. During the third stage of the ice melting process, where the melted ice, which is now water, heats up to the ambient air temperature, both the analytical and experimental models follow a similar trend with similar slopes. The experimental model has a slightly steeper slope than the analytical model and reaches the ambient temperature of the air prior to the analytical model due to the experimental model entering the third stage of the melting process before the analytical model.

The difference between the analytical and experimental models during this initial test could have been due to inaccuracies in the measurement of how much water was used in the test. Also, the thermal resistance that was calculated in the analytical model could have been inaccurate as both average surface areas of the

materials and a generic thermal conductivity of plastic were used. An average convection coefficient of the air was also used to calculate the thermal resistance in the analytical model.

Overall, both experimental tests followed the approximate melting curve of the analytical model. The three part analytical model, composed of both mass and heat transfer equations, was accurate in predicting the melting history of the ice in the experimental model. After running these tests, the analytical model can be used to get an accurate approximation of melt times for a variety of different melting scenarios with various masses of ice.

Experimental Modeling Discussion:

The initial two tank experiment that was run to determine the benefits of adding a drain to the system aligned with the initial hypothesis: that adding a drain to the system would increase the time it took for the ice or snow to melt. The graph in Figure 19 shows that the system with the drain had a core ice temperature around 32°F 3 times longer than the system without a drain. The thermocouple location in the middle of the two tanks was chosen as it most closely models the temperature of the stored ice and snow at the core. The center of the ice also helps resemble a compact chunk of snow or ice that the real ITES system would have. This model also worked well as the initial temperature of both tanks was slightly below 32 °F when the experiment began. Having an initial temperature below the freezing point to start helps accurately model the ice phases as the ice reaches its melting point, transitions from a solid to a liquid, and then reaches room temperature.

The second experiment that was run was to determine the benefits of adding a metal base grate to the system. The experimental setup for this new experiment involved a mass of ice that was 10 times greater than the mass from the first experiment (1500mL) and was done using larger storage containers that allowed the ice to be surrounded by a layer of air inside each of the containers. Both of the storage containers had their drains opened and one of the containers had a metal base grate that the ice block was placed on. The data from the thermocouple in the middle of each ice block was graphed versus time as seen in Figure 20. The data from the experiment shows that the system that had the metal base grate kept the ice core around 32°F for about 75 minutes longer than the system without a base grate. This experiment shows the advantage of adding the base grate to the storage container as it extends the life of the ice by reducing heat transfer through the bottom of the bottom of the storage container. The addition of the base grate also keeps the ice core out of the melted ice water at all times as the ice block is completely surrounded by air. Although the added metal base grate extended the life of the ice, a base grate that has a lower thermal conductivity value would theoretically extend the life of the ice even more than the metal grate did.

The third experiment that was run was to determine the affects of adding a plastic base grate to the system as opposed to a metal base grate. The experimental setup for this experiment was the exact same as the second experiment run which tested the affects of a metal base grate except the metal base grate was replaced with a plastic base grate. The data from the thermocouple in the middle of each ice block was graphed versus time as seen in Figure 21. The data from the experiment shows

that the system that had the plastic base grate kept the ice core around 32°F for about 25 minutes longer than the system without a base grate. Although the difference between the system without the base grate and the system with the plastic base grate is smaller than the difference in systems seen in the second experiment using the metal base grate, the time the ice stayed in the phase change region with the plastic base grate is about 200 minutes longer than with the metal base grate. This experiment shows the advantage of using a plastic base grate as opposed to the metal base grate. Both base grates extended the life of the ice but due to the lower thermal conductivity of the plastic base grate, the ice was able to stay in the phase change region for a longer period of time than with the metal grate.

The extended life of the ice for the system without the base grate in the third experiment when compared to the life of the ice in the system without the base grate in the second experiment could have been due to slight variations in the initial mass of each ice block. The difference in the life of the ice could also be due to differences in the ambient air temperature when each of these experiments was run.

