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Tertiary Safety System for Nuclear Spent Fuel Pool

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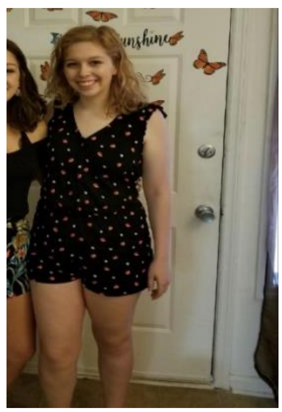

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Table of Contents

Tables

Figures

Overview and Goals

The spent fuel pool (SFP) in nuclear power stations serves to remove residual decay heat from recently burned fuel assemblies before the assemblies are removed and placed in dry cask storage systems. Although the decay heat is a fraction of the heat produced during normal operation in these spent fuel assemblies, the heat must still be continuously removed by pumping cooling water through the pool. If the heat is not removed, the assemblies will heat the surrounding water until it boils away exposing the assemblies to air followed by the individual rods heating up until they reach their thermal limits and fail. Once the spent fuel rods fail, the radioactive material can leak into the surrounding environment.

Cooling in the SFP is maintained during normal operations through pumps circulating the water. The water then passes through a heat exchanger to remove heat from the system. These pumps are able to operate under normal operation of the plant, but during a station blackout they become inoperable due to the lack of power.

The goal of this project is to design a system to maintain cooling to the spent fuel pool that can operate under on-site and off-site loss of power conditions (a station blackout). The system must be self-sufficient, while properly circulating and cooling the SFP water.

Introduction

A passive cooling system requires that cooling can be maintained without operator intervention; examples of passive systems include natural convection, backup systems, and natural and physical forces. In the event of a complete and prolonged station blackout, the reserve power system must be able to continuously circulate water from the spent fuel pool while removing the decay heat deposited in the pool from the spent fuel assemblies. The heat must be removed to prevent boiling and thus loss of water in the spent fuel pool. The spent fuel pool is usually kept at 60 °C during normal operation [1], but the goal of this project is to keep the spent fuel pool temperature below 100 °C for at least 3 days, based on the requirements of The Diverse and Flexible Coping Strategies (FLEX) [2].

Background information

The accident at the Fukushima Daiichi plant in 2011 highlighted the importance of maintaining cooling to the SFP of a nuclear power plant in the event of prolonged loss of power. During the accident, all six units were able to reach a safe shut down state diesel generators were used to remove residual decay heat from the core and spent fuel pool. However, two of the diesel generators for Unit 4 became inoperable due to flooding from tsunami waves that breached the flood walls of the plant, leaving the pumping system that cools the spent fuel pool without power. The lack of cooling in the pool (which had a full core offload during a refueling outage) caused the water temperature in the pool to rise from 27 °C to 75 °C [3]. Once powered cooling was restored, the pool temperature stabilized at 40 °C [3]. Although the SFP did not boil, this accident highlighted the spent fuel pool as an area of concern for future accidents with prolonged loss of power.

To address this area of concern, this project aims at developing a method to provide cooling to the water in an SFP during a loss of power accident for up to 72 hours. This includes designing an auxiliary power system to supply electrical power to the SFP pumps, or a method to maintain cooling without power.

Constraints and specifications

While investigating potential methods, several constraints and specifications are assumed. The first is that the designed system must be able to operate and keep the pool water below 100 C for 72 hours. This requirement is based on the FLEX system [2], which requires additional diesel generators and backup equipment to be brought on site within 24 hours. The 3 day assumption is a conservative estimate to ensure that the system would be able to adequately remove decay heat on its own without the SFP water boiling and exposing the spent fuel to air.

It is also assumed that 2 MW of power will need to be removed from the pool during the 3 days of system operation. This is based on the 2.2 MW of heat that had to be removed from the Unit 4 SFP at Fukushima Daiichi [3]. The assumption of 2 MW is intended to be conservative for the average amount of power in a SFP during normal operation.

