EMERGENCY THERMAL ENERGY STORAGE: COST & ENERGY ANALYSIS

by

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Abstract

The need to store and access electronic information is growing on a daily basis as more and more people conduct business and personal affairs through email and the internet. To meet these demands, high energy density data centers have sprung up across the United States and around world. To ensure that vital data centers run constantly, proper cooling must be maintained to prevent overheating and possible server damage from occurring. Emergency cooling systems for such systems typically utilize traditional batteries, backup generator, or a combination thereof. The electrical backup provides enough power to support cooling for essential components within the data centers. While this method has shown to be reliable and effective, there are several other methods that provide reliable emergency cooling at a fraction of the cost.

This paper address the lack of information regarding the initial, operation, and maintenance costs of using Thermal Energy Storage (TES) tanks for emergency cooling. From research and various field examples, five emergency cooling system layouts were designed for various peak cooling loads. Looking at the different cooling loads, components, and system operations an economic evaluation of the system over a 20 year period was conducted. The economic analysis included the initial and maintenance costs of each system. In an effort to better understand power consumption of such systems and to help designer's better estimate the long term costs of TES tanks systems, five layouts were simulated through a program called TRNSYS developed for thermal systems. To compare against current systems in place, a benefit to cost ratio was done to analyze TES versus a comparable UPS.

The five simulated systems were one parallel pressurized tank, one parallel and one series atmospheric tank, one parallel low temperature chilled water, and one series ice storage tank. From the analysis, the ice storage and pressurized systems were the most cost effective for 1 MW peak cooling loads. For 5 MW peak cooling loads the ice storage and chilled water systems were the most cost effective. For 15 MW peak loads the chilled water atmospheric TES tanks were the most cost effective. From the simulations we concluded that the pressurized and atmospheric systems consumed the least amount of power over a 24 hour period during a discharge and recharge cycle of the TES tank. From the TRNSYS simulations, the ice storage system consumed 22 – 25% more energy than a comparable chilled water system, while the low temperature storage system consumed 6 – 8% more energy than the chilled water system. From

the benefit-cost-ratio analysis, it was observed that all systems were more cost effective than a traditional battery UPS system of comparable size. For the smaller systems at 1 MW the benefit-cost-ratio ranged between 0.25 to 0.55, while for larger systems (15 MW) the ratio was between 1.0 to 3.5 making TES tanks a feasible option for providing emergency cooling for large and small systems.

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I would also like to thank my family and friends for their constant words of encouragement throughout this process. I knew that with them behind me I would be able to accomplish any task. Support from my family and friends have always been the key to my success. For everyone that either helped me directly or indirectly, I thank you.

Preface

This thesis is submitted to partially fulfill the requirements of the thesis option of my Master's degree at the Department of Mechanical Engineering, College of Engineering, Kansas State University. It represents a documentation of my research which was conducted from August 2009 until December 2010. The project "Thermal Energy Storage Design for Emergency Cooling, 1387-rp" was sponsored by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

The research conducted during this project will be incorporated into the ASHRAE handbook as seen fit by the sponsoring ASHRAE Technical Committee 6.9. This document will provide detailed cost and layout information to provide designers with a greater understanding of when and where Thermal Energy Storage Tanks should be used for emergency cooling applications.

CHAPTER 1 - Introduction

The use of data centers for digital information storage and transfer has been increasing rapidly with continued growth expected in the coming years (Silicon Valley Leadership Group 2009). Consumer and business demand are the main drivers creating the need to produce more powerful server processors to handle this increase in data load. With increases to processor speed and data transfer come increased cooling loads that need to be dealt with to effectively remove excess heat from the server's components. Great strides have been made in the cold air distribution system of high density data centers to increase the longevity of the server components and building location. The increase in cooling loads and dependence on data centers will require larger uninterruptible power supply (UPS) to maintain operation during an outage.

The current long standing solution to backup power has been generators and batteries. While this solution provides electricity to the cooling system, it is not cost effective and can significantly increase the initial capital cost of the project. Another disadvantage to installing such a backup system are the large initial loads placed on the systems by the chiller and pumps during startup. In addition to the high capitals costs, long term battery storage requires tightly controlled temperature environments to prevent premature storage power loss (Active Power 2009).

There are several options in the current market place to provide cooling for data centers and other high load applications. The use of thermal energy storage (TES) tanks has become a more recent development to provide effective and reliable emergency cooling. TES tanks have typically been used in the past for load shaving applications to cut down on higher energy costs by shifting peak loads to the night time when electrical costs are lower.

A recent example of ice TES tanks being used to provide emergency cooling was for a computer center on the east coast operated by Verizon. The ice storage system would provide emergency cooling to the computer center should the chiller shutdown for any reason. During the chiller shutdown, the system utilizes the ice storage system with the pumps on a back-up power supply. For this installation the ice storage system provides approximately 30 minutes worth of cooling to the computer center. This additional emergency cooling will allow Verizon to restore power to the chiller by starting the back-up generators. (Baltimore AirCoil Experience 2010)

The objective of this research is to provide designers of emergency cooling systems with a detailed cost analysis of TES systems using various system layouts and methods. For this analysis different peak cooling loads and temperature differences across the thermal load will be used to determine the effects on the system costs. There will be a total of five unique systems designed for cost analysis to provide a wide array of system layouts and design features. By utilizing different TES options, the designer will be able to choose which system layout would be most cost effective and beneficial for his/her application. Along with the initial capital costs of each system, the maintenance costs will be included over a 20 year period. The total cost of each system will be evaluated using net present worth analysis, to make an “apples to apples” comparison. From the 5 layouts, a simulation of each using a computer program called TRNSYS (Transient Systems Simulation Program 2009) will be conducted to better understand what the operational costs could be in comparison to one another. From the detailed costs analysis, each system will be compared to a traditional UPS system typically found in data centers. This comparison will be analyzed using the Benefit to Cost ratio method (Newnan, Eschenbach, Lavelle 2004 and Park 2007). From this detailed cost analysis, a better understanding of what the associated costs are for installing TES tanks for emergency cooling applications.

CHAPTER 2 - Emergency Cooling Methods and Designs

The following sections in this chapter will provide detailed information regarding the current use of TES tanks for emergency cooling applications. The information will include important design criteria, as well as the advantages and disadvantages of each emergency cooling method. The purpose of this section is not to identify which cooling methods are best for a particular application but to explain how they work and what one could expect during operation. The second section of this chapter will include how these emergency cooling methods are built into an existing or new system.

Emergency Cooling Methods

The current market provides several long standing cooling methods that are well understood and quite reliable during an electrical outage. The use of various techniques to provide emergency cooling ranges from backup generators for chillers, to thermal energy storage (TES) tanks. The following sub sections describe in brief detail how TES approaches are utilized in emergency cooling, and whether or not they will be used in the development of storage systems for this report. The importance of this section is to determine which approaches will be most applicable to emergency cooling.

TES – Chilled Water

TES chilled water tanks are a cost effective way to provide emergency cooling to a system experiencing a power outage. TES chilled water tanks become most economical for 7000 kWh (2,000 ton-hours or 200,000 gal) (Dorgan and Elleson 1993). Chilled water TES tank's use the sensible heat capacity (1 Btu/lb-F) of water to provide cooling. The cooling capacity is directly correlated to the temperature differential of the outgoing cold water and the returning warm water. The temperature differential for most current systems is between 10 to 20°F (Dorgan and Elleson 1993). Maintaining a thermocline layer between the two temperature differences is very important to maximize the cooling capacity of the chilled water storage tank. An advantage that well stratified tanks have is that they provide "ragged cooling". Ragged cooling is the additional cooling available from the thermocline layer within the tank. While this additional amount of ragged cooling is limited to only a few minutes, it as advantage other TES methods do not offer. A chilled water TES tank operates the most efficiently when the return and the supply storage water have a well defined thermocline layer. This degree of separation can be achieved through the following tanks designs:

- Stratification
- Multiple tank design
- Membrane or diaphragm
- Labyrinth and baffle.

Stratification chilled water tanks rely on the densities of water at different temperatures to maintain a 1 – 3 ft thermocline layer as shown in Figure 2-1 (Dorgan and Elleson 1993). The thermocline layer breaks down over time due to the external heat gains on the sides of the TES tank. The heat gains cause a fluctuation in the waters density, thus causing water to float up along the sides of the tank and cause mixing. Internal diffusers are mounted at the top of the tank to provide a steady stream of return water to prevent mixing and disturbances within the tank. It should be noted that well designed stratified tanks can provide between 85 – 95% of the stored chilled water for cooling. Stratified tanks are generally the simplest, most efficient, and cost effective method for providing cooling (Dorgan and Elleson 1993).

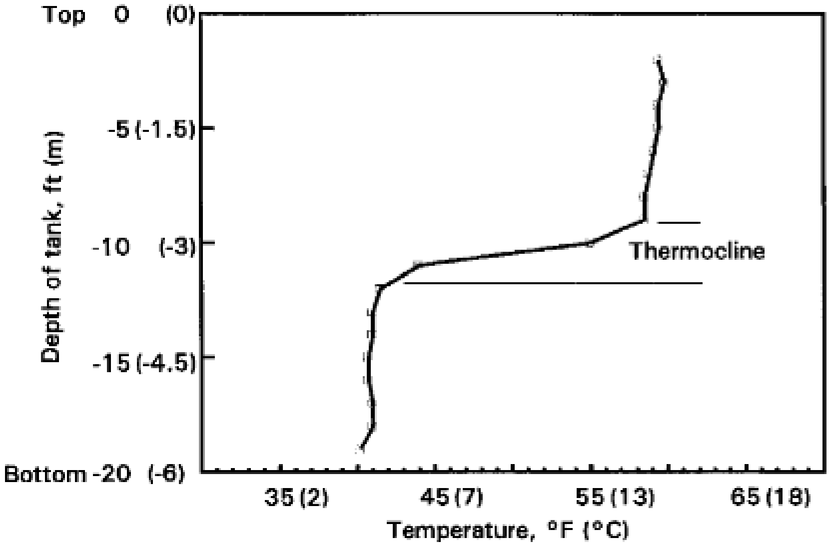

Figure 2-1 Thermocline layer for a stratified tank (Dorgan and Elleson 1993)

Multiple tank systems operate under the assumption that one tank will hold the chilled water to be used for cooling, while the other tank will remain empty to hold the warm return water. Multiple tank systems require more complex control and piping to deal with the pumps working against the varying dynamic head (Dorgan and Elleson 1993). The additional tank and control mechanisms contribute to the costs, and do not generally support the additional cooling obtained by separating the supply and return water when compared to a stratified tank. The membrane or diaphragm tank design utilizes a membrane that is mounted inside the tank that moves vertically with the water providing a barrier between the return and supply. Tran et al (1989) found that stratified and membrane systems provide essentially equivalent thermal separation performance. The additional costs of the membrane/diaphragm tank along with the possibility of cuts in the membrane make it less cost effective than well stratified tanks. The labyrinth and baffle system separate the return and supply water by breaking up the tank into compartments through walls and baffles. Labyrinth and baffle systems often incur significant thermal mixing due to the high turbulence, thermal conduction, density currents, and dead flow areas. From the systems described to provide chilled water, stratification offers the most cost effective and least complicated method of delivering emergency cooling. Well stratified TES tanks will be the primary focus of this economic study when describing chilled water systems.

TES tanks using chilled water as the medium typically maintain the temperature between 39 to 44°F (ASHRAE HVAC Systems and Equipment 2007). While decreasing the storage temperature will yield greater cooling capacity, temperatures below 39.2°F will hamper the effects of stratification and will be referred to as LTCW (Low Temperature Chilled Water). When lowering the temperature below 39.2°F, a proprietary sodium nitrate mixture must be introduced into the system to maintain thermal stratification within the tank. While this option greatly increases the cooling capacity, it significantly increases initial and maintenance costs to the operator/owner. While chilled water tanks have proven to be quite reliable and inexpensive to maintain there are some draw backs. Chilled water tanks require a considerable amount of space and are not visually appealing. This can be overcome by installing part or the entire tank underground. However, this will end up leading to increased initial and maintenance costs over the life of the system.

Understanding the way in which chilled water storage tanks recharge and discharge within a system is very important to provide the proper amount of cooling during an emergency situation. Below in Figure 2-2 is an example of how a chilled water tank would recharge and discharge while in a parallel with respect to the chillers location within the system. During the recharge cycle the cold water would enter through the bottom diffuser and exit through the top diffuser. In the discharge cycle the cold water exits through the bottom diffuser and the warm water enters through the top diffuser. The other system setup is when the TES chilled water tank is in a series configuration with the chiller. The recharge and discharge cycle for those systems are the same, in that there is only one flow direction and it is from top to bottom.

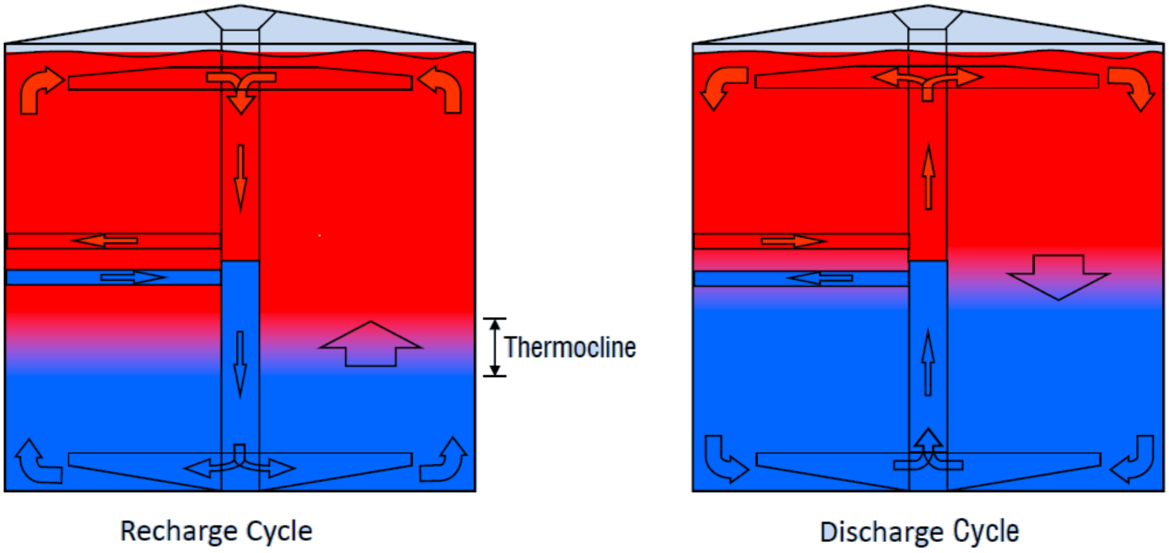

Figure 2-2 TES Chilled water charging and discharging

The two main types of chilled water tanks are pressurized and unpressurized. While many cool storage technologies use unpressurized TES tanks for large applications, smaller load applications would benefit from a pressurized TES tank. The control mechanisms for a pressurized TES tank tend to be less complicated and can decrease the cost (Sorell 2010). Pumping considerations for closed systems are simple because the required flow rate can be determined and a pressure drop can be calculated using standard engineering practice. However, with an open system, the static pressure must be controlled to prevent overflowing in an atmospheric tank. Depending on where the tank is located in the system, control may not be needed if it is located at the highest point in the system. However, in most cases unpressurized storage tanks will be located at ground level or at the low point in the chilled water distribution system. Unpressurized tanks typical have pressure sustaining valves on the tank's inlet and outlet to separate the static head of the tank from the remainder of the system. The sustaining valve is self-contained and modulates to maintain the desired upstream static pressure through a throttling action. The valves minimum set point is typically 5 psig (35 kPa) or more (Dorgan and Elleson

1993). The majority of pressurized systems do not have TES tanks that are larger than 40,000 to 50,000 gallons. The main reason for this is because of the increased costs associated with such large pressurized tanks (Sorell 2010).

TES – Ice

There are several types of ice storage systems used for cooling purposes within the industry. The most common and effective are ice harvesting, external melt ice-on-coil, internal melt ice-on-coil, and encapsulated ice. From research and Bembry (2010) contacts it has become apparent that external melt is the only feasible system that can meet the demand of providing emergency cooling for short durations. Ice harvesting systems are relatively expensive and are typically used to augment existing cooling systems to minimize electrical costs during peak times of the day. The internal melt ice-on-coil systems are better utilized when emergency cooling is required over longer time periods of time (2 hours) and require lower flow rates. (Bembry 2010) For this analysis we will only be looking at an external melt storage system due to its quick discharge rate, high reliability, and cost effectiveness. The tank sizes require on average 23 liters of storage tank volume per kWh (2.8 ft^3/ton-hour). The primary advantage of ice storage systems is that they tend to be smaller in size. This is due to the fact that the ice has a higher energy density 143.5 Btu/lb and more cooling for a given tank size. (Moran and Shapiro 2004). Typically brine or refrigerant is passed through the tubes (acting like an evaporator coil) within the tank from a refrigeration system to cause a layer of ice to form on the outside of the coils. Figure 2-3 is a diagram of how water passes through the tank during a discharge cycle, thus melting the ice on the evaporator coils. For most commercial applications ice storage tanks coils buildup 1.5 to 2.5 in of ice depending on the application and cooling load. For a system with 1.5 in of ice the charging temperatures typically range from 20 to 26°F, while for thickness greater than 2.6 in the temperatures are between 10 to 15°F. (Dorgan and Elleson 1993)

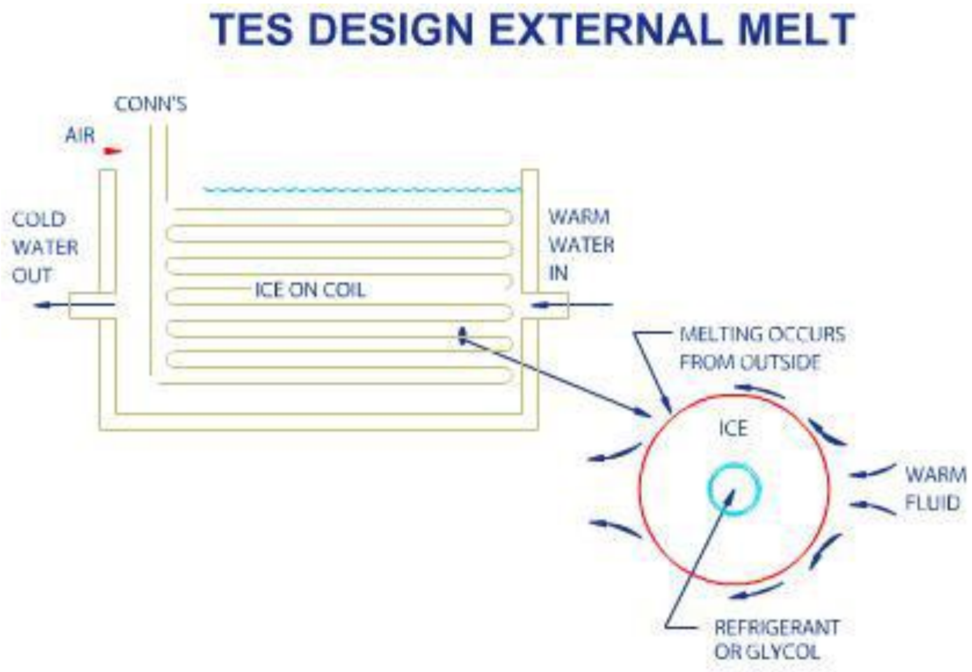

Figure 2-3 External Melt Discharge (Baltimore AirCoil Design/Selection 2010)

Using ice to provide emergency cooling yields discharge temperatures between 34 to 36°F (Dorgan and Elleson 1993). All external melt ice storage systems are unpressurized and require more complex control schemes than their counter parts chilled water systems. The down side to ice storage systems is that they typically have their own dedicated refrigeration system which can lead to an increase in maintenance, operation, and initial capital costs. External melt ice storage systems are available in a variety of sizes ranging from 45 to over 500 ton-hours (CALMAC 2010). An average installation size ranges around 20 tanks with some installations of 200+ tanks (30,000 ton hrs) Ice storage systems tend to be cost prohibitive at larger cooling loads due to the fact that hundreds of tanks would be required.