The final experimental test that was run was to compare the new large ITES storage container that contained a drain, the plastic base grate, and insulation to the traditional large ITES system, which did not have a drain, a base grate, or insulation. As seen in Figure 22, the new ITES system was able to keep the 1500 mL ice block in the phase change region for twice as long as the traditional system. The addition of the drain and base grate in the new ITES system helped reduce the heat transfer to the ice block as the ice block was insulated by a layer of air, while the added insulation lessened the heat transfer from the ambient air into the system. The new

additions to the new ITES system were able to double the life of the ice, making the new ITES system a more feasible energy option.

Solidworks Modeling Discussion:

The Solidworks transient thermal modeling done on the full scale ITES system yielded that after three months the ice in the storage container would still be useable (below 55°F) as a cold source for the cooling of buildings based on the boundary conditions applied to the system. The four studies run were to see how the temperature gradient throughout the system changed over time.

The first study, which was run for one day, showed that there was only a small change in the temperature of the center of the ice block. The majority of the temperature change in the first study was the conduction from the outside of the soil through the soil. Both the concrete and air layers stayed close to their starting temperature with some small fluctuations in temperature throughout each layer. The top of the ice block also experienced a temperature change as the top of the system transferred heat to the ice block.

The second study, which was run for a week, showed a larger change in the temperature of the center of the ice block compared to the first study. The rise in the ice block temperature was seen on the top, the bottom, and both sides. The rise in the ice block temperature along the sides and the bottom was due to the exterior temperature boundary condition completely conducting through the soil layer and into the concrete storage container and air layer. The top of the ice block continued to rise in temperature due to the high temperature of the top of the container.

The third and fourth studies, which were run for one month (30 days) and three months (90 days) respectively, showed a rising temperature of the components of the system inside the soil layer and a relatively constant soil layer temperature. The exterior temperature boundary condition applied to the system fully conducted through the soil layer, making it relatively constant throughout. This warmer soil temperature affected the internal components as they all experienced a temperature rise as well. Both the concrete storage container layer and air layer rose in temperature throughout with the warmest part of both layers being on the bottom. The temperature was greatest on the bottom of these two layers as the soil layer was thinner on the bottom of the system, which allowed for the exterior temperature boundary condition to conduct through it and into the concrete storage container easier and quicker. The increase in the base temperature of the concrete storage container and air layer led to warmer ice block temperatures at the bottom of the block. The main visual difference between the one month study and the three month study was that the "cold" part or blue region of the ice block got a lot smaller in the three month study and the "warm" or green region expanded in the three month study. Based on the results from the experimental tests run that yielded a doubling of the life of the ice in the new ITES system, it can be assumed that with a full-scale model of the new ITES system, the life of the ice would double that of the traditional system, yielding an ice life of around 6 months.

Conclusions and Future Work:

Over the course of the first term of this project, the background knowledge and information was gathered to begin working on the project. The first thing that was done for the project was the way in which ice melts was analyzed. This initial study led to a new ITES system idea. The new ITES system was designed and the first major change to the system, the addition of a drain was tested. The addition of a drain proved to be beneficial for extending the time the snow and ice stay frozen. Once the system was tested experimentally, the other components of the new system were considered and designed. The specific materials for the thermal energy storage tank were chosen and the cool water storage tank was designed.

During the second term of this project, a larger scale experimental ITES system was designed and used to run a number of experimental tests. An analytical model, to predict the melting history of ice was done and compared to the experimental results from the various experimental tests run. The last part of the project that was completed was the completion of the Solidworks transient thermal study done on the full-scale model of the ITES system. The complete list of the tasks that were completed during the second term of the project can be found in Figure 34.