The final assumption is that the pool is for Westinghouse 17x17 Pressurized Water Reactor (PWR) assemblies. This assumption is made because Westinghouse 17x17 is one of the most common assembly designs used in the US, so it will be the most representative of the current fleet.

Alternative designs

The first method explored was a condensing shield over the pool. If the water evaporated off the pool, the shield would be able to capture the water and condensed it back into the pool. There would be no power put into this process, but it requires that some of the water evaporates off, which needs to be avoided. It was assumed that the rate of evaporation would be greater than the rate of condensing. It was concluded that this would result in an ineffective cooling method for the SFP.

A second method considered was the use of the radiolytic hydrogen produced by the spent fuel within the pool to power a fuel cell and provide power to the SFP pumps. However, research into this method showed that the overall yield of radiolytic hydrogen was minimal and would not be enough to power the pumps needed to properly circulate the water in the SFP. To increase the yield of hydrogen, impurities would need to be added to the water. Although this would improve the system's performance, literature was unclear on how much it could be improved. The impurities also introduce additional regulatory concerns over the water composition of the SFP. In addition, the storage of hydrogen around the pool would be a hazard due to its explosive nature. Finally, the limited power production is slow and would be used with battery storage, making this system similar to regular battery usage. Therefore, this design was determined to be ineffective at meeting the goals of this project.

The final alternate method explored was geologic storage of natural gas. This process is already well established and would readily provide power for the pump. However, it could not be implemented into current plants, and would require favorable geology for new plants. Assuming a site could be built on one of these repositories, there is a risk of an explosion due to a gas leak, which could cause a fire and the release of nuclear material. This large safety hazard makes it an impractical solution.

The basis of the final design was to use thermoelectric generators (TEGs) to produce electricity and power the SFP water circulation pumps. TEGs use a temperature difference across the module to induce a current. The output current of a single TEG is small, but when wired in series, this current will grow linearly. TEGs are very small, around 25 cm^2, so many of them can fit into a specified area.

Initially, two different methods to get the required power output for the TEGs were considered: having the hot leg be the cladding of the fuel and the cold leg be the water of the pool or the hot leg be an aluminum raft on the pool surface and the cold leg be the air. After experimental testing of both these designs, it was found that TEGs could not produce sufficient power due to the temperature gradient being too small across them.

The final design selected was to utilize TEGs, along with a large ice block acting as a heat exchanger, to provide enough power to circulate the SFP water. The TEGs will be placed on the outside of the pipes (along the ice block), so that the hot side will be created by the water in the pipe and the cold side will be against the ice block. The temperature gradient is large enough to allow the TEGs to produce enough power to operate six 1 hp pumps, which provides sufficient mass flow of the SFP water to maintain the water temperature below 100 °C.

Standards: Include a discussion of potentially applicable standards for the design

All the standards used come from the U.S. Nuclear Regulatory Commission (NRC) Code of Federal Regulations (CFR). From appendix A, part 50.61 it states, "The fuel storage and handling, radioactive waste, and other systems which may contain radioactivity shall be designed to assure adequate safety under normal and postulated accident conditions." [4]. This is a reminder that while any work is done on the fuel pool, safety must remain the number one priority for normal and accident scenarios. The system designed will also assist reactor sites in meeting this regulatory requirement.

The most important regulations come from Regulatory Guide 1.155 (Task SI 5014), 3.2.4 [5], outlining how anything that will be added into the pool must, "cope with a station blackout for the required duration and recovery period should be addressed and evaluated as appropriate for the associated environmental conditions." Finally, 10 CFR Part 72 [6] describes how to handle spent fuel and other waste. Understanding exactly what can and cannot be done in the spent fuel pool designated what the design of the project could be.