TES – Eutectics (Phase Change Materials)

A eutectic is a ratio of two or more chemicals that have a freezing/melting point which is lower than the corresponding freezing points of the individual chemicals (PCM 2010). The mixture is comprised of inorganic salts, water, and nucleating agents that freeze/melt at 47°F. The material is typically encapsulated within a rectangular container that is then stacked on top of each other. Eutectic salts are typically charged with chilled water around temperatures of 40 to 42°F. The discharge temperatures for TES tanks using eutectics are high (48 to 50°F) for HVAC applications (Dorgan and Elleson 1993). Eutectic salt phase-change materials require 6 ft^3/ton-hour of cooling and are used typically in retrofits to enhance an already existing system. Eutectic salts are best used in systems where space is limited and low temperatures are not required. Some of the disadvantages of salt-based eutectics are: additives are required for long term use, super cooling, and corrosion of metal tanks. Ice storage systems better serve low temperature TES applications while chilled water systems are best used for conventional temperatures. Eutectic TES tanks offer more cooling per cubic foot when compared to chilled water TES tanks (between 11 to 21 ft^3 per ton-hour), however they also have a high cost per ton hour (Dorgan and Elleson 1993). Maintenance costs for this type of system are comparable to chilled water TES tanks (Turner and Doty 2007).

Compressed Air

Another option to provide emergency cooling is through a process that converts compressed air into electrical power to keep the chillers online during an outage. Figure 2-4 provides a diagram and greater explanation of how the compressed air is converted.

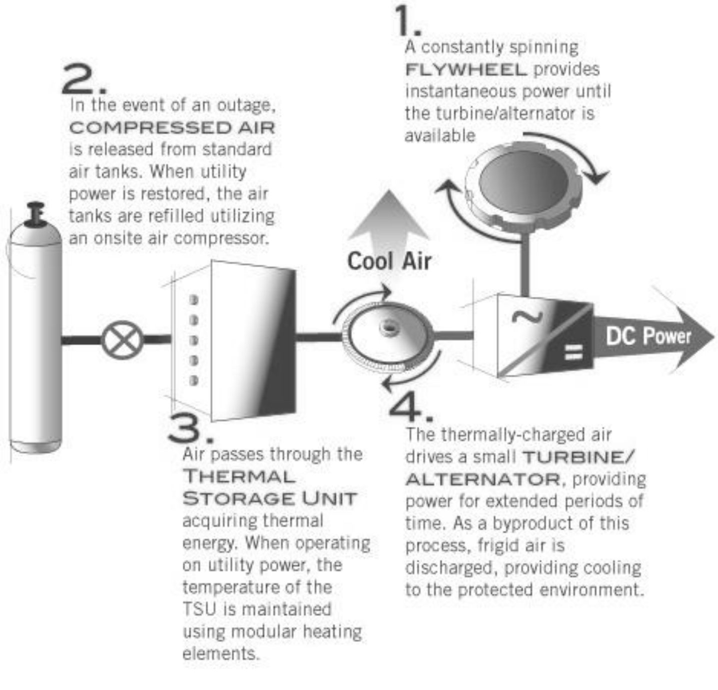

Figure 2-4 Compressed Air Process (Active Power 2009)

The main benefit of this type of system is that the electrical output will remain constant with respect to time. When installing a UPS system typical lead acid batteries degrade with respect to time and need to be replaced after a certain time period. This type of system does not require strict environmental room control operations that typical batteries require. The downside to this type of backup power is that it is limited to cooling storage sizes of 100 kW (.3413 MBtu/hr) (Active Power 2009). This limitation makes its application very limited, and not appropriate for this study.

Emergency Cooling Systems Comparison

Before selecting a TES tank method, a comparison utilizing chilled water, LTCW, external melt ice storage, and eutectics must be made. An example of how each of the tanks are sized and what their approximate costs would be as a retrofit project for partial storage is provided as a basis for selection. For this example, the partial load required by the TES tank to help during on peak periods is set at 2,000 ton-hrs. This does not account for thermal losses and stratification (chilled water) that occur among each of the various TES cooling methods. Table 2-1 includes the expected thermal losses for each of the various TES tank cooling methods as well as the predicted \$/ton-hr for partial load applications at a 2,000 ton-hrs cooling requirement:

Table 2-1 Thermal Losses and Costs

TES Cooling Method	Thermal Losses*	$/Ton-hr*
Chilled water	20%	200
LTCW	20%	175
External Melt Ice	50%	150
Eutectics	20%	250

*The following thermal losses and costs were taken from an EPRI study and are conservative estimates for illustration purposes (Turner and Doty 2007).

The thermal losses and costs vary greatly depending on the locations of the project as well as available space required to install such a system. For example, atmospheric chilled water TES tanks tend to be more expensive for smaller sized tanks (25,000 gallon tanks), due to the additional equipment, high initial construction costs, and maintenance required. To better understand how the sizing of the tanks is completed, an example of each of the systems is provided to determine which systems would be the most cost effective and best suited for large and small applications. When determining the emergency cooling capacity C (Btu) required to provide cooling, a relationship must be identified that takes into account the mass M (lb_m), the specific heat of the material c_p (Btu / lb_m °F), and the temperature difference ΔT (°F) across the cooling coil. The following is the heat transfer equation used to estimate the required tank sizes:

$$C = M\, c_p\, \Delta T$$

$$C = Btu$$

$$M = lb_m$$

$$c_p = Btu / lb_m\ {}^{\circ}F$$

$$\Delta T = {}^{\circ}F$$

The ΔT across the cooling coil will dictate how much mass is required for the chilled water system. For this example we will assume a $\Delta T = 15\ {}^{\circ}F$ for the chilled water system, thus identifying all of the required variables to solve for the amount of water in the chilled storage system. Once the amount (mass) of water has been calculated, the conversion to volume is simply the division by the water's density using the appropriate units. For the LTCW system, the temperature difference would be greater since the external refrigeration unit is lowering the internal temperature of the water below 39.2 °F. Therefore the same equation can be used except that the temperature difference between the return and supply temperature will be greater, assumed here is a $\Delta T = 20\ {}^{\circ}F$. The following is an example of how the equation would be used to calculate the amount of water required for a chilled water system.

$$M = \frac{C}{c_p\, \Delta T} = \frac{(2{,}000\ ton - hr * 1.2 * 12{,}000\ Btu\ per\ ton - hr)}{(1\ Btu\ per\ lbm\ {}^{\circ}F)\ (15\ {}^{\circ}F)} = \ 19.2\ x\ 10^5\ lbm\ water$$

For the ice storage and eutectic systems, the mass of material can be calculated by simply dividing the required capacity by the latent heat of fusion. For ice this is approximately 144 Btu/lb_m and for eutectics this is around 40 Btu/lb_m depending on the solution used (Turner and Doty 2007). From these equations and information, we can develop an initial cost estimate to be used to evaluate the four TES tank systems. The following shows an example of how each of the systems costs are approximated based on the 2,000 ton-hrs of peak cooling load required.

$$Total\ Estimated\ Cost = (2{,}000\ ton - hrs * 1.2) * \frac{\$200}{ton - hrs} = \$480{,}000$$

Table 2-2 provides an overview of the required space for each system as well as the initial capital investments to provide cooling for a partial load application.

Table 2-2 Thermal Storage Comparison

TES Cooling Method	Volume Required (ft^3)*	Total Cost (USD)
Chilled water	30,720	$480,000
LTCW	23,040	$456,000
External Met Ice	4,000	$450,000
Eutectics	11,520	$600,000

*Assumed a water density of 62.5 lb_m / ft^3 for all systems.

From this analysis we can see that chilled water, LTCW, and external ice melt TES systems are all within the same relative costs. Eutectics are significantly more expensive than the average cost of all four systems by about 21%. While it does provide less volume than chilled water and LTCW systems, it is almost three times the size of the ice storage system and at a significantly greater cost. The cost of eutectics will need to come down significantly if it is to compete with other more cost effectives methods for providing emergency cooling. Figure 2-5 provides an overview of the relative costs of various TES systems when compared to one another at different capacities. For larger systems chilled water systems tend to be the most cost effective assuming there is plenty of storage space available for the unit. This is true due to the fact that at large load sizes, chilled water systems only require between two to three tanks. Alternatively, the ice storage and LTCW systems would require as many as thirty or more tanks to meet the same cooling demand. For larger systems the ice and LTCW systems will require significantly more maintenance and control mechanisms to ensure that all of the TES tanks are operating at their rated capacities.

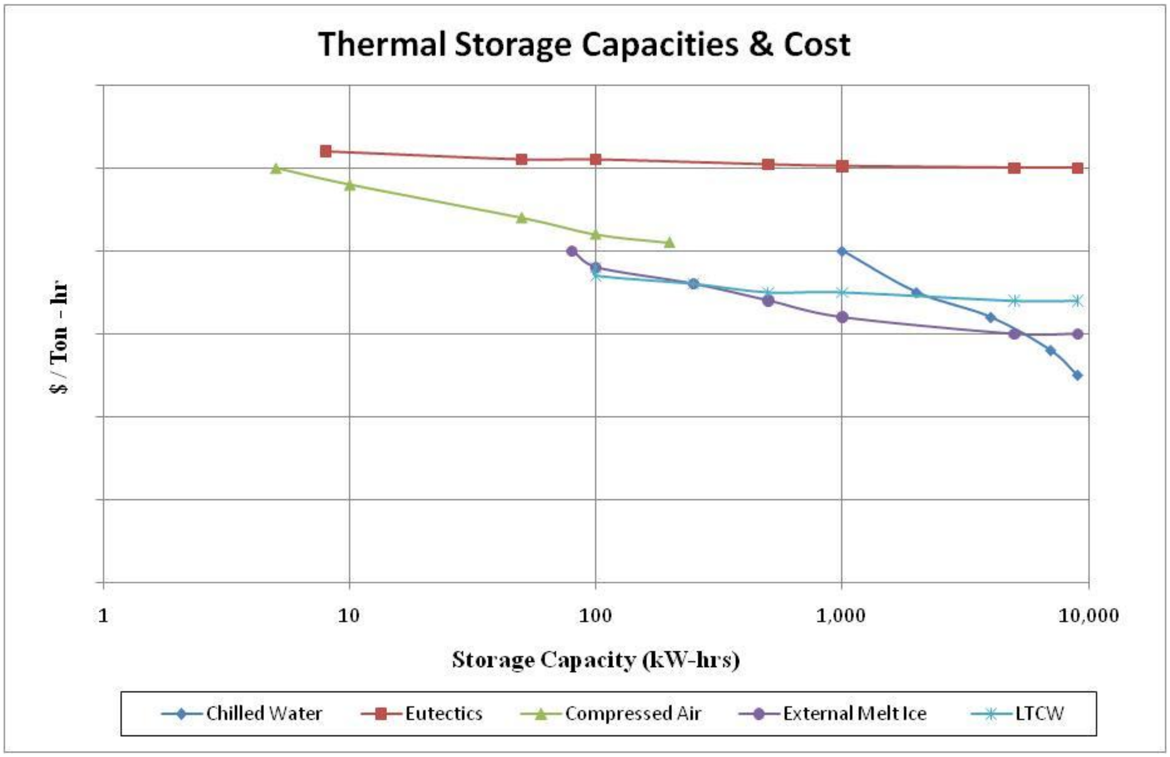

Figure 2-5 Thermal storage capacities compared to their relative costs.

The eutectic TES tanks simply are not a cost effective method for providing cooling at such larger loads. For this study, compressed air will not be used due to its low capacity and high costs, when compared to chilled water and ice storage systems. From this analysis it is easy to conclude that chilled water, LTCW, and external ice melt TES tanks are currently the most cost effective methods that are viable options to provide emergency cooling at various cooling load profiles. In an effort to better understand the systems, the next section will address the various configurations in which these systems are currently deployed.

Emergency Cooling Designs

There are two primary configurations in which the methods listed above are implemented into existing or new construction design. The first setup is the parallel system configuration where the TES tank is placed is parallel with the chiller. Figure 2-6 is an example of how typical TES tanks are installed in emergency cooling systems. The TES tank could represent four 200,000 gallon tanks to provide 10,000 ton-hours worth of cooling for an emergency situation.

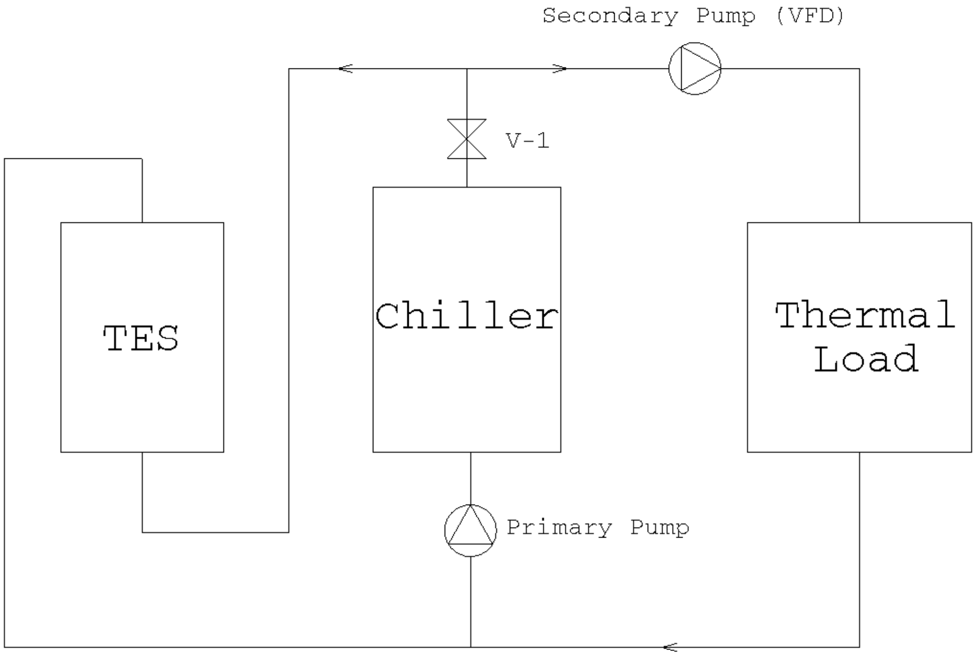

Figure 2-6 Parallel TES Tank

The main benefit of this type of system is that during recharge there is no warm water passing through the thermal load thus causing an unnecessary spike in the temperature. During normal operation the chilled water would pass through the thermal load and excess chilled water would go through the TES tank for a trickle recharge. During a discharge the chiller would be off line and valve V-1 would be closed while the secondary variable frequency drive pump would pull the chilled water from the TES tank through the thermal load. During a recharge cycle, the chiller would produce excess chilled water that would enter through the bottom of the TES tank and force the warm water out of the top of the TES tank. The warm water would enter the through the primary pump and this action would continue till the TES chilled water temperature was set to the design temperature.

The other system configuration found in most field applications is the series configuration where the TES tank and chiller are in line with one another. Figure 2-7 is a diagram of how the series system would be implemented.

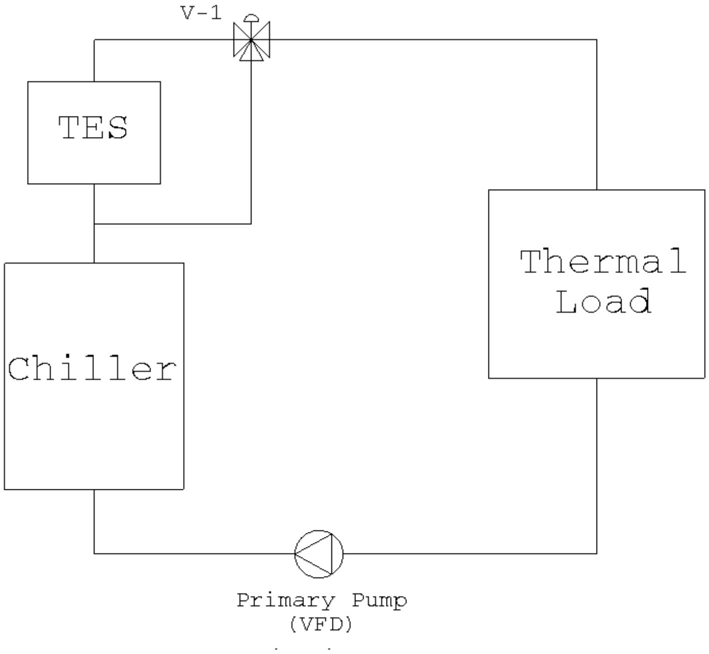

Figure 2-7 Series TES Tank

During normal operation the primary variable frequency drive pump maintains the correct flow through the system, while valve V-1 is used to bypass water around the TES tank. During a discharge situation, the chiller is shutoff and the TES tank is discharged from top to bottom. The recharge cycle is exactly the same as the discharge cycle except that valve V-1 now controls how much flow is diverted to the tank.

The parallel and series tank designs each have their advantages and disadvantages. Depending on whether the install is new construction or retrofit, there could be limitations already in an existing system that could lead to only one design being possible. Both systems are implemented with a great amount of success in the field and will be used to form the foundation of our models to be analyzed economically.