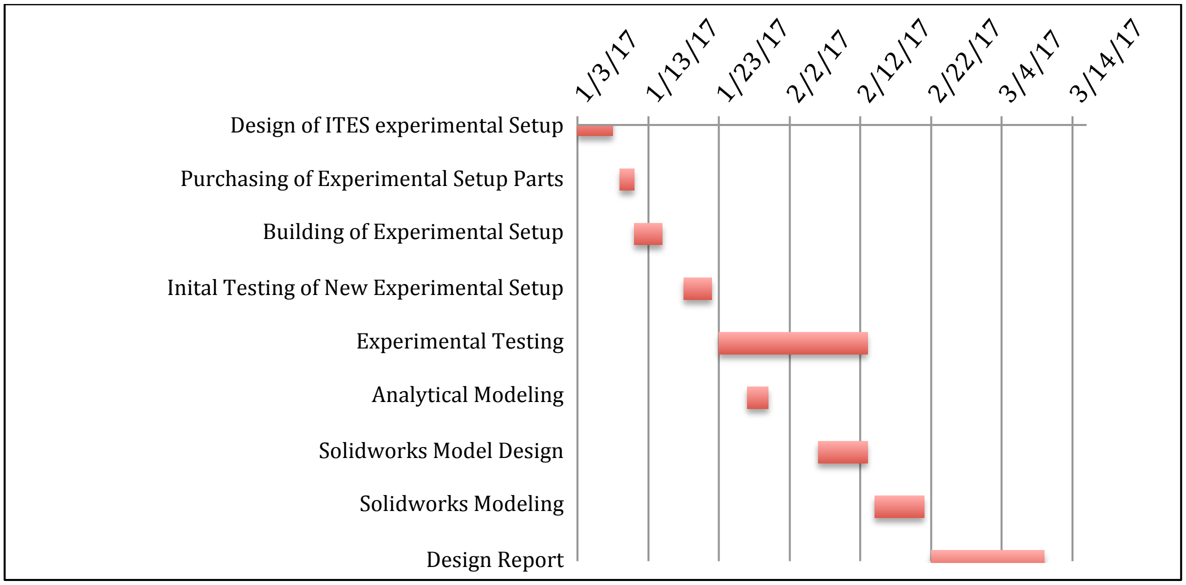

Fig.34. Gantt chart for tasks for second term of project, Winter 2017

The use of experimental, analytical, and Solidworks modeling all helped in the design of the new ITES storage system. The use of experimental and analytical modeling to predict the melting history of ice on a small scale allowed for the determination of the affects of components added to the system. This small scale modeling helped determine that the new ITES model, with the drain, plastic base grate, and insulation, was able to double the life of the ice in the system compared to the life of the ice in the traditional ITES system. The Solidworks transient thermal study modeling was able to model the full scale system and get an estimated life of the ice in the traditional system of around 3 months, which is about 6 months in the new system. The extended life of the ice in the new ITES system makes ITES energy a more reliable and feasible energy source for the cooling of buildings.

Further work can be done using the analytical model to predict the melting history and life of ice for various systems with different masses of ice. Using the

analytical model, the large-scale ITES system can be modeled and compared to the results from the Solidworks transient thermal studies.

Further experimental modeling can be done on the new ITES system with the addition of coolant pipes. Testing the new system experimentally with the added heat transfer from the coolant pipes would give a better estimate on the life of the ice in the new system compared to the traditional system. An experimental model could also be set up outside to get a better approximation of how the ice life is affected by the exterior climate.

Further refinements of the Solidworks transient model created can be done. The initial size and outline of the system can remain but added detail to various aspects of the model can be done. Temperature boundary conditions that vary with the depth of the soil can be added to the model. Different soil compositions and soil properties can also be added to the model to see the affect of the exterior soil component on the system. Daily and monthly temperature models can also be added to the study to show how the model is affected by actual weather and climate patterns. The last components that need to be added to the Solidworks model are the drain and base grate. Applying these two components will allow for the new ITES system to be modeled. Creating a more realistic and detailed full-scale model of the ITES system will yield the most accurate results to determine if the new ITES system is a feasible energy source.

Lastly, an economic analysis of the system must be done to determine the feasibility of creating such a system. The capital cost of building the system and

maintaining the system will be looked at as well as the benefits of the system in terms of reducing both energy costs and polluting emissions.

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