Methods

The experimental methods used include building prototypes to test the possible output power of a TEG under various scenarios. This information is then used in the calculation of the required mass flow rate required to remove the 2 MW of power and the number of TEGs required to generate the power required to meet the mass flow rate.

Experimental procedure

In order to obtain an accurate value for power output per TEG, a single TEG was tested under similar circumstances. The first test was to replicate the TEG on the fuel cladding design.

A TEG was attached to a steel pan using thermal paste. The steel pan was heated up to represent the hot fuel. When the pan reached the desired temperature, it was filled with cool water to simulate the SFP water. The power output for this test was 0.18 W per TEG.

The second design tested was the raft design, in which the hot side is the pool water (with an aluminum layer holding the TEGs afloat) and the cold side is the ambient air of the SFP building. A sample raft was constructed using pipe insulation, aluminum foil, and skewers. This raft was placed in a pool of 95 °C water, with ambient air above. The TEG was attached to the top of the raft using thermal paste. Small heat sinks were placed on top of the TEGs to help cool the top side, while a large fan was helping to circulate the air above the TEGs and heat sinks. The power output for this design was 0.13 W per TEG.

The final design tested was flowing the SFP water through an ice block, such that the hot side of the TEG is the pool water (with an aluminum pipe between the water and TEG) and the cold side is the surrounding ice. To obtain a power per TEG for this design, it was attached to a piece of aluminum using a thermal paste. Ice was placed on top of the TEG to form the "cold side" and the aluminum was placed onto the hot plate to simulate the hot piping. The ice was partially melted, which is what the system would have in a realistic accident scenario. Under these circumstances, the power output from a single TEG was 0.5 W. This value was driving factor in choosing this design for the project and was carried through the rest of the design process.

Description of computational methods

There were three different methods which calculations were performed for. The first was using TEGs attached directly to the fuel assemblies such that the hot side of the TEGs is the fuel assembly and the cold side is the surrounding water. The second method examined was floating the TEGs on a raft on the surface of the water so that the hot side of the TEGs would be the water and the cold side would be the air. It was determined through these calculations and the power output obtained during experimentation that neither design was feasible. Therefore, the final design examined the use of a large ice block with pipes running through it and TEGs attached to the exterior of the pipes such that the water flowing through the pipes would be the hot side and the ice would serve as the cold side.

In the first two designs, the power need was calculated to be 15 kW; assuming that the system would utilize the existing cooling loops, with smaller 10 hp pumps added in parallel with the existing pumps to circulate enough water to keep the spent fuel pool from boiling.

The first design used TEGs attached to the fuel assemblies inside of the spent fuel. The most important number that is needed to be calculated is the temperature difference present across the TEG. This was calculated using heat output profiles from ORIGAMI [7] simulations. The ORIGAMI simulations were performed under the condition of the fuel being removed from the core for 300 days. This was done because the majority of nuclear reactors operate on 18 month or approximately 500 day cycles. Therefore, if the TEGs are placed on the most recently removed fuel, that fuel will be less than 500 days removed from the core. Using equation (1) below, and given the heat output from the ORIGAMI simulations, the delta temperature between the fuel assembly and the water was calculated to be about 2 °C.

$$Q = hA\Delta T \tag{1}$$

For this calculation, the heat transfer coefficient was assumed to be 1000 W/(m-K). This assumption is valid within an order of magnitude given normal heat transfer coefficient values for natural convection with water. The resulting temperature difference is not sufficient for TEGs to achieve the power output necessary even within an order of magnitude therefore this method was not pursued further.

The second option considered was that of floating the TEGs on a raft as stylized in Figure 1. For this design, the water can heat up close to boiling, put at 95 °C, and the air would be kept no higher than 30 °C. Because of this, a large temperature difference of greater than 60 °C can be achieved. A spent fuel pool has a surface area in the range of 100 m^2. This allows for an absolute maximum of 40,000 TEGs of size 5cm x 5cm. This number assumes full surface coverage with TEGs, which is unrealistic but will be used for consideration. From the power need listed above, each TEG in this design would have to output 0.375 W to be sufficient. Experimentation showed that the TEGs, could only produce 0.07 W each. By using high flow air fans blowing air across the heat sinks on top of the TEGs, this number was doubled, but is still well below the required power output needed. For this reason, this solution was not pursued further.