Emergency Cooling System Guidelines and Layouts

Now that the basic design concepts have been understood, the creation of simplified models can be created using field examples and industrial contacts for TES tanks. The purpose of the following section is to provide guidelines for how the systems will be designed and analyzed from an economic point of view. To provide a wide range of information for designers, various peak cooling loads were selected. This will allow for small and large sized systems to be analyzed at various temperature differences. The systems will be designed for a 1, 5, and 15 MW peak cooling load at temperature difference's across the thermal load of 10, 15, 20°F.

Table 2-3 is an example of how each system's total costs (USD) will be shown in the results portion of this report.

Table 2-3: Cooling Load Cost Example

Temperature Difference	Cooling Load		
	1 MW	5 MW	15 MW
ΔT = 10	\$100.00	\$200.00	\$300.00
ΔT = 15	\$300.00	\$400.00	\$500.00
ΔT = 20	\$500.00	\$600.00	\$700.00

The TES tanks will be sized to provide approximately 30 minutes worth of emergency cooling during any given time of the day. Typical emergency cooling or UPS backup power supplies have a 15 to 30 minute cooling or power supply based-off industry experience (Fenton, Basgall, and Bembry 2011). The 30 minutes will provide adequate chiller restart time for most applications and allow for a shutdown of vital equipment should the regular cooling system require further downtime.

To compare several different cost models, five layouts utilizing the information from the previous sections were created and are explained in detail in the following section. Each of the system layouts and cooling methods were using the design guidelines outlined in the previous sections. The initial capital costs for each of the systems will only include the components of the system that make up the emergency cooling portion of the system. The reason for only including the emergency components (tank, piping, insulation, etc) is because we are only interested in what the increase in cost would be should we decide to install a particular emergency cooling device. The goal is not to determine what the most cost effective layout is, but instead it is to determine the most cost effective emergency cooling method depending on the applications and design temperatures. In addition to the capital costs, maintenance cost over a 20 year period will be incorporated into each system layout to provide the user with a present worth initial cost. By determining what the initial and maintenance costs are for various system types, a true estimate of the total cost can be derived.

In an effort to provide additional information regarding the operation of each system, a simulation for each layout was run. The simulations were run on the Transient System

Simulation Program (TRNSYS 2009) computer program. This program allows users to input the components (chillers, pumps, heat exchangers, etc.) that make up a system and complete a transient simulation of how the systems would operate with a given set of inputs. The main purpose for using TRNSYS 2009 is to determine what the additional electrical usage would be for each system layout. While the electrical usage will depend highly on the applications and usage, a good estimate can be made for generalized calculations. Once the total costs of each system have been determined, a benefit-to-cost ratio can be calculated to see what kind of savings can be created by using an alternative backup cooling source rather than a traditional battery and generator system. The following sections will identify what system layouts and cooling methods are to be analyzed, as well as their operation.

System 1 – Parallel Pressurized TES Tank, Chilled Water

This system was selected for a detailed costs analysis due to its high usage within the data center industry and simple control philosophy. Pressurized tanks allow for a closed system with less complex control mechanisms to maintain the proper water line within the tank. Pressurized tanks tend to be smaller in size, not exceeding 50,000 gallons due to cost and overland transportation constraints. Figure 2-8 is a simplified diagram of the parallel pressurized TES tank system, with all the major components identified.

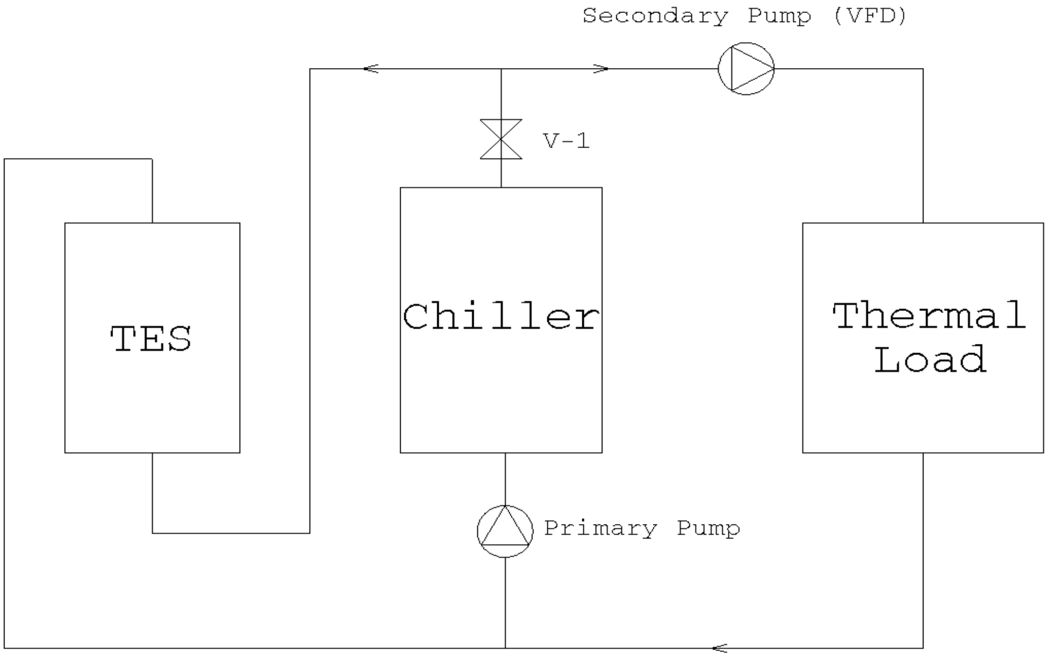

Figure 2-8 Parallel Pressurized TES Tank

Normal Operation: The TES tank is fully charged while V-1 is open. The chiller operates at capacity that may or may not meet the thermal load. The secondary pump provides flow that gives the desired temperature change across the thermal load. The primary pump operates at a constant flow.

Emergency Cooling: The valve V-1 is closed during an emergency cooling situation. The secondary pump provides sufficient flow to meet the temperature difference across the thermal load by drawing chilled water from the TES tank. The secondary pump is powered by a backup power system. The primary pump would remain off until chiller restart.

Recharge TES: When the chiller capacity exceeds the thermal load, the excess chilled water will flow into the TES tank. When total volume flowed equals the tank volume, the TES has been recharged. The time to recharge will be a function of the excess chiller capacity and the TES volume.

System 2 – Parallel Atmospheric TES Tank, Chilled Water

This particular system utilizes an atmospheric tank in parallel with the thermal load and is widely used for large thermal load applications. By selecting the atmospheric tank setup in parallel, we will be able to compare it to pressurized tanks for economic analysis and provide information on the economic break point for different peak thermal loads and temperature differences.

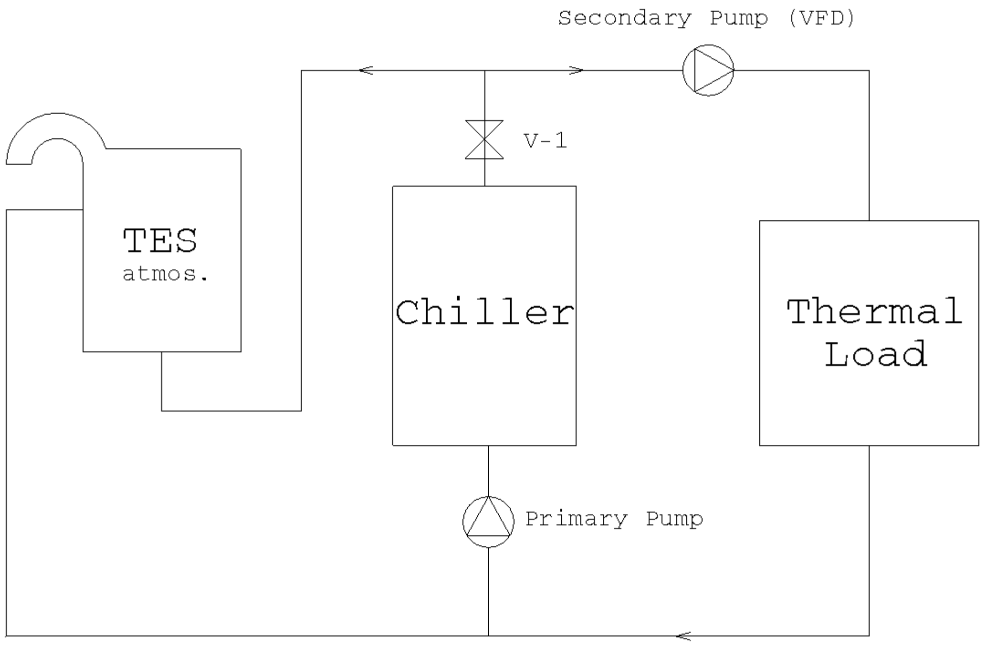

Figure 2-9 Parallel Atmospheric Tank, Chilled Water

Normal Operation: The TES tank is fully charged while V-1 is open. The chiller operates at capacity that may or may not meet the thermal load. The secondary pump provides flow that gives the desired temperature change across the thermal load. The primary pump operates at a constant flow.

Emergency Cooling: Valve V-1 is closed during an emergency cooling situation with the primary pump and chiller shut off. The secondary pump provides sufficient flow to meet the temperature difference across the thermal load by drawing chilled water from the TES tank. The secondary pump is powered by a backup power system.

Recharge TES: When the chiller capacity exceeds the thermal load, the excess chilled water will flow into the TES tank. When total volume flowed equals the tank volume, the TES has been recharged. The time to recharge will be a function of the excess chiller capacity and TES volume.

System 3 – Series Atmospheric TES Tank, Chilled Water

This particular system is similar to the second system of this report; however, the chilled water tank is in series with the thermal load and will yield different system operation, sizing, and costs. This is also a widely adopted layout found in practice that will provide designers with important economic information in deciding which system is the most appropriate.

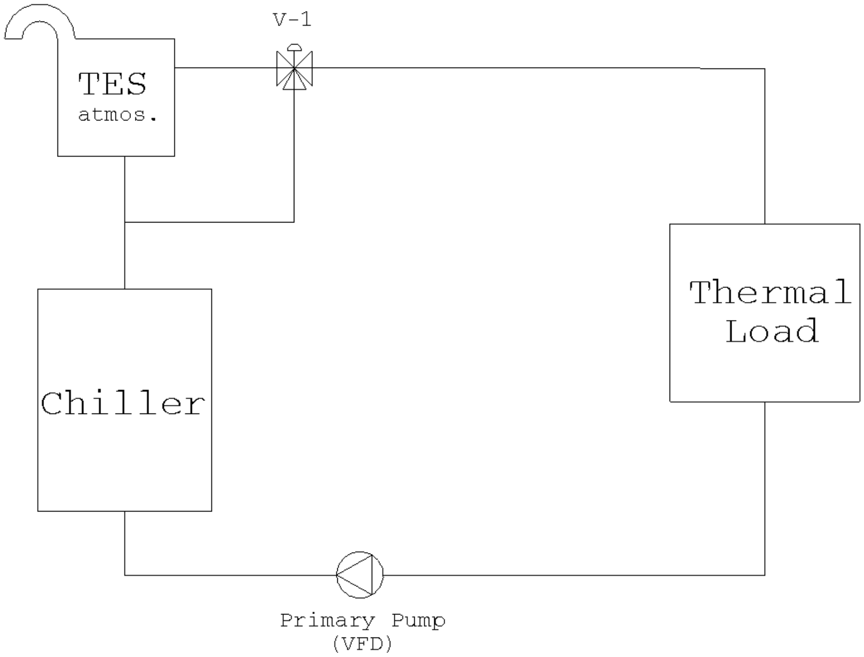

Figure 2-10 Series Atmospheric Tank, Chilled Water

Normal Operation: The primary pump regulates the flow to maintain the desired change in temperature across the thermal load. The primary pump reduces flow to maintain the desired change in temperature as the load decreases. V-1 is allowing all of the flow to bypass the TES tank during normal operation.

Emergency Cooling: The primary pump operates at a flow such that the desired change in temperature is maintained at the load and V-1 is diverting all flow through the TES tank. Chilled water flows from the atmospheric TES tank to the thermal load. The chiller is powered down during this operation.

Recharge TES: When the chiller is operating at capacity greater than the thermal load, V-1 modulates the flow to partially allow the tank to recharge. Once the entire flow equals the tank volume then it is considered fully charged.

System 4 – Parallel Atmospheric TES Tank, LTCW

The low temperature chilled water layout in parallel with the thermal load will provide a designer with additional cooling options that require a smaller foot print. This setup is not as common in the field due to its high initial costs. However, this layout and equipment allows the user to provide higher cooling capacity in a much smaller area than would be possible with traditional chilled water tanks; where the water temperature is above 4.1°C (39.2°F).

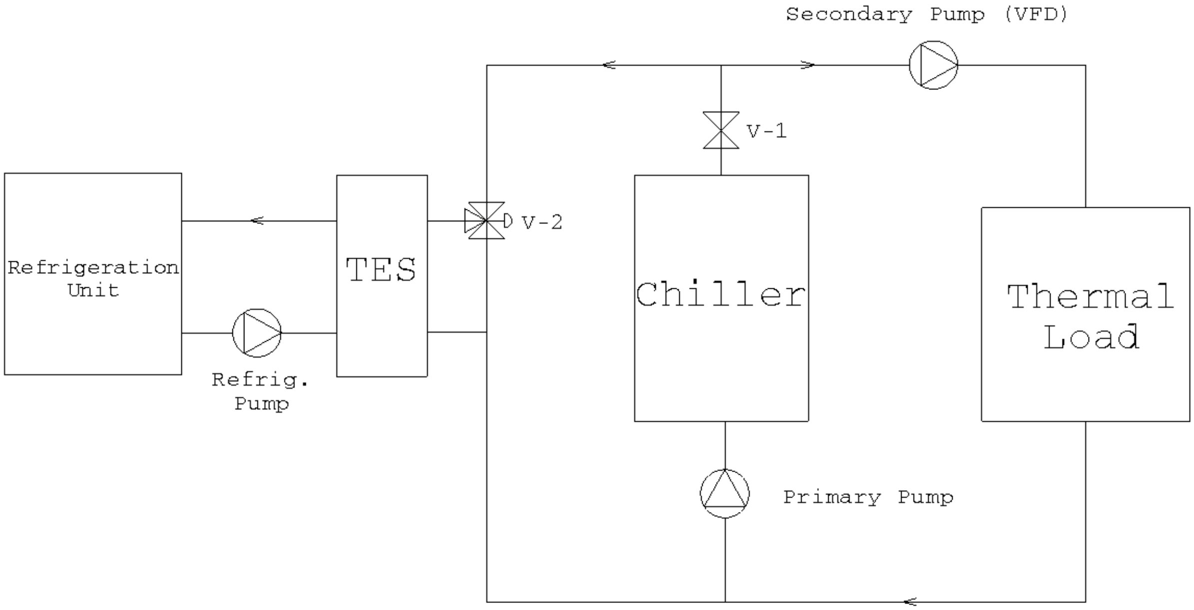

Figure 2-11 Parallel Atmospheric Tank, LTCW

<u>Normal Operation:</u> During this operation V-1 remains open to allow for chilled water to reach the thermal load. The chiller operates at full capacity while the primary pump operates at a constant flow and the secondary pump (VFD) provides the appropriate amount of flow to maintain the desired temperature difference across the thermal load. As the load reduces, excess flow from the chiller goes through V-2 returning to the chiller return line. If the load exceeds the chiller capacity, V-2 allows TES water to mix with the return water and meet the desired thermal load.

<u>Emergency Cooling:</u> For this operation V-1 will remain closed and the primary pump is shut off. The secondary pump provides sufficient flow to maintain the temperature difference across the thermal load. The chilled water will be drawn from the TES tank by modulating V-2.

Recharge TES: Normal operation will apply for main chiller system in that V-2 allows the excess chilled water to bypass the TES tank. The refrigeration unit would operate to lower the TES temperature to 1.7°C (35°F). The refrigeration unit contains a direct expansion (DX) heat exchanger (HX) to lower the TES temperature. The time to recharge is a function of the excess chiller capacity, refrigeration capacity, and TES volume.

System 5 – Series Ice Storage Tank

The external melt, TES series layout was selected for economic analysis due to its wide use in the commercial sector for load shifting applications. By using an ice storage system to provide emergency cooling, the user will be able to have a higher cooling capacity per sq. ft due to the high cooling energy density of ice. By conducting an economic analysis on this system, a set of guidelines can be created for designers to use in their initial evaluation of an ice storage system.

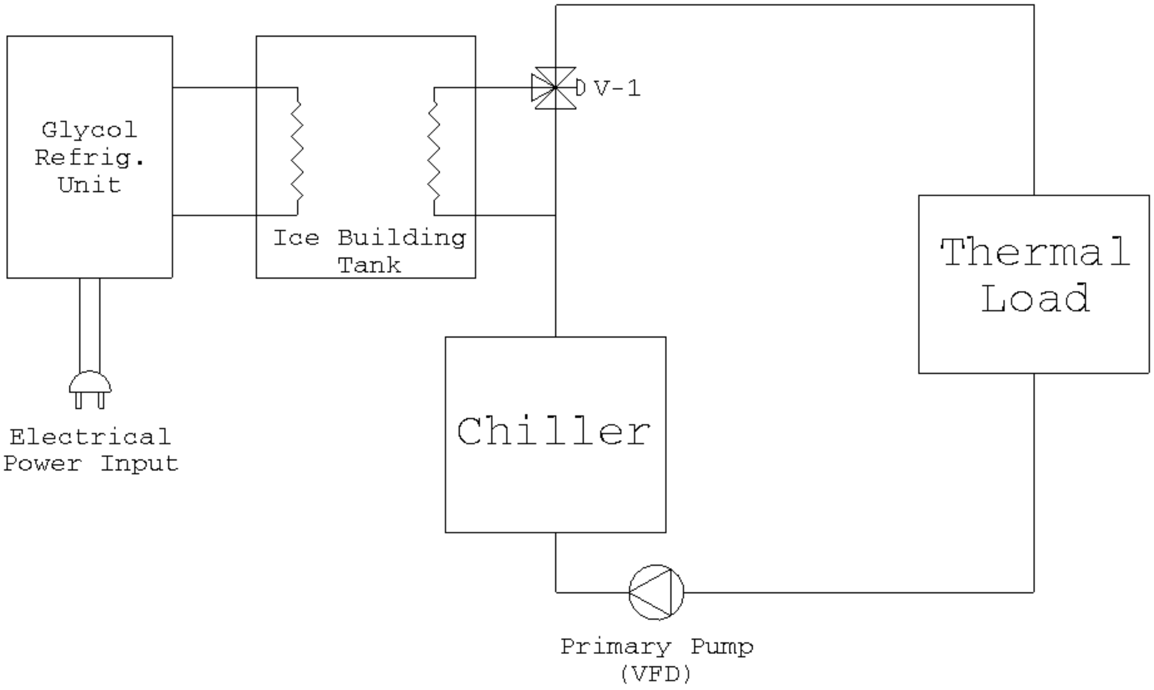

Figure 2-12 Ice Storage Tank, Series Configuration

Normal Operation: During this mode of operation the ice builder tank is fully charged while, V-1 diverts the flow to bypass the ice tank. The primary VFD pump provides the flow to meet the desired temperature difference across the thermal load. As the load decreases, the secondary pump reduces flow to maintain the change in temperatures across the thermal load.

Emergency Cooling: For this mode of operation, V-1 modulates the flow so a portion enters the ice tank while the rest bypasses the ice tank. The primary pump provides flow to the load using backup power and, to maintain the desired temperature difference across the thermal load. The chiller remains off in this mode of operation.

Recharge TES: The ice tank will recharge using the glycol refrigeration unit. The recharge time is dependent upon the size of the glycol refrigeration unit and storage tanks effectiveness to buildup the required 1.5 inches of ice on the coils.

CHAPTER 3 - Detailed Cost Analysis

The following section will provide a detailed cost analysis for the five cooling systems that were selected for economic study. To provide accurate cost models for each of the systems, the RS Means-Cost Works Online Construction Cost Data (2009) website was used as one of the estimation tools. RS Means is a supplier of construction cost information (RS Means Cost Works 2009). A product line of Reed Construction Data, RS Means provides accurate and up-to-date cost information that is used throughout industry. Along with the RS Means-Cost Works website, independent contractors and builders have given estimates for tank sizes and installation costs (Bembry 2010, Frankenfield 2010). The information received from vendors was equation fitted and used as an approximation for each of the individual TES tanks. (RS Means Maintenance 1996)

From the simulated TRNSYS models of the five layouts, initial costs for the emergency cooling components of the system were developed. The following is a list of assumptions made to calculate the present worth of each individual system:

- The initial cost for the construction of these systems will assume a 15% markup for general contractor's overhead and profit margins. The range of markup can range from 10% to 30% depending on the area and amount of risk involved in the project.
- The construction crew will be selected as a standard union crew and the individual costs for each of the components will be taken from a national average database within the RS Mean-Cost Works website.
- These assumptions are industry standards and are subject to change depending on the economic climate and amount of usage of the particular system.
- The detailed costs do not include transportation of the components to job locations simply due to the fact that they are extremely variable. This can however be a significant cost when selecting a system and should be taken into consideration when selecting a site and design.
- The maintenance costs were also taken from the RS-Means website and a fixed interest rate of 5.00% was used over the 20 year period. While interest rate changes on a regular basis, the purpose of this report is to not predict them over the long term but to obtain a present worth cost for each particular system.

Design and Sizing of System Components

Each of the systems were constructed utilizing several mathematical models and basic design equations to develop TES tank sizes, pump flow rates, cooling coil, etc. The following section will explain how each of the system components was sized so that an accurate and working model could be created for present value cost analysis as well as power consumption. The computer program TRNSYS 2009 was used to describe and evaluate complicated components of an energy system that work in unison to provide cooling during an emergency situation. The program is provided with a set of inputs (i.e. chiller performance data) that are used to calculate flow rates and temperatures throughout the system over the time duration of the cooling event. When combining these individual components together, a transient simulation can be created that provides a better understanding of system operation. Each of the components selected for cost evaluation is described in further detailed in Appendix A.

TES Tank Design

The TES tank capacity used for chilled water systems was calculated using the following heat transfer equation (similar to Chapter 2).

$$C = \dot{M}\, c_p\, \Delta T$$

Capacity (C) = Btu/hr

Flow Rate ($\dot{M}$) = lb_m/hr

Specific Heat (c_p) = $Btu / lb_m\ ^\circ F$

Temperature Difference (ΔT) = $^\circ F$

According to Dorgan and Ellson (1993) as well as Frankenfield (2010) TES tanks are approximately 85 – 95% stratified with the thermocline layer occupying around 10% of the tank volume. The tank volume will also be somewhat larger since there will be some clearance between the top of the tank and the water level. The external heat gains to the environment can be between 1 – 2% depending on the locations and insulation of the TES tanks (Sorell 2010). For the sizing of the chilled water TES tank, a 10% increase in tank volume was assumed based-on the information gathered. The tank was sized to provide approximately 30 minutes of emergency cooling to the system during an electrical outage. With the capacities (1, 5, 15 MW) and various ΔT's (10, 15, 20 °F) known a flow rate can be calculated. The flow rate is multiplied by the desired amount of storage time (30 minutes), which provides us with the storage amount when converted to gallons. Each of the tank sizes calculated were rounded up to a more practical size, which was typically in 5,000 gallon increments for smaller tanks (100,000 gallon or less). The flow rates were then used to calculate the required pump capacities throughout the system to provide the necessary flow rate throughout the system and cooling coils.

Chiller

The chiller for each system was designed to provide enough capacity so that the maximum peak load seen by the system (1, 5, 15 MW) will be the minimum capacity that the chiller is designed for. Depending on the application, a certain level of redundancy is designed into the cooling system to allow for additional capacity to meet short term cooling requirements not typically seen by the system. For this system, the chillers were sized to provide an additional 10% capacity to ensure that the TES tanks are able to trickle charge even during peak loading capacities, which is a fairly common design practice according to Sorrell (2010) for TES systems. For the 1 MW cooling load, the chiller will be increased by an additional 10% to meet the design criteria. The following are the design criteria used to construct the 1, 5, and the 15 MW peak cooling load systems:

Chiller Design Criteria				
	Units			
Design Load	MW	1.0 MW	5.0 MW	15.0 MW
Maximum Chiller Load	MW	1.1 MW	5.5 MW	16.5 MW

Pumps

Each of the five systems designed utilized different methods and control schemes to maintain the desired flow rates across the cooling coils. In order to size the pumps correctly, the desired flow rates must be calculated utilizing the following heat transfer equation. The sizing for the constant and variable speed pumps will be the same; their operation is what will influence the cost and electrical consumption for each of the systems. The 1 MW peak cooling determined the load on the system, while the return and supply temperature differences are what changed the flow rates for each of the individual systems. The following is an example of how the flow rates were acquired using the heat transfer equation from the TES tank design section:

$$Q = \dot{M}\, c_p\, \Delta T$$

$$Q = 3.75\ MBtu/hr\ (1.1\ MW)$$

$$c_p = 1.0\ Btu/lb\text{-}F\ (4.2\ kJ/kg\text{-}K)$$

$$\Delta T = 10\ °F\ (5.56\ °C)$$

$$\dot{M} = 104.2\ \text{lb/s}\ (47.3\ \text{kg/s})$$

From the calculated flow rates, a catalog program provided by Bell and Gossett (2009) was used to identify the relevant pumps required to maintain the proper flow through the system. The catalog pumps provided vital information to be used in the simulation of the system (head loss, gallons per minute, pressure drop, efficiency).

Detailed Cost System 1: Parallel Pressurized TES Tank, Chilled Water

The cost analysis was comprised of the main components that made up the emergency cooling portion of the system. For this particular system, the total costs shown below in Table 3-1 include the pressurized thermal energy storage tank structure, additional piping, insulation, and maintenance. The table is broken up into the various cooling loads that were setup for this particular system, and the temperature differences across the coils. For pressurized tanks, the 15 MW cooling load costs are not shown because it becomes uneconomical at such large cooling loads. For additional information on the cost break down for this system please refer to Appendix A.

Table 3-1: System 1, Parallel Pressurized TES Tank, Chilled Water

Temperature Difference (°F)	Cooling Load	
	1 MW	5MW
ΔT = 10	$163,725	$779,237
ΔT = 15	$111,754	$578,256
ΔT = 20	$83,130	$416,015

Detailed Cost System 2: Parallel Atmospheric TES Tank, Chilled Water

The cost analysis was limited to only the components that made up the emergency cooling portion of the system. For this particular system the total costs shown below in Table 3-2 include the thermal energy storage tank, additional piping, insulation, and maintenance. The table is broken up into the various cooling loads that were setup for this particular system, and the temperature differences across the coils. For additional information on the cost break down for this system please refer to Appendix A.

Table 3-2: System 2, Parallel Atmospheric TES Tank, Chilled Water

Temperature Difference (°F)	Cooling Load		
	1 MW	5 MW	15 MW
ΔT = 10	$149,757	$467,245	$645,935
ΔT = 15	$124,163	$373,128	$603,513
ΔT = 20	$97,607	$303,539	$559,197

Detailed Cost System 3: Series Atmospheric TES Tank, Chilled Water

The cost analysis was limited to only the components that made up the emergency cooling portion of the system. For this particular system the total costs shown in Table 3-3 include the thermal energy storage tank, additional piping, three way valve, insulation, and maintenance. The table is broken up into the various cooling loads that were setup for this particular system, and the temperature differences across the coils. For additional information on the cost break down for this system please refer to Appendix A.

Table 3-3: System 3, Series Atmospheric TES Tank, Chilled Water

Temperature Difference (°F)	Cooling Load		
	1 MW	5 MW	15 MW
ΔT = 10	$156,404	$473,892	$654,896
ΔT = 15	$130,810	$379,776	$612,474
ΔT = 20	$104,254	$310,186	$568,158

Detailed Cost System 4: Parallel Atmospheric TES Tank, LTCW

The cost analysis was limited to only the components that comprised the emergency cooling portion of the system. For this particular system the total costs shown below in Table 3-4 include the thermal energy storage tank, additional piping, three way valve, refrigeration unit, refrigeration pump, insulation, and maintenance. The table is broken up into the various cooling loads that were setup for this particular system, and the temperature differences across the coils. For additional information on the cost break down for this system please refer to Appendix A.

Table 3-4: System 4, Parallel Atmospheric TES Tank, LTCW

Temperature Difference (°F)	Cooling Load		
	1 MW	5MW	15MW
ΔT = 10	$156,070	$591,494	$1,309,198
ΔT = 15	$139,771	$536,396	$1,262,933
ΔT = 20	$130,740	$497,879	$1,224,661

Detailed Cost System 5: Series Ice Storage Tank

The cost analysis was limited to only the components that made up the emergency cooling portion of the system. For this particular system the total costs shown below in Table 3-5 include the ice storage tank, additional piping, three way valve, refrigeration unit, insulation, and maintenance. The costs for the systems remain constant for various temperature differences across the cooling coil of the thermal load. This is due to the fact that the components are not sized up or down because the ice storage tanks have the same declining energy rate regardless of the temperature difference. For the previous four systems it was necessary to have different tank sizes because the declining energy rate was different depending on the temperature difference. For additional information on the cost break down for this system please refer to the Appendix A.

Table 3-5: System 5, Series Ice Storage Tank

	Total Cost
1 MW	$117,891
5 MW	$469,000
15 MW	$1,351,259

Detailed Cost Analysis for TES Systems

A plotted cost break down for the 1 MW peak cooling load system can be seen in Figure 3-1. For the 1 MW peak cooling loads we can see that at a ΔT = 10˚F the ice storage system will be the most inexpensive solution to provide emergency cooling. This is due to the fact that the ice storage tank can provide a high cooling energy density at a smaller ΔT with minimal increase in equipment and tank costs. The chilled water systems (1, 2, 3) require larger tanks to achieve the same cooling capacity that a smaller ice storage tank can achieve. As we move to a ΔT = 15˚F, the tank sizes for the chilled water systems become smaller due to the larger temperature difference and are thus more competitive with the ice storage system. The pressurized system was the most cost effective for this temperature range due to the reduced tank equipment and construction costs. The pressurized tank system has fewer internal mechanisms, and metering devices that are commonly associated with atmospheric tank systems Atmospheric tanks require additional equipment and controls to monitor the water level and thermocline layer within the tank. Unpressurized tanks typical have pressure sustaining valves on the tank's inlet and outlet to separate the static head of the tank from the remainder of the system. The sustaining valves are self-contained and modulate to maintain the desired upstream static pressure through a throttling action. Unpressurized tanks are exposed to the atmosphere and frequently require chemical additives to prevent bacterial contamination. The most expensive system for this temperature difference was the low temperature chilled water TES tank. While the tank size for system four is smaller by about 8,500 gallons when compared to the chilled water system, the increased costs from the refrigeration unit and chemical additives eat up any savings that could have been gained by lowering the temperature of the water. For a temperature difference of 20˚F, we can see that the pressurized TES tank is the most cost effective due to the lower tank equipment costs and controls when compared to an atmospheric tank. With the increase in temperature difference across the tank, a smaller tank can be used due to the lower flow rates. Again the cost savings using a smaller tank for system four will not offset the principal cost of the refrigeration unit required to maintain the LTCW system. From the 1 MW detailed cost analysis it is easy to see that there is no one single system solution. However, system one pressurized regular chilled water TES is the most cost effective at a 15˚F load temperature difference and clearly the most cost effective at a 20˚F load temperature difference.

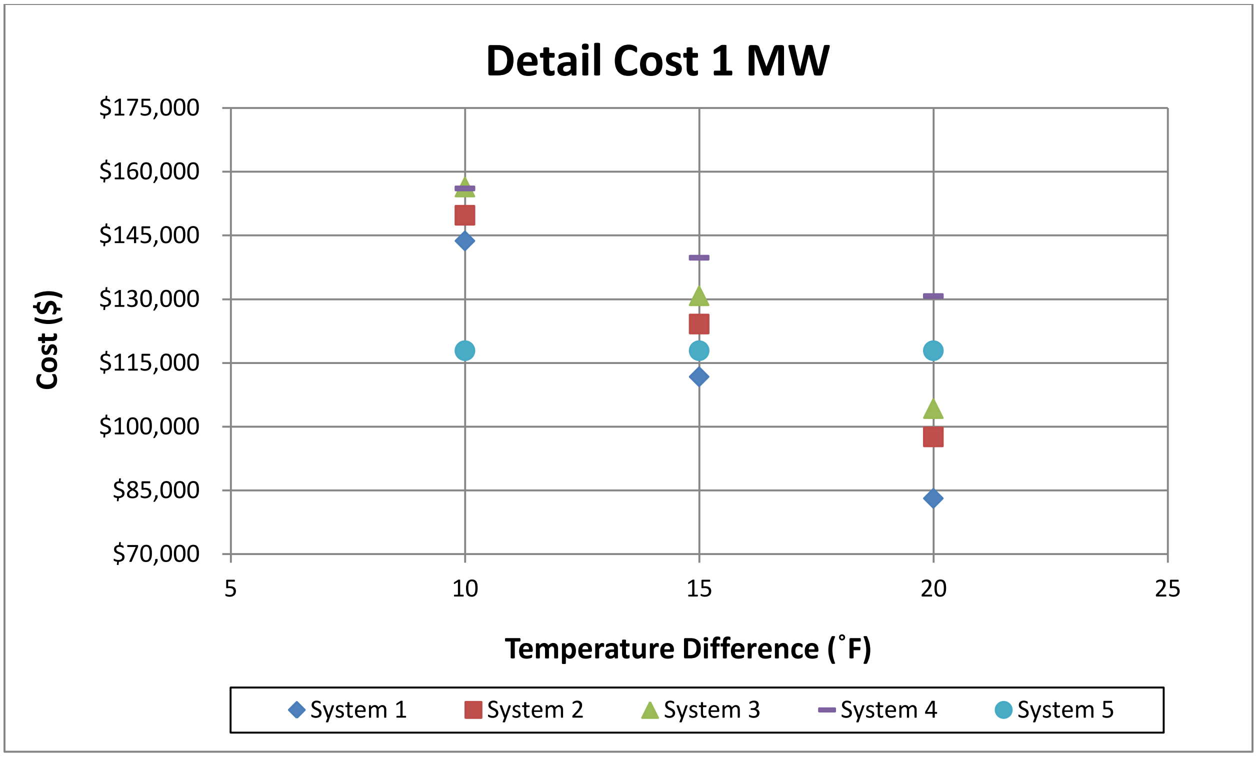

Figure 3-1 Totals cost for 1 MW cooling load

System 1: Chilled Water Parallel Pressurized TES Tank, Two Pumps

System 2: Chilled Water Parallel Atmospheric TES Tank, Two Pumps

System 3: Chilled Water Series Atmospheric TES Tank, One VFD Pump

System 4: Low Temperature Chilled Water Parallel TES Tank, Two Pumps

System 5: Series Ice Storage Tank, One Pump

As we increase the load to 5 MW as shown in Figure 3-2, the price differences between each of the systems becomes more apparent. For a load temperature difference of 10˚F, systems utilizing an atmospheric tank and ice storage system are the most cost effective. The pressurized tank system requires multiple tanks to obtain the same 30 minutes worth of cooling. The high costs of manufacturing and installing pressurized tanks of such large magnitude typically eat up any savings in simplified system controls associated with pressurized tanks. The reduction in tank size for system four again is not cost effective for any of the temperature differences at the 5 MW peak cooling load. For a load temperature difference of 15˚F and 20˚F, the atmospheric tank systems (System 2 and 3) provide the most cost effective means for providing emergency cooling. With the reduction in tank sizing at a load temperature difference of 20˚F, the pressurized tank becomes more cost effective than the ice storage and LTCW systems.

For the 15 MW detailed analysis, it is apparent that the atmospheric tank systems provide the most cost effective means for providing emergency cooling when compared to the ice storage and LTCW systems. At such large loads, the refrigeration unit costs for the ice and LTCW systems become the dominating factor and consume any savings in utilizing a smaller tank size. However, chilled water TES tanks require a considerable amount of space to be constructed upon. If space is limited, it may not be an option in which case the LTCW system could provide the same amount of cooling at a reduced cost when compared to the external melt system. Table 3-6 provides a breakdown of what systems were the most cost effective for a particular cooling load and temperature differences across the thermal load. This table provides designers with a quick overview of what kinds of systems will be the best fit for a particular application.