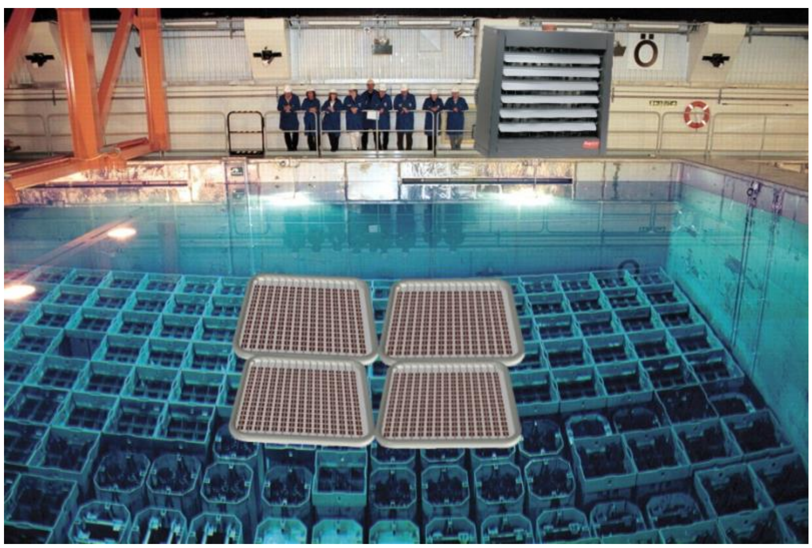


Figure 1: Rendering of TEG Raft Design

The final solution utilized a block of ice with piping running through it acting as both the heat exchanger, and the temperature difference source for the TEGs. This solution is depicted in Figure 2.