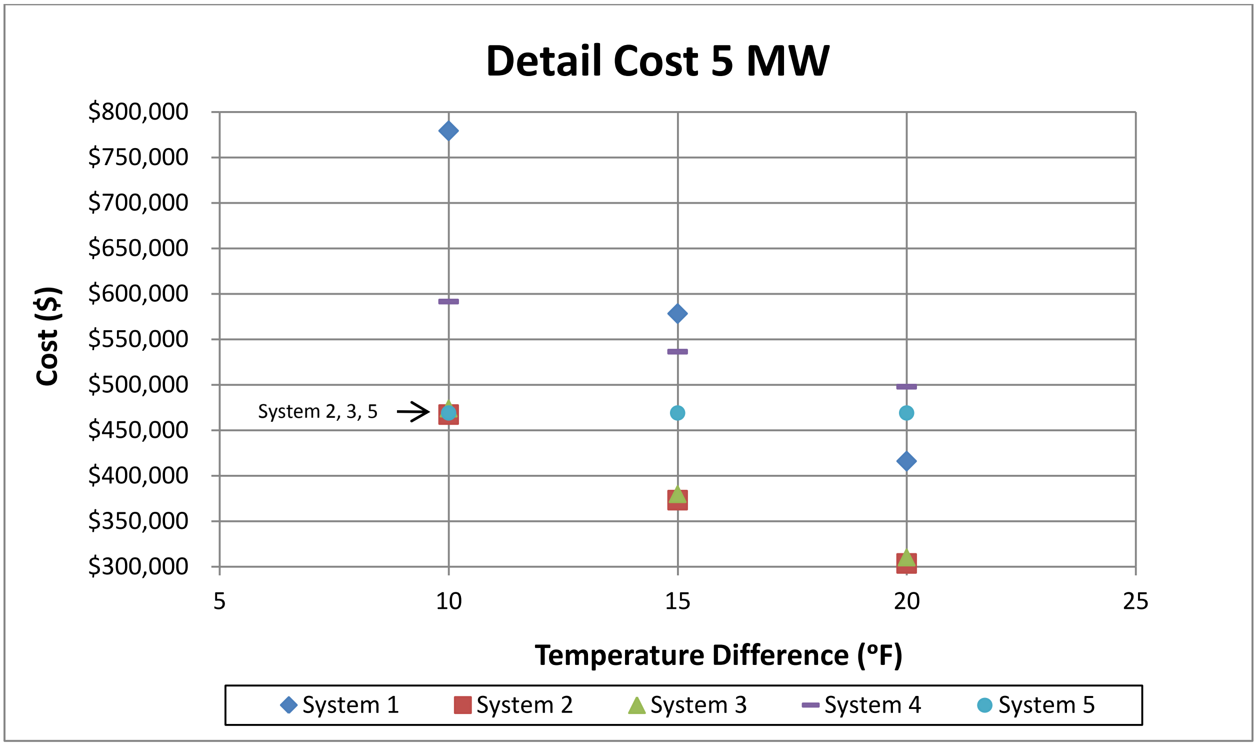

Figure 3-2 Totals cost for 5 MW cooling load

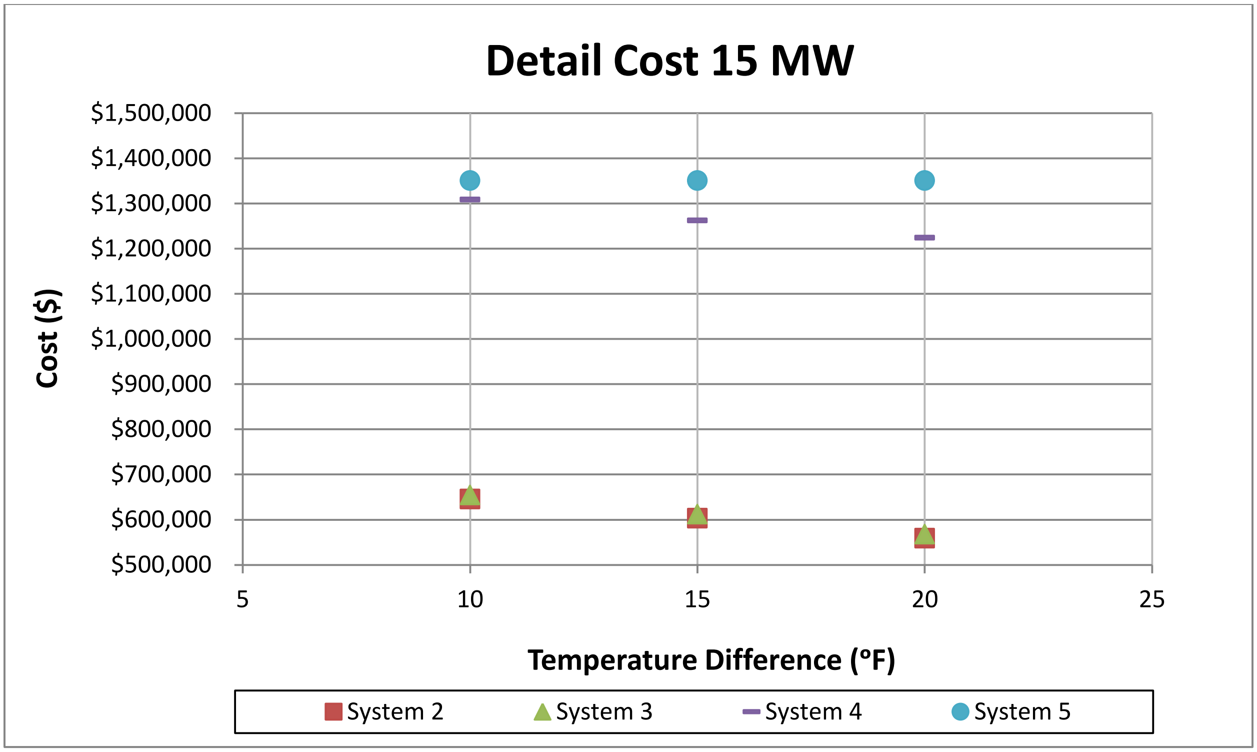

Figure 3-3 Total costs for 15 MW cooling load

Table 3-6: System Selection Table

	Temperature Difference (°F)		
	10	**15**	**20**
System 1	-	1 MW	1 MW
System 2	5, 15 MW	5, 15 MW	5, 15 MW
System 3	5, 15 MW	5, 15 MW	5, 15 MW
System 4	-	-	-
System 5	1, 5 MW	-	-

From the analysis we can see that there are significant increases in costs when varying the temperature difference between the return and supply water, as well as the peak cooling loads. Figure 3-4 gives an overview of how the costs increased with each temperature difference, allowing designers to better predicted the associated costs for loads in between 1, 5, and 15 MW. Observe that for a load temperature difference of 10 °F at 1 MW, the costs are all relatively close to one another when compared to larger peak cooling loads. As the systems become larger the chilled water systems become the most cost effective due to the low maintenance and low initial costs. It is important to note that ice storage tanks were very cost effective for the 1 and 5 MW peak cooling loads due to the lower temperature difference. This was in part due to the fact that larger tanks were required by the chilled water and LTCW systems. The ice storage systems benefit from the higher energy density and can perform the same operation but with smaller tanks. Ice storage breaks down at the 15MW peak cooling load due to the fact that several tanks need to be constructed were with chilled water tanks only one tank needs to be constructed. As noted earlier, if space is a concern then the additional costs of acquiring more space for the large chilled water tanks could make ice storage tanks or LTCW systems more competitive. This analysis assumes that space is not a concern and allows the designer to incorporate any additional costs to the calculated values for a more custom estimation.

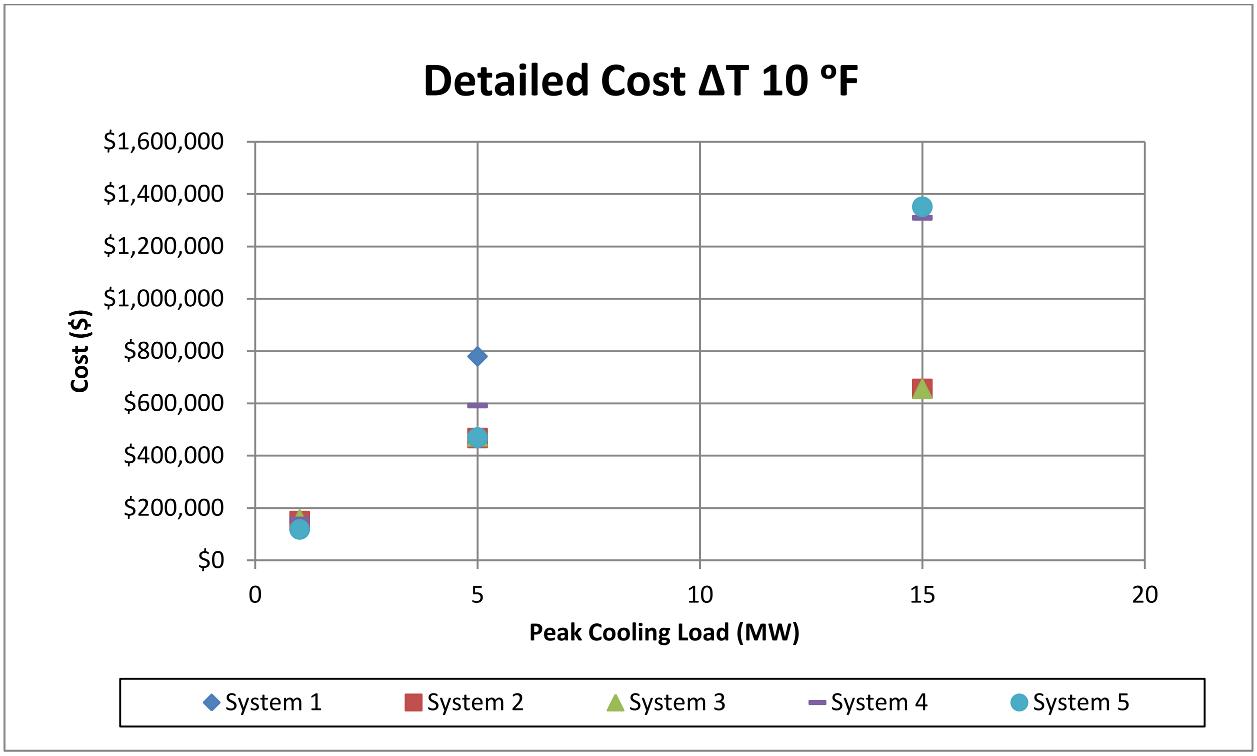

Figure 3-4 Total Costs for ΔT 10 °F

The total cost analysis for a temperature load of 15 °F is shown in Figure 3-5. The initial peak load of 1 MW shows that the cost of each of the systems are all fairly close when compared to larger more expensive systems. The chilled water storage systems (2 and 3) benefit from the increase in temperature load by allowing for a smaller tank size. The LTCW system reduced tank size cannot offset the additional costs of the refrigeration unit and chemical additives.

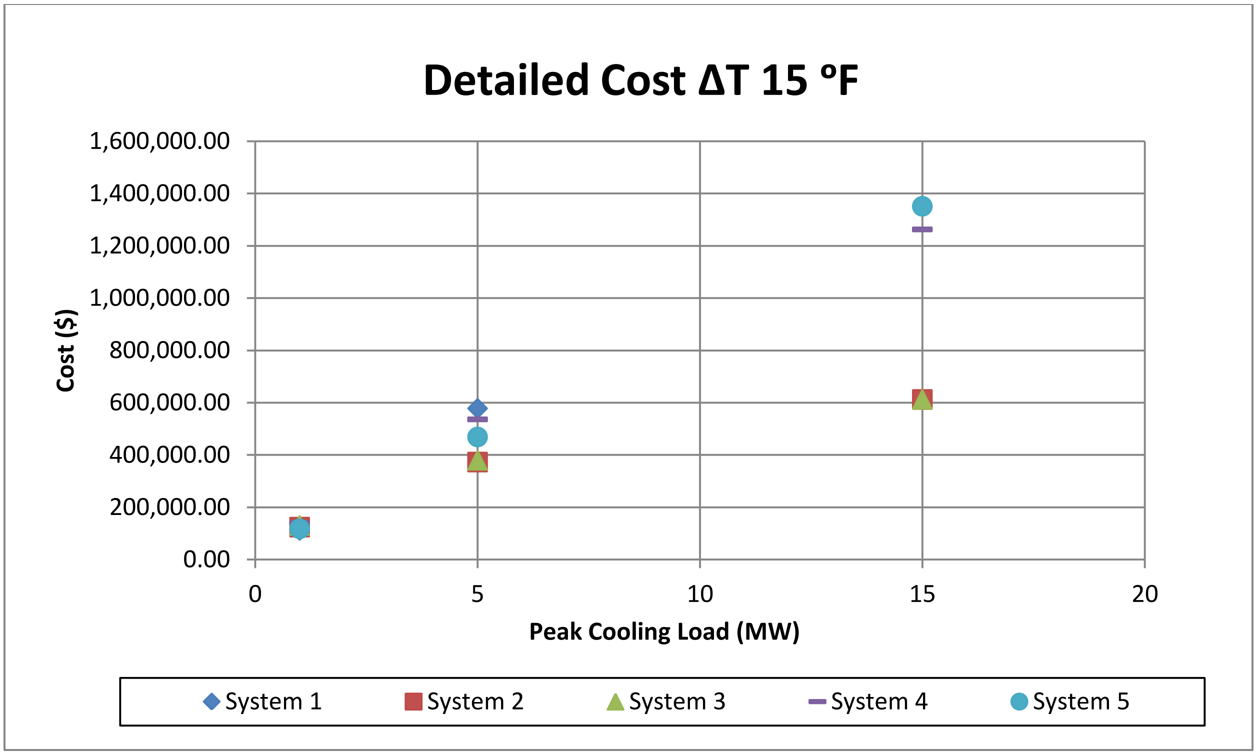

Figure 3-5 Total Costs for ΔT 15 °F

Figure 3-6 provides a detailed cost for the various peak cooling loads at a temperature load of 20 °F. It is to the designers benefit to increase the temperature load difference so that a reduced tank size can be selected thus reducing costs. The trends established for a temperature load of 10 °F and 15 °F continue to hold true for the 20 °F case. The disparity between the chilled water tanks and ice storage and LTCW continue to increase due to the fact that ice has a fixed size independent of the temperature difference, and LTCW systems additional refrigeration unit increases the initial total costs of the system.

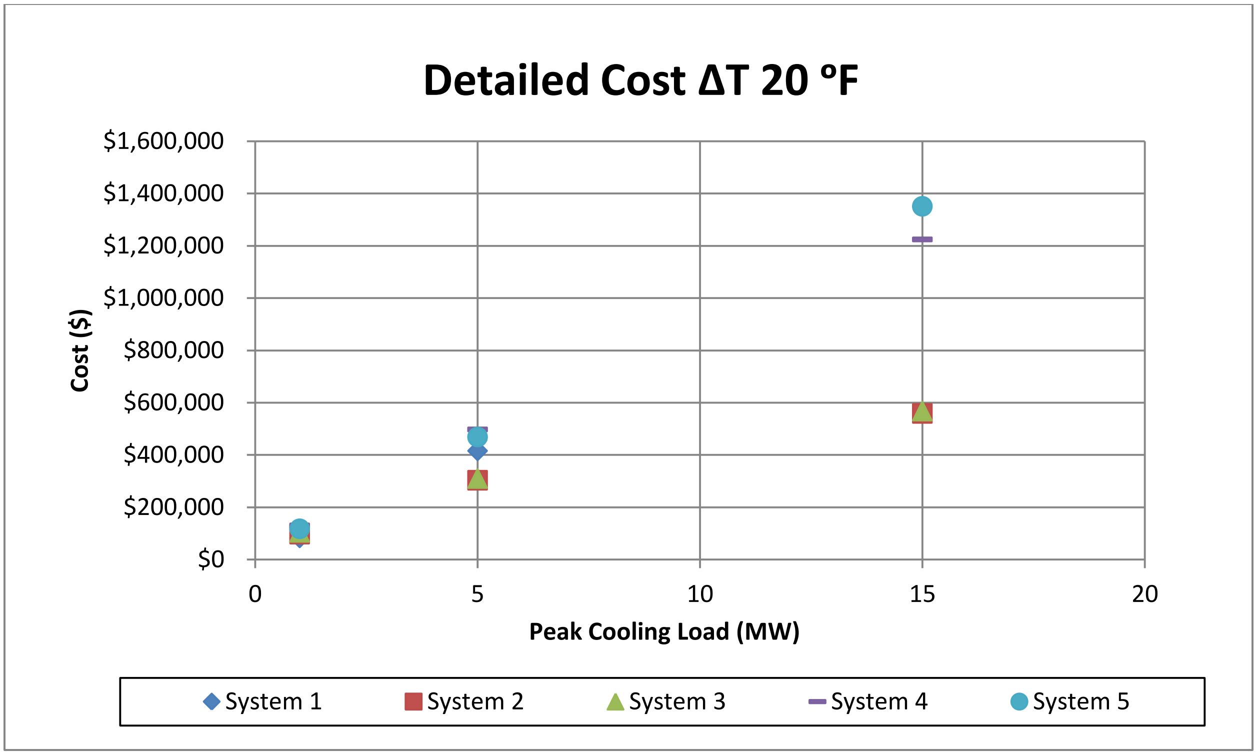

Figure 3-6 Total Costs for ΔT 20 °F

CHAPTER 4 - ELECTRICAL USAGE

By simulating various system layouts at different peak cooling loads, a better understanding of the associated electrical costs for TES systems can be determined. To accomplish this task, a FORTRAN based computer program called TRNSYS (2009) was used. TRNSYS is a well known and documented program throughout the HVAC industry for simulating transient energy systems. The program interface contains several components (valve, chiller, cooling tower, etc.) that hold mathematical models which are connected to one another through a series of inputs and outputs. Each of the components have parameters that will be used to size the emergency cooling equipment for various desired cooling loads. Through the use of TRNSYS, the sizing of the components for each of the five system layouts created in chapter 3 can be completed for a 1, 5, and 15 MW peak cooling load. Once the components have been sized and a cooling load selected, each layout can be simulated at various loads. The intent of simulating these systems is not to acquire an exact cost, but instead to gain a better understanding of what the approximate power consumption could be for each of the various cooling systems. The following sections will discuss the simulations in greater detail along with the outcomes.

Electrical Guidelines and Assumptions

Estimating the electrical costs for various TES system layouts will vary greatly depending on the efficiency of the chiller, refrigeration unit, load, external and internal heat gains, and pump sizes. In an effort to come up with a meaningful comparison between each of the systems, assumptions must be made. For this analysis each system layout will be run for a 24 hour period to determine the electrical usage of the entire system. During the 24 hour simulation, the system will undergo an emergency cooling event for a period of 30 minutes. After 30 minutes, the power will be restored to the system for normal operations, commencing recharging of the TES tank. The cooling load that will be used to analyze each system will be that of a typical data center. Below in Figure 4-1 is an example of a thermal load experienced by a data center. This example cooling load will be sized up for the 5 and 15 MW peak cooling load simulation.

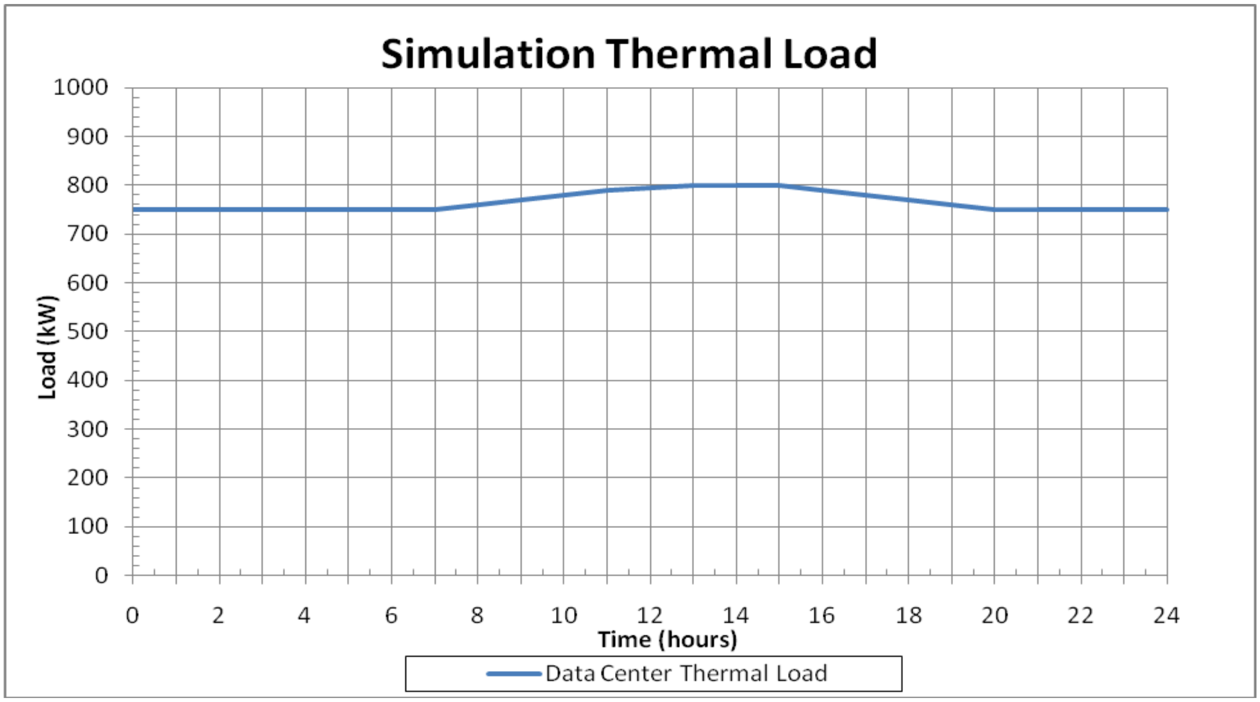

Figure 4-1 Thermal Load for a Data Center at 80% peak load of 1 MW

Each of the system components were sized for a 1, 5, and 15 MW peak cooling load. The chiller component was designed at a set point temperature of 45 °F, with a redundancy capacity of 10% (example: A 1 MW peak cooling load equates to 1.1 MW chiller capacity). By using this set point temperature the recommended temperature range according to ASHRAE HVAC Applications (2007) can be achieved.

Table 4-1 Data Center Temperature

	Allowable Range	**Stability Range**
Data Centers	64.4 to 80.6 °F	+/- 3.6 °F

Each of the systems incorporated either a constant speed or variable speed pump depending on the layout and operation. The thermal load and temperature differences between the supply and return water dictated the rated flow capacities and motors for each of the pumps. The sizing of the emergency cooling parts of the system, such as the TES tanks, was dependent on the return and supply temperatures as well as the flow rates. For the TES tanks 90%, stratification is assumed so therefore the tanks needed to be increased by about 10% to accommodate this loss. During the 24 hour simulation a 2% heat gain was assessed to the system to include internal and external heat gains from the equipment and surroundings. The recharging time for each system layout will be different depending on the thermal load and refrigeration unit providing the TES tanks with chilled water or ice generating capacities. For a chilled water system, the recharge time will be dependent on the amount of excess chilled water that can be diverted to the TES tank. For the ice storage and low temperature chilled water systems, the recharge time will be determined by the refrigeration units cooling capacity. From industry experts, the typical recharge time for an ice storage unit can be between 7 to 9 hours (Bembry 2010). For this simulation the ice storage system will have a recharge time of 7 hours. From these guidelines the systems were simulated and the results are presented in the following section.

Simulation Results

From the TRNSYS simulations, only the major components (pumps, chillers, refrigeration units, etc) to the system were recorded and included in the total power consumption. The simulation results for the 1 MW cooling load profile can be seen in Figure 4-2 for each of the system layouts. From the analysis we can see that systems 1 and 2 do not differ in electrical usage over the 24 hour period. This is due to the fact that the layouts are the same and only differ in their control schemes. While system 3 had the lowest power consumption, systems 1 and 2 were within 1 to 2% of system 3's total power consumption at a temperature difference of 10 °F and ΔT 15 °F. As the temperature difference was increased to 20 °F, there was practically no difference in power consumption between systems 1, 2, and 3. For system 4, the energy consumption was between 6 to 8 % more than that of system 3. This was due to the increased power consumption by the refrigeration unit that was used to cool the water below 39 °F. System 5 also required an external refrigeration unit which required a significant amount of power consumption to recharge the ice TES tank. Since ice systems operate below the freezing point, the refrigeration unit's temperature lift increases, which in turn decreases the unit's performance. The increase in power consumption can also be attributed to the fact that ice is a poor thermal conduction medium, thus causing the refrigeration unit to operate outside of its design conditions as the ice begins to surround the coils of the evaporator. The power consumption for system 5 was between 22 to 25% more than that of the chilled water systems (Systems 1, 2, and 3). This percentage increase agrees with Niehus (1994) in that, using a rule of thumb average of 2%

increase in energy usage per °F of suction temperature drop, the ice system will have an energy consumption 20% to 24% greater than comparable chilled water systems. The modeled system is well within this acceptable range, proving that the model is working as predicted for a detailed electrical cost comparison for an ice storage system.

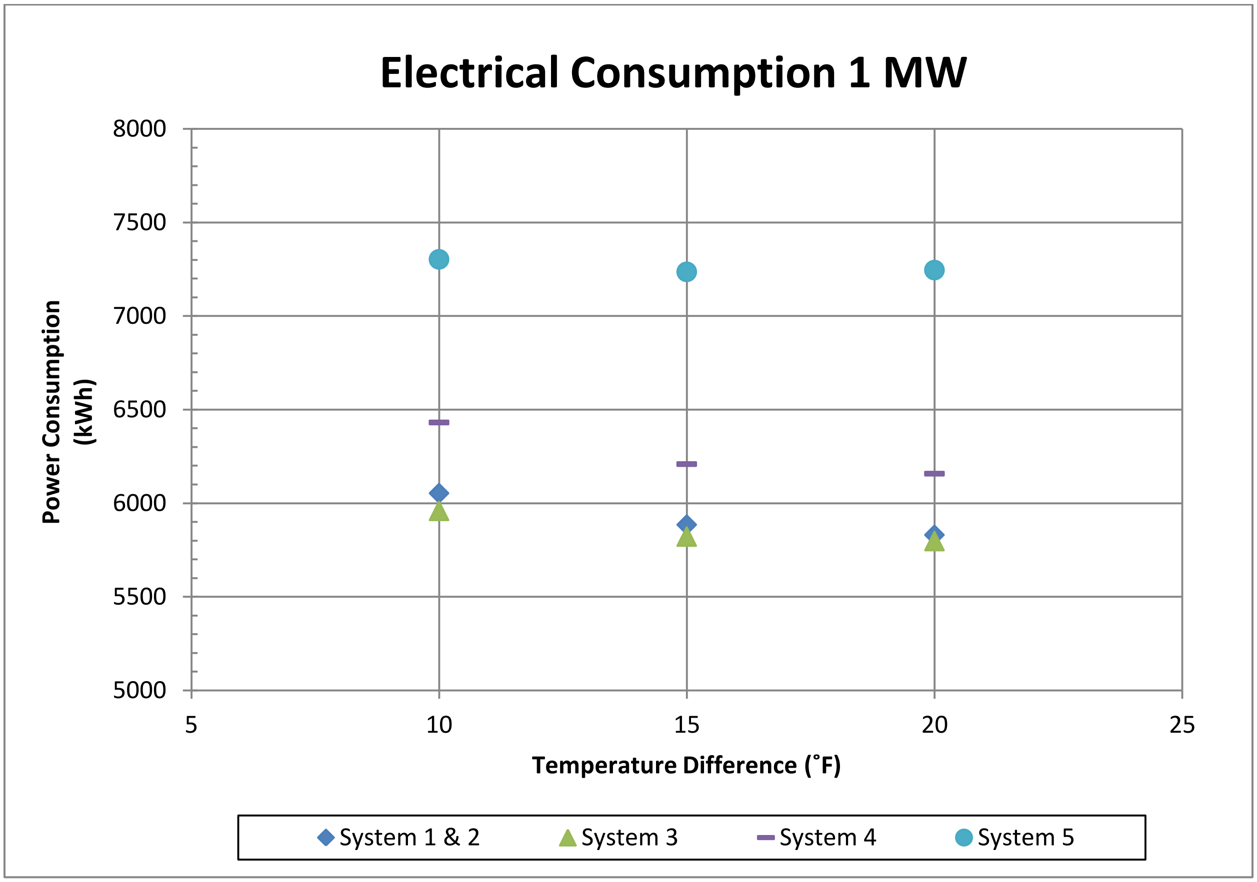

Figure 4-2 Electrical Consumption for 1 MW peak cooling load

As the systems were increase to 5 and 15 MW, the power consumption for each of the layouts were very similar to that found in Figure 4-2. Figure 4-3 provides an overview of the electrical costs for the 5 MW peak cooling load system for the five system designs at different temperature loads. An important point to note for the 5 MW systems is that as the temperature difference is increased from 10 °F to 20 °F the LTCW system (System 4) requires less energy while the ice storage system increases its energy consumption. The ice storage system requires more energy because the return and supply water have not completely melted all of the ice within the storage tank. Therefore causing the refrigeration unit to increase the refrigerant amount across the evaporator coils to build up the required amount of ice. An important point to add regarding ice storage recharge operation is that at the beginning of a charge cycle when the coils are bare, the system operates at the highest suction temperatures, and therefore peak efficiency requiring the least amount of energy. Towards the end of a recharge cycle, the last layer of ice being built is formed at the lowest suction temperature, lowest efficiency, and therefore highest energy usage. For the LTCW and chilled water systems the energy decreases with respect to the temperature load difference because the pumps operate at greater efficiencies. While the amount of power consumed by the pumps is minimal in comparison to the chiller, it does have an impact over an extended period of time that should be accounted for.

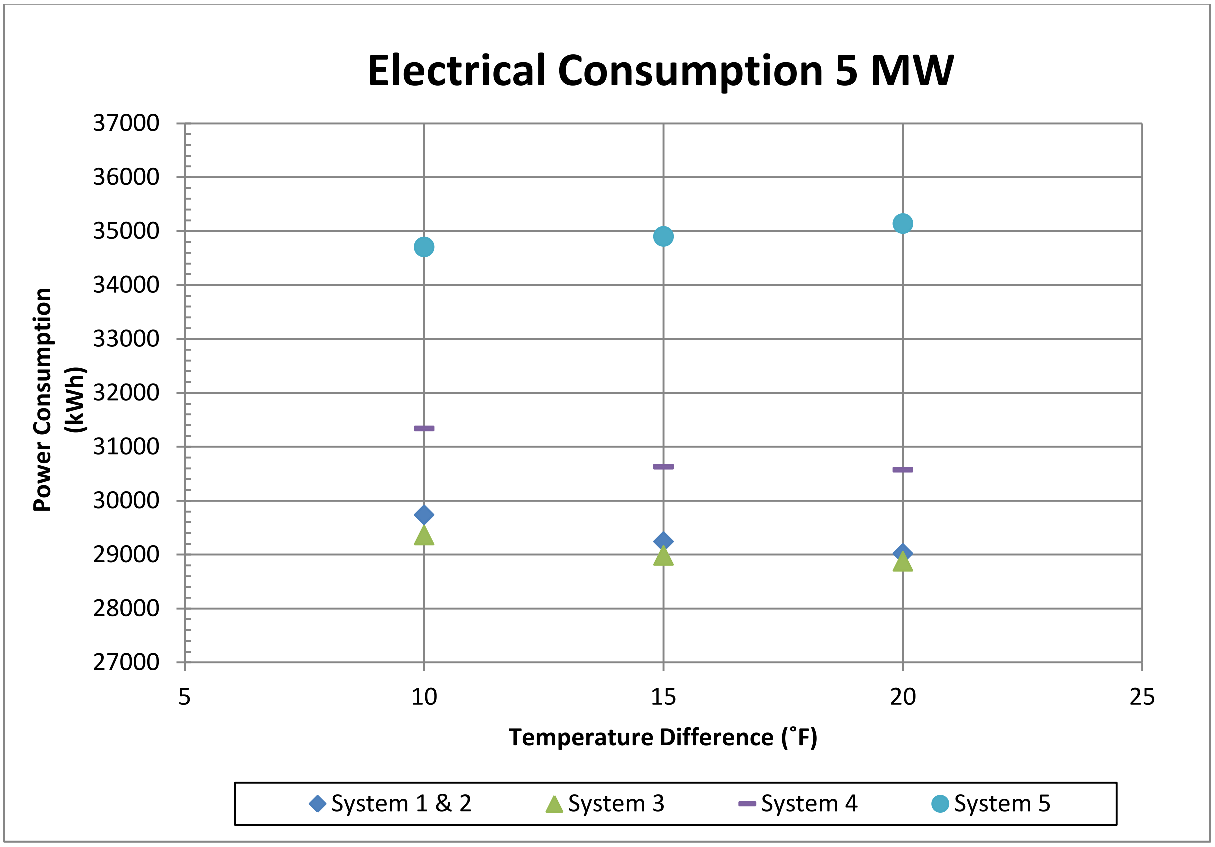

Figure 4-3 Electrical Consumption for 5 MW peak cooling load

For further review of the large systems, additional information is provided in Appendix B -. From the electrical power analysis we can see that the chilled water systems were the most efficient in conserving energy. Not only during the recharging portions of the simulations, but also during the regular operations of each system. While the layouts had some effect on the systems' power consumption, the differences were minimal (1 to 2%) of each other. The simulations provide guidelines for which systems are the most energy efficient. There were several assumptions addressed in the previous section that should be taken into account when estimating a new emergency cooling system. The power consumption for each system will vary with location, operation, and maintenance.

CHAPTER 5 - BENEFIT-TO-COST RATIO

The total costs of each system has been identified and will now be used to compare what kind of savings one might incur if they would have installed a TES tank instead of a traditional backup power supply. The primary economic decision measure-of-merit used in the public sector is the benefit-to-cost (B/C) ratio. This measure is calculated as a ratio of the equivalent worth of the benefits of investments in a project divided by the equivalent worth of costs. The B/C ratio is used to evaluate both single investments and sets of mutually exclusive projects and can be computed using the following equation (Newnan, Eschenbach, Lavelle 2004 and Park 2007),

$$B/C-Ratio = \frac{\text{Equivalent worth of net benefits}}{\text{Equivalent worth of costs}}$$

For this case we intend to use the conventional cost-to-benefit ratio analysis. When computing the B/C ratio, we will take into account the displaced cost of backup electrical power, the possibility of redundant power systems, and the maintenance cost. Below in Table 5-1 is the cost estimation for a backup generator which includes the present worth capital and maintenance costs over a 20 year period at an interest rate of 5.00%. The costs for these systems were developed from the RS Means Cost Works (2009) website as well as field engineers (Small 2009, Frankenfield 2010, Sorell 2010). To use the previous section's costs as a comparison basis, the assumption is made that during an outage the electrical use by the pumps and motorized valves for the TES tanks will be minimal. The pumps and valves electrical needs will be met by the building's main generators surplus and would not warrant the purchase of additional backup power to run less energy intensive components in comparison to the chiller.

Table 5-1 Backup Generator Cost for Emergency Cooling

	Generator Initial Costs	Installation	Maintenance	Total
1 MW	$124,965	$17,760	$40,378	$183,103
5 MW	$621,435	$88,800	$201,888	$912,123
15 MW	$1,862,610	$266,400	$605,663	$2,734,673

For this analysis, the benefit is the cost of the backup generator minus the cost of an emergency TES tank system being installed. Therefore, the benefit will be the savings created by switching to a TES emergency cooling system instead of a backup power supply system. The cost portion of the ratio is represented by the cost of the backup cooling system; which for this case will be the detailed cost average of each emergency cooling system calculated in CHAPTER 3 - . It should be noted that for the 15 MW peak cooling loads, system 1 was not included due to the fact that pressurized tanks become uneconomical for large systems. Using an average cost for each of the TES systems, a B/C ratio for each cooling load was calculated. Table 5-2 below is a matrix that organizes the average cost of each system and the resulting B/C ratio.

Table 5-2 Benefit to Cost Ratio for Various System Layouts and Cooling Loads

	1 MW				
Systems	1	2	3	4	5
Average Cost	$119,536	$123,842	$130,489	$142,194	$117,891
B/C Ratio	0.532	0.479	0.403	0.288	0.553

	5 MW				
Systems	1	2	3	4	5
Average Cost	$591,169	$381,304	$387,951	$541,923	$469,000
B/C Ratio	0.54	1.39	1.35	0.68	0.94

	15 MW			
Systems	2	3	4	5
Average Cost	$602,882	$611,843	$1,265,597	$1,351,259
B/C Ratio	3.54	3.47	1.16	1.02

From the tables we can see that for a 1 MW cooling load, the pressurized and ice storage TES tank systems would be the most cost effective regardless of the temperature difference across the thermal load. The pressurized tank offer the same tank size as an atmospheric tank, however the controls and maintenance for such system are less. The ice storage system benefits from the high energy density of ice which allows for smaller tank sizes and less initial capital costs. The chilled water storage system was also more cost effective than a comparable UPS backup power supply system. The LTCW system (System 4) is also more cost effective than a comparable UPS system due to the smaller backup power systems that only require power for the pumps and control devices. Figure 5-1 provides an overview of the different peak cooling loads and their perspective B/C ratio is when compared to the design UPS backup system.