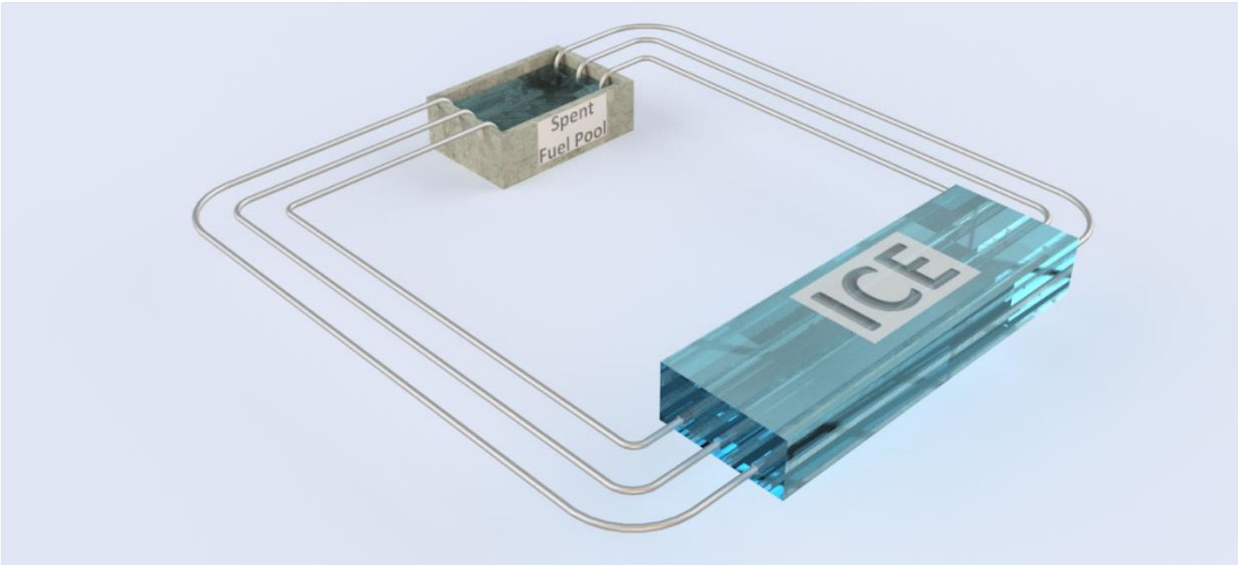


Figure 2: Rendering of Ice Block Heat Exchanger Design

Using the assumed heat load and the length of time necessary to provide cooling, the total energy needed to be removed from the spent fuel pool is calculated as 144,000 kWh. The mass of ice needed to provide this much energy in a heat sink can be calculated as seen below assuming that the ice completely melts, and the water is allowed to heat up to 20°C.

$$144{,}000\ kWh = \left(L_f + 20 * C_p\right)m \tag{2}$$

From this the mass of ice necessary was found to be 1.24E6 kg which is equal to 1350m^3. The dimensions used for the ice block in this project are 30m x 10m x 4.5m. The ice block is acting as a heat exchanger with hot water flowing from the spent fuel pool through the ice block and transferring that heat into the ice. The piping going through the ice block will be 5 cm square pipe so that TEGs can be fit along all 4 sides of the pipe. Given the length of piping traveling through the ice block is 30 m, and each TEG is 5 cm in width, 600 TEGs can be fit on each side of the pipe. This yields a total of 2400 TEGs per pipe. Assuming that the temperature of the water flowing through the ice block drops by 20 °C, the mass flow rate of water needed to flow through the ice block is found by equation 3 to be 23.8 kg/s which is equal to 377 GPM.

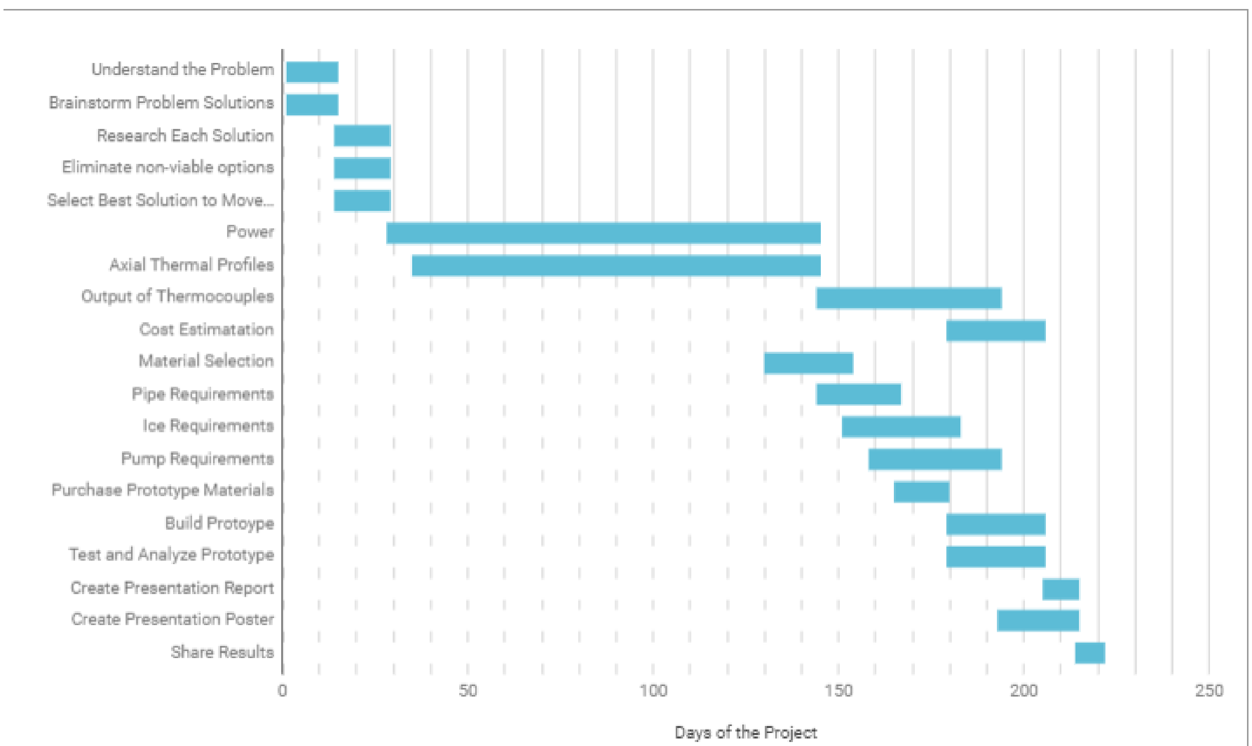
$$\dot{Q} = \dot{m} C_p \Delta T \tag{3}$$