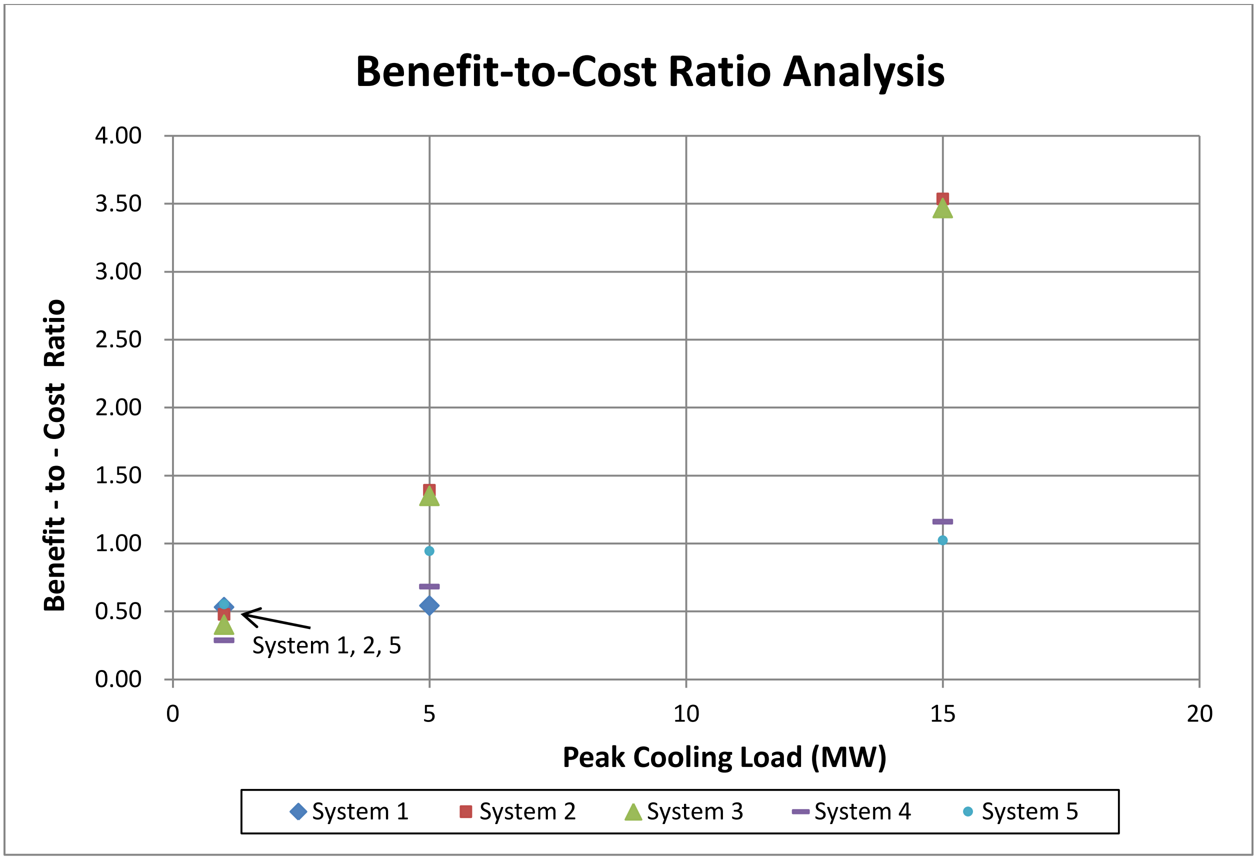

Figure 5-1 Benefit-to-cost ratio analysis for various peak cooling loads

An interesting point to be made is that regardless of the emergency cooling system, all TES cooling systems were more cost effective to the end user than a traditional back power supply. As the cooling load is increased to 5 and 15 MW, the chilled water systems utilizing atmospheric tanks for emergency cooling become the most cost effective method. For the 5 MW systems, the chilled water tanks become the most economical choice due to its low \$ / ft^3 at larger peak cooling loads. As the peak load is increased to 15 MW it become more apparent that using chilled water to provide emergency cooling will be the best solution for meeting emergency cooling demands.

The previous section discusses alternatives for new construction regarding emergency cooling. It is also important to look at possible retrofit projects that could save the end user money over the long term, depending on the age and maintenance expectations of the current operation systems. The following guidelines provide designers with simple indicators for the systems that are best suited for new and retrofit installations.

(1) For a B/C > 0 a TES system would be more cost effective than installing a similarly sized UPS backup system for a new project. From the table we can see that as the systems become larger traditional UPS batteries and generators can be almost three and half times more expensive to install and maintain over a 20 year period than a chilled water TES tank.

(2) For a B/C > 1, a TES tank should be considered for a retrofit projects since it will effectively pay for itself. This should only be considered for larger systems since the margin is much higher, and the operator would be able to save on maintenance and operations costs over the following years. A detailed study should be performed to identify the future maintenance costs of the existing system as well as the future needs.

Something to take into consideration that is not incorporated into the costs are the operational costs of such systems. Typically UPS systems will require that the generators be run at a minimum of once per month over a 12 to 24 hour period. Housing batteries requires temperature controlled environments to prevent premature battery degradation and corrosion. For a TES tank, chilled water systems need to be monitored regularly and typically should be flushed out and refilled approximately once per week. For ice storage systems the tank should also be closely monitored and is typically flushed and recharged every one to two weeks. For both UPS and TES tank systems, the operation costs will depend heavily on the application and the user’s discretion.

While the above costs provide simplified guidelines, each site is very specific and should be treated as such. While the chilled water system might be the most cost effective means for providing emergency cooling for a 15 MW peak cooling load, the amount of space needed to install such a system is considerable. The property cost for the area might make up a significant part of the costs and then a smaller ice storage system might be the best choice. Assumptions were made in this analysis that might not necessarily be the exact same for every case. However, from the detailed cost analysis, it is reasonable to split the systems into the following three groups,

- Low Cooling Load Applications (1 MW)
    - Pressurized Chilled Water TES Tank
    - Ice Storage TES Tank
- Medium Cooling Load Applications (5 MW)
    - Atmospheric Chilled Water TES Tank

    - Ice Storage TES Tank
- High Cooling Load Applications (15 MW)
    - Atmospheric Chilled Water TES Tank

CHAPTER 6 - Conclusion

The research and analysis conducted for this project was successful in identifying possible alternative emergency cooling systems that are both cost effective and reliable. By conducting a detailed cost analysis from existing TES tank layouts, a set of guidelines and generalizations were made. The detailed cost and electrical information developed from this research will help in the aid of installing and optimizing reliable emergency cooling methods using TES tanks.

From the information gathered in Chapter 2, it is easy to see the applicability of using TES tanks for emergency cooling applications. The research provided information regarding the advantages and disadvantages of each system and how they would be best suited to provide emergency cooling for a wide array of cooling load applications. The following are key points identified during the research to be utilized in the development and sizing of the components for each of the various TES tank cooling methods:

Chilled water and LTCW:

- A well stratified tank with internal flow diffusers provide the most cost effective method for maintaining a well defined thermo cline layer within a chilled water TES tank.
- Pressurized TES tanks require less flow control devices and piping than unpressurized tanks, however the maximum tank sizes are limited to 40,000 to 50,000 gallons.
- Chilled waters energy density for temperature differentials of 10 to 20 °F is between 11 – 21 ft^3 per ton hour.
- A chemical additive must be added to LTCW systems to prevent mixing within the tanks due to waters change in density at 39.2 F.
- Chilled water systems lose 10% of their cooling capacity due to internal/external heat gains and the thermo cline layer.
- Atmospheric tanks are best suited for larger peak cooling loads while pressurized tanks are most cost effective for smaller peak cooling loads.

Ice storage:

- From the ice storage TES systems, external melt systems are best suited to provide emergency cooling for short durations (1 hour or less) due to the high flow rates that are required.
- Internal melt storage systems are better suited for applications with longer discharge times of 2 hours or greater.
- Recharge times for ice storage units range between 7 to 9 hours depending on the application.
- Ice storage TES tanks high energy density allow for smaller systems to be installed, utilizing approximately 2.8 ft^3 per ton-hour.
- External melt TES systems are unpressurized systems that require complex control mechanisms and piping.

Each of the TES systems provided distinct advantages for different sized applications, which was the basis for selecting various peak cooling loads. By selecting a 1, 5, and 15 MW peak cooling load, a broad spectrum of detailed costs and power consumption results could be analyzed to determine which systems were the most cost effective and energy efficient. The information reviewed showed that chilled water, LTCW, and external melt ice systems were operational and economically the most cost effective means for providing emergency cooling for this study. TES systems utilize a series and parallel system configurations to provide cooling to an existing system. From the three identified TES methods (chilled water, LTCW, external melt ice) a set of five systems was developed, incorporating the key design points and parallel/series configuration to examine the detailed costs, power consumption, and benefit to cost ratio. The following is a list of the five systems identified and examined for analysis for reference:

System 1: Chilled Water Parallel Pressurized TES Tank, Two Pumps
System 2: Chilled Water Parallel Atmospheric TES Tank, Two Pumps
System 3: Chilled Water Series Atmospheric TES Tank, One VFD Pump
System 4: Low Temperature Chilled Water Parallel TES Tank, Two Pumps
System 5: Series Ice Storage Tank, One Pump

The RS Means website (RS Means Cost Works 2009) was used to provide accurate and up to date capital, installation, and maintenance costs for many of the systems studied. Several external sources from reputable vendors helped in determining what the current price points and design features were for TES tanks found in service to date around the world. By using this information, a system layout was developed and simulated on a computer program called TRNSYS (2009). The models provided estimates on system component capacities and power consumption for each of the system layouts.

The detailed cost analysis results were broken up into the various peak cooling loads with various thermal load temperature differences. For 1 MW peak cooling loads, the external melt TES tanks are the most cost effective at ΔT of 10 °F because of ices high energy density. For a ΔT of 15 °F and 20 °F at the 1 MW peak cooling load, pressurized tanks provide the most effective means for providing emergency cooling due to the reduced tank size and simplified control systems. For peak cooling loads of 5 MW, the external melt and atmospheric chilled water tanks are the most cost effective means for providing cooling at a temperature load difference of 10 °F. This is due to the high energy density of ice and reduced number of tanks required, while atmospheric chilled water tanks see a reduction in costs due to the larger sizing of the tanks. The chilled water tanks $ / ft^3 begins to reduce significantly when tank sizes exceed 200,000 gallons or more. For the 15 MW peak cooling load, chilled water tanks are clearly the most cost effective means for providing emergency cooling due to their low $ / ft^3 being much less than the external melt and LTCW system. The external melt and LTCW systems cost twice as much as a comparable atmospheric TES system for the 15 MW peak cooling load.

The simulations of the five systems through the use of the computer program TRNSYS (2009) provided valuable insight to designers and end users of TES systems. The results of the 1, 5, and 15 MW peak cooling loads followed similar trends in establishing which system consumed the most energy over a 24 hour operation. The power consumption between systems 1 and 2 were essential the same since there operation and configuration were only different in their control schemes. System threes simulation provides the end user with the lowest electrical consumption, followed by systems 1 and 2 which were with 1 to 2% of system 3.System 4 was within 6 to 8% of system 3 total power consumption and was due to the increased power consumption by the additional refrigeration unit that was used to chill the water below 39 °F. System 5 (External Melt) total power consumption was between 22 to 25% more than that of system 3. This increase in power consumption is attributed to the fact that the ice system operates below the freezing point, and the refrigeration unit's temperature lift increases which in turn decreases performance.

The B/C ratio analysis allowed for a direct comparison of battery UPS system and TES methods. From the estimations it would appear that for all peak cooling loads, a TES system would be more cost effective to install than a comparable battery UPS. For smaller loads, the margin of savings can range between 28 to 53%. For larger peak cooling loads of 15 MW the margin of savings ranges from 100% to 350%. This comparison provides designers with a basis for determining the most cost effective means for providing emergency cooling for various applications.

From the analysis listed above, a set of key points have been identified to help aid designers looking to provide emergency cooling using TES systems:

- Thermal energy storage tanks are a feasible option to provide emergency cooling to large and small systems. Several field examples to date have proven that TES tanks are reliable, clean, and efficient methods for providing emergency cooling.

- When installing TES tank systems it is important to determine what the peak thermal load is in conjunction with the temperature difference across the thermal load. For low load (1 MW, ΔT = 10°F to ΔT = 20°F) applications pressurized TES tanks and ice storage system will be the most cost effective method to provide emergency cooling. For medium load (5 MW, ΔT = 10°F to ΔT = 20°F) applications atmospheric chilled water and ice storage system will be the most cost effective. For high load (15 MW, ΔT = 10°F to ΔT = 20°F) applications atmospheric chilled water tanks will be the most cost effective.

- Besides the capital and maintenance costs of each system, it is important to take into account the transportation and site costs. For smaller applications were space is a luxury, ice storage systems might be more cost effective due to the higher energy density storage capacity when compared to a pressurized chilled water system. If the application has a large space allotted for the emergency cooling system then a pressurized or atmospheric tank might be a more economical choice.

- The electrical consumption for chilled water system will in general be lower than that of a low temperature chilled water system and external melt ice storage tanks.

According to the research and results, TES systems are a cost effective and reliable method for providing emergency cooling for small and large systems. Currently TES tanks are commercially used for load shaving applications to reduce the peak electrical loads when rates are the highest. A further study of TES tanks to be used in combination with emergency cooling and load shaving applications should be considered to determine the advantages and disadvantages of such a system.

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Appendix A - Detailed Cost Estimations

The following section provides a simplified break down of the costs for each of the components along with information concerning the individual parts description and source. As noted in the report, several external sources and TES tank manufactures were consulted to confirm accurate capital and maintenance costs.

Detailed Costs for 1 MW Systems

Storage 1 Components	1 MW D10		
Part	**Cost**	**Notes**	**Source**
25,000 Gallon Tank	$111,956	Tank structure	Equation Fit (External Contact)
Tank Equipment	$19,793	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$143,725**		

Storage 1 Components	1 MW D15		
Part	**Cost**	**Notes**	**Source**
20,000 Gallon Tank	$86,764	Tank structure	Equation Fit (External Contact)
Tank Equipment	$13,015	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$111,754**		

Storage 1 Components	1 MW D20		
Part	**Cost**	**Notes**	**Source**
15,000 Gallon Tank	$61,874	Tank structure	Equation Fit (External Contact)
Tank Equipment	$9,281	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$83,130**		

Storage 2 Components	1 MW D10		
Part	**Cost**	**Notes**	**Source**
25,000 Gallon Tank	$96,447	Tank structure	Equation Fit (External Contact)
Tank Equipment	$41,334	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$149,757**		

Storage 2 Components	1 MW D15		
Part	**Cost**	**Notes**	**Source**
20,000 Gallon Tank	$78,531	Tank structure	Equation Fit (External Contact)
Tank Equipment	$33,656	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$124,163**		

Storage 2 Components	1 MW D20		
Part	**Cost**	**Notes**	**Source**
15,000 Gallon Tank	$59,942	Tank structure	Equation Fit (External Contact)
Tank Equipment	$25,689	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$97,607**		

Storage 3 Components	1 MW D10		
Part	**Cost**	**Notes**	**Source**
25,000 Gallon Tank	$96,447	Tank structure	Equation Fit (External Contact)
Tank Equipment	$41,334	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$156,404**		

Storage 3 Components 1 MW D15

Part	Cost	Notes	Source
20,000 Gallon Tank	$78,531	Tank structure	Equation Fit (External Contact)
Tank Equipment	$33,656	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$130,810**		

Storage 3 Components 1 MW D20

Part	Cost	Notes	Source
15,000 Gallon Tank	$59,942	Tank structure	Equation Fit (External Contact)
Tank Equipment	$25,689	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$104,254**		

Storage 4 Components 1 MW D10

Part	Cost	Notes	Source
14,250 Gallon Tank	$57,152	Tank structure	Equation Fit (External Contact)
Tank Equipment	$26,204	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$51,425	Condensing unit, water cooled, compressor, heat exchanger, 60 ton, includes standard controls	RS Means
Maintenance (20 years)	$10,331	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$156,070**		

Storage 4 Components 1 MW D15

Part	Cost	Notes	Source
11,500 Gallon Tank	$45,974	Tank structure	Equation Fit (External Contact)
Tank Equipment	$21,083	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$51,425	Condensing unit, water cooled, compressor, heat exchanger, 60 ton, includes standard controls	RS Means
Maintenance (20 years)	$10,331	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$139,771**		

Storage 4 Components 1 MW D20

Part	Cost	Notes	Source
10,000 Gallon Tank	$39,778	Tank structure	Equation Fit (External Contact)
Tank Equipment	$18,248	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$51,425	Condensing unit, water cooled, compressor, heat exchanger, 60 ton, includes standard controls	RS Means
Maintenance (20 years)	$10,331	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$130,740**		

Storage 5 Components 1 MW

Part	Cost	Notes	Source
Ice Building Tank 11,000 kg ice	$96,601	Includes Ice Storage Tank, Refrigeration Unit , Installation, Foundation, piping	Equation Fit (External Source)
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	RS Means
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (196 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance Costs	$10,331	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$117,891**		

Detailed Costs for 5 MW Systems

Storage 1 Components	5 MW D10		
Part	**Cost**	**Notes**	**Source**
115,000 Gallon Tank	$589,698	Tank structure (2 x 50,000 gallon tanks, 1 x 15,000 gallon tank)	Equation Fit (External Contact)
Tank Equipment	$176,910	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$7,477	Tank Inspection, Water Treatment	RS means
Total	**$779,237**		

Storage 1 Components	5 MW D15		
Part	**Cost**	**Notes**	**Source**
80,000 Gallon Tank	$435,097	Tank structure (2 x 40,000 gallon tanks)	Equation Fit (External Contact)
Tank Equipment	$130,529	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$7,477	Tank Inspection, Water Treatment	RS means
Total	**$578,256**		

Storage 1 Components 5 MW D20

Part	Cost	Notes	Source
60,000 Gallon Tank	$310,296	Tank structure (2 x 30,000 gallon tanks)	Equation Fit (External Contact)
Tank Equipment	$93,089	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$7,477	Tank Inspection, Water Treatment	RS means
Total	**$416,015**		

Storage 2 Components 5 MW D10

Part	Cost	Notes	Source
115,000 Gallon Tank	$318,689	Tank structure	Equation Fit (External Contact)
Tank Equipment	$136,581	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$467,245**		

Storage 2 Components	5 MW D15		
Part	**Cost**	**Notes**	**Source**
80,000 Gallon Tank	$252,807	Tank structure	Equation Fit (External Contact)
Tank Equipment	$108,346	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$373,128**		

Storage 2 Components	5 MW D20		
Part	**Cost**	**Notes**	**Source**
25,000 Gallon Tank	$204,094	Tank structure	Equation Fit (External Contact)
Tank Equipment	$87,469	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$303,539**		

Storage 3 Components	5 MW D10		
Part	**Cost**	**Notes**	**Source**
115,000 Gallon Tank	$318,689	Tank structure	Equation Fit (External Contact)
Tank Equipment	$136,581	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$473,892**		

Storage 3 Components	5 MW D15		
Part	**Cost**	**Notes**	**Source**
80,000 Gallon Tank	$252,807	Tank structure	Equation Fit (External Contact)
Tank Equipment	$108,346	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$379,776**		

Storage 3 Components 5 MW D20

Part	**Cost**	**Notes**	**Source**
25,000 Gallon Tank	$204,094	Tank structure	Equation Fit (External Contact)
Tank Equipment	$87,469	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$310,186**		

Storage 4 Components 5 MW D10

Part	**Cost**	**Notes**	**Source**
71,500 Gallon Tank	$232,744	Tank structure	Equation Fit (External Contact)
Tank Equipment	$108,327	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$223,800	Condensing unit, water cooled, compressor, heat exchanger, 300 ton, includes standard controls	RS Means
Maintenance (20 years)	$15,665	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$591,494**		

Storage 4 Components	5 MW D15		
Part	**Cost**	**Notes**	**Source**
57,000 Gallon Tank	$195,393	Tank structure	Equation Fit (External Contact)
Tank Equipment	$90,580	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$223,800	Condensing unit, water cooled, compressor, heat exchanger, 300 ton, includes standard controls	RS Means
Maintenance (20 years)	$15,665	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$536,396**		

Storage 4 Components	5 MW D20		
Part	**Cost**	**Notes**	**Source**
47,500 Gallon Tank	$169,229	Tank structure	Equation Fit (External Contact)
Tank Equipment	$78,227	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	Equation Fit (RS Means)
Refrigeration Unit	$223,800	Condensing unit, water cooled, compressor, heat exchanger, 300 ton, includes standard controls	RS Means
Maintenance (20 years)	$15,665	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$497,879**		

Storage 5 Components 5 MW

Part	Cost	Notes	Source
Ice Building Tank 27,000 kg ice	$442,376	Includes Ice Storage Tank, Refrigeration Unit , Installation, Foundation, piping	Equation Fit (External Source)
8" Valve 3 Port Mixer	$5,806	Mixing valve, automatic water tempering, 8" size	RS Means
Pipe 40 ft	$4,384	Pipe, steel, black, welded, 8" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (196 ft of pipe in system)	RS Means
Pipe Insulation Cost	$768	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 8" iron pipe size, includes cover	RS Means
Maintenance Costs	$15,665	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$469,000**		

Detailed Costs for 15 MW Systems

Storage 2 Components 15 MW D10

Part	Cost	Notes	Source
345,000 Gallon Tank	$442,672	Tank structure	Equation Fit (External Contact)
Tank Equipment	$189,716	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$645,935**		

Storage 2 Components	15 MW D15		
Part	**Cost**	**Notes**	**Source**
230,000 Gallon Tank	$412,976	Tank structure	Equation Fit (External Contact)
Tank Equipment	$176,990	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$603,513**		

Storage 2 Components	15 MW D20		
Part	**Cost**	**Notes**	**Source**
170,000 Gallon Tank	$381,955	Tank structure	Equation Fit (External Contact)
Tank Equipment	$163,695	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
Maintenance (20 years)	$6,823	Tank Inspection, Water Treatment	RS means
Total	**$559,197**		

Storage 3 Components 15 MW D10

Part	Cost	Notes	Source
345,000 Gallon Tank	$442,672	Tank structure	Equation Fit (External Contact)
Tank Equipment	$189,716	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$654,896**		

Storage 3 Components 15 MW D15

Part	Cost	Notes	Source
230,000 Gallon Tank	$412,976	Tank structure	Equation Fit (External Contact)
Tank Equipment	$176,990	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$612,474**		

Storage 3 Components	15 MW D20		
Part	**Cost**	**Notes**	**Source**
170,000 Gallon Tank	$381,955	Tank structure	Equation Fit (External Contact)
Tank Equipment	$163,695	Foundation, Internals, Piping, Insulation	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Maintenance (20 years)	$7,664	Tank Inspection, Water Treatment, Valve	RS means
Total	**$568,158**		

Storage 4 Components	15 MW D10		
Part	**Cost**	**Notes**	**Source**
225,000 Gallon Tank	$411,224	Tank structure	Equation Fit (External Contact)
Tank Equipment	$203,239	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Refrigeration Unit	$648,225	Condensing unit, water cooled, compressor, heat exchanger, 860 ton, includes standard controls	RS Means
Maintenance (20 years)	$31,666	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$1,309,198**		

Storage 4 Components 15 MW D15

Part	Cost	Notes	Source
172,000 Gallon Tank	$383,290	Tank structure	Equation Fit (External Contact)
Tank Equipment	$184,907	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Refrigeration Unit	$648,225	Condensing unit, water cooled, compressor, heat exchanger, 860 ton, includes standard controls	RS Means
Maintenance (20 years)	$31,666	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$1,262,933**		

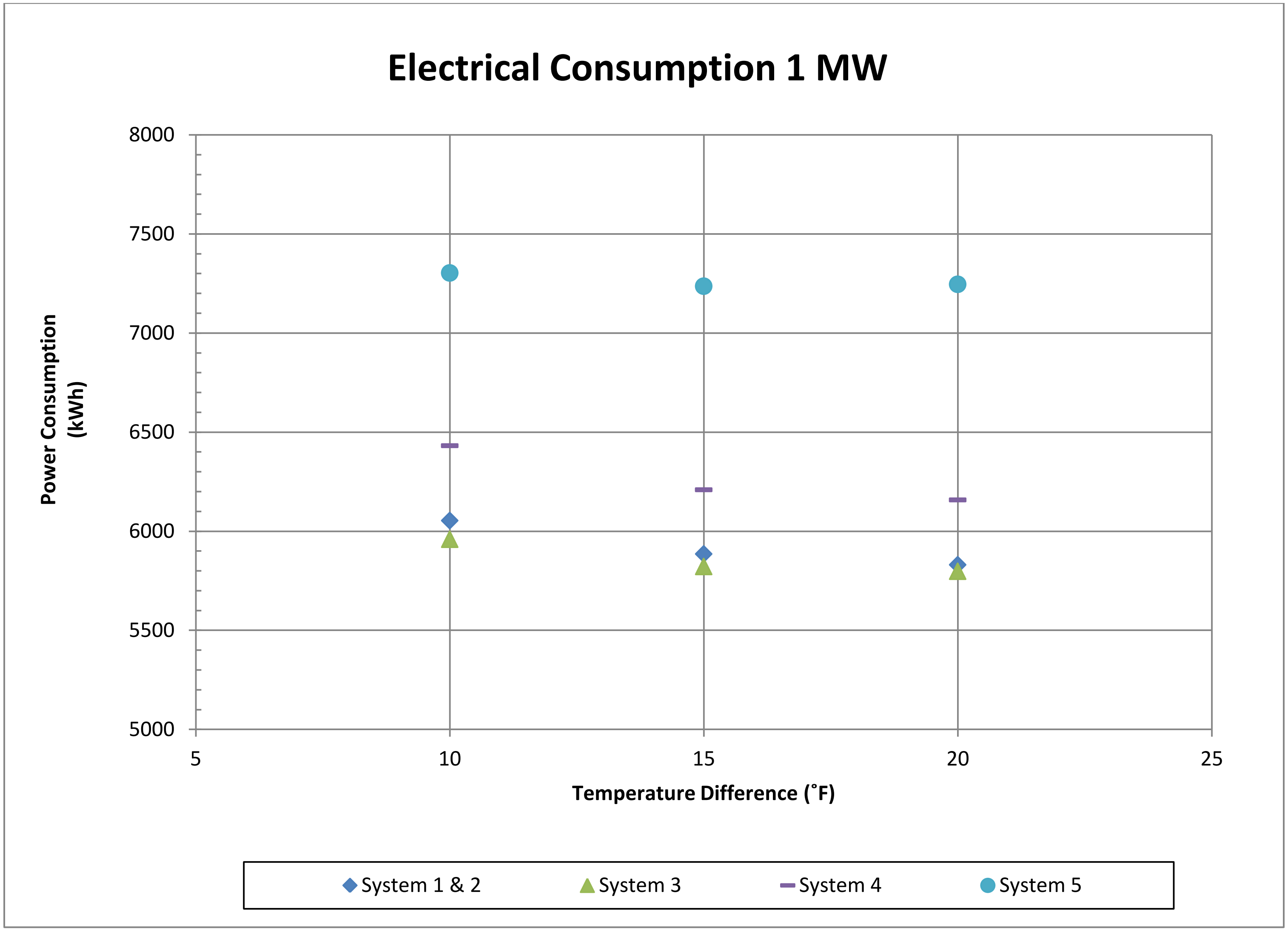
Storage 4 Components 15 MW D20

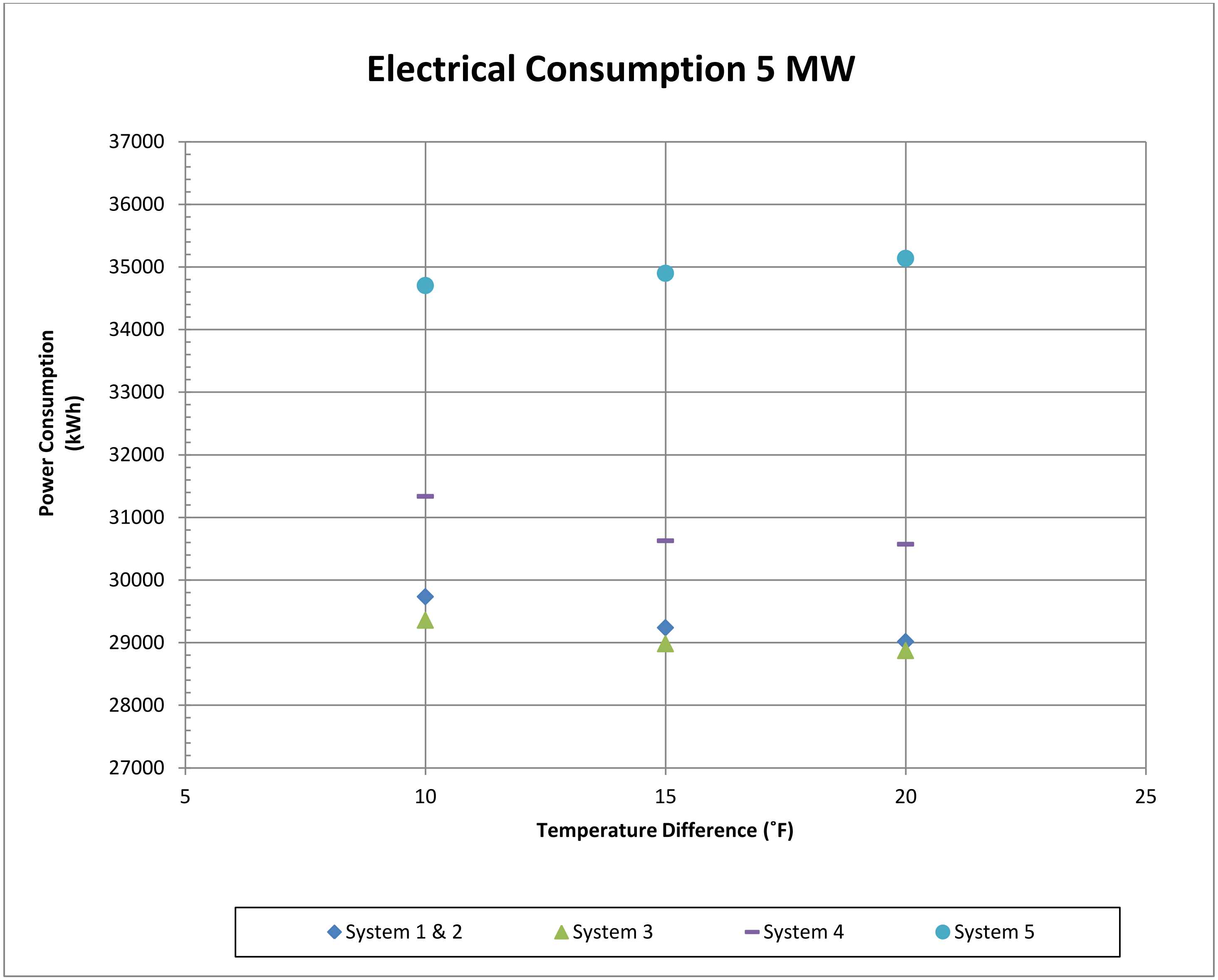
Part	Cost	Notes	Source
145,000 Gallon Tank	$358,768	Tank structure	Equation Fit (External Contact)
Tank Equipment	$171,158	Foundation, Internals, Piping, Insulation, Chemical Additives	Equation Fit (External Contact)
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (40 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	Equation Fit (RS Means)
Refrigeration Unit	$648,225	Condensing unit, water cooled, compressor, heat exchanger, 860 ton, includes standard controls	RS Means
Maintenance (20 years)	$31,666	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$1,224,661**		

Storage 5 Components 15 MW

Part	**Cost**	**Notes**	**Source**
Ice Building Tank 81,000 kg ice	$1,304,748	Includes Ice Storage Tank, Refrigeration Unit , Installation, Foundation, piping	Equation Fit (External Source)
10" Valve 3 Port Mixer	$8,120	Mixing valve, automatic water tempering, 10" size	RS Means
Pipe 40 ft	$5,802	Pipe, steel, black, welded, 10" diameter, schedule 40, Spec. A-53, includes yoke and roll hanger assembly, sized for covering, 10' OC (196 ft of pipe in system)	RS Means
Pipe Insulation Cost	$922	Insulation, pipe covering (price copper tube one size less than I.P.S.), calcium silicate, 1" wall, 10" iron pipe size, includes cover	RS Means
Maintenance Costs	$31,666	Refrigeration Unit, Tank Inspection, Water Treatment, Valve	RS Means
Total	**$1,351,259**		

Appendix B - Power Consumption Diagrams




Electrical Consumption 5 MW
Power Consumption (kWh)
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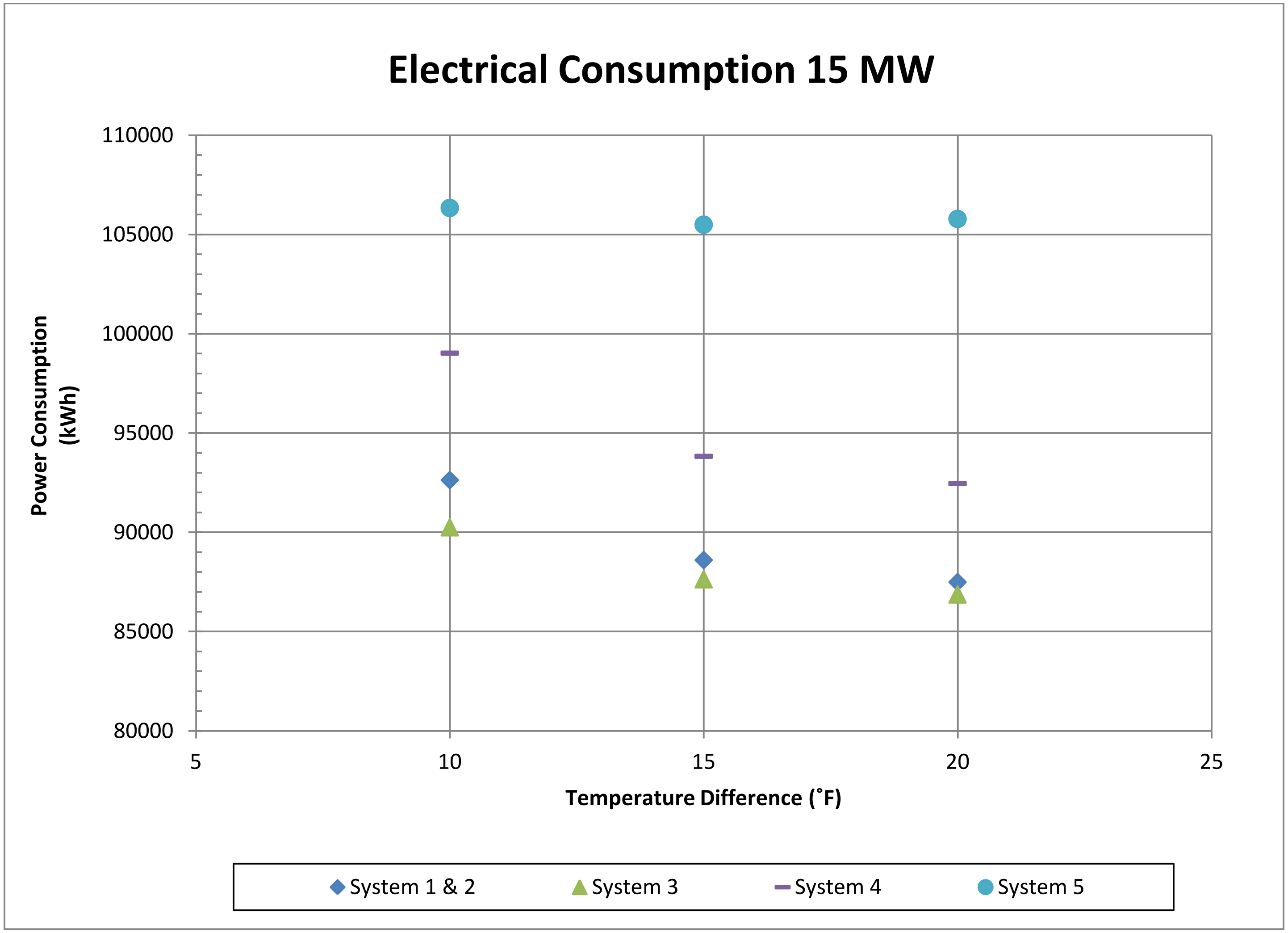
36000
35000
34000
33000
32000
31000
30000
29000
28000
27000
5
10
15
20
25
Temperature Difference (˚F)
System 1 & 2
System 3
System 4
System 5


Electrical Consumption 15 MW
Power Consumption (kWh)
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105000
100000
95000
90000
85000
80000
5
10
15
20
25
Temperature Difference (˚F)
System 1 & 2
System 3
System 4
System 5