Given that each 1 hp pump can provide 70 GPM of flow rate [8], 6 piping systems are necessary to adequately cool the spent fuel pool. Each TEG can generate 0.5 W of power as found through experimentation, which means that each piping system generates 1.2 kW of power which is self-sustaining as each piping system only requires 1 HP = 0.75 kW of power. In the 6 piping systems used to cool the spent fuel pool, 4.5 kW is required, and 7.2 kW are generated.

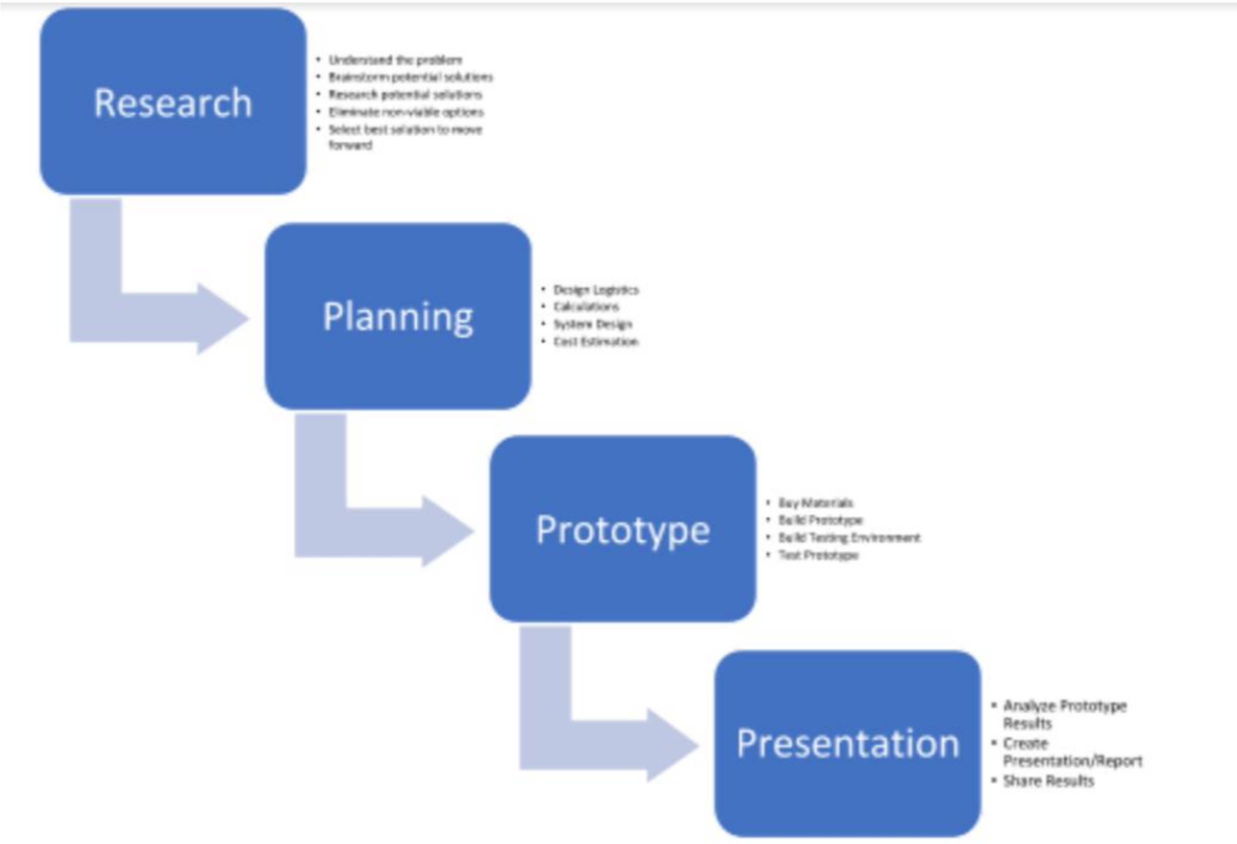
Work Breakdown Structure

Gantt Chart

TASK NAME	START DATE	DAY OF PROJECT	END DATE	DURATION (WORK DAYS)	DAYS COMPLETE	DAYS REMAINING	TEAM MEMBER	PERCENT COMPLETE
Reasearch								
Understand the Problem	9/18	1	10/1	14	14	0	All	100%
Brainstorm Problem Solutions	9/18	1	10/1	14	14	0	All	100%
Research Each Solution	10/1	14	10/15	15	15	0	All	100%
Eliminate non-viable options	10/1	14	10/15	15	15	0	All	100%
Select Best Solution to Move Forward	10/1	14	10/15	15	15	0	All	100%
Data (Calculations)								
Power	10/15	28	2/8	117	117	0	All	100%
Axial Thermal Profiles	10/22	35	2/8	110	110	0	All	100%
Output of Thermocouples	2/8	144	3/29	50	50	0	All	100%
Cost Estimatation	3/15	179	4/10	27	27	0	All	100%
System Configuratin								
Material Selection	1/25	130	2/17	24	24	0	All	100%
Pipe Requirements	2/8	144	3/2	23	23	0	All	100%
Ice Requirements	2/15	151	3/18	32	32	0	All	100%
Pump Requirements	2/22	158	3/29	36	36	0	All	100%
Purchase Prototype Materials	3/1	165	3/15	15	15	0	All	100%
Build Protoype	3/15	179	4/10	27	27	0	All	100%
Test and Analyze Prototype	3/15	179	4/10	27	27	0	All	100%
Presentation								
Create Presentation Report	4/10	205	4/19	10	10	0	All	100%
Create Presentation Poster	3/29	193	4/19	22	22	0	All	100%
Share Results	4/19	214	4/26	8	8	0	All	100%



PERT Chart



Cost estimate

The considerations for the cost estimate include the piping fixtures, the pumps, the ice block, and the TEGs. Aspects not considered in this cost analysis include the installation of the system and a refrigeration system to keep the ice block in tact during normal plant operation. All of the price estimates for piping were in English units, while all of the technical analysis was done in metric units. Therefore, the price needed is based on the closest converted measurement in English units to what was calculated in metric but rounded up to be conservative on pricing.

The piping for the design will use a square pipe of aluminum of 2.5" x 2.5" x 21' with a thickness of .125" cost a total of $189.84. There will be six square pipes used, so this cost will amount to $569.52. The remainder pipes that enter the pool and meet the square pipes will be rounded steel pipes 10' long with a radius of 2''. The needed length of pipe for the project will be 1200m or about 4000'. This total for the round piping will roughly be $22,500. The cost of each pump will be $730, totaling to $4,380 for the six needed pumps. The rough cost to produce the amount of ice needed would be $15,000 for 1.2 million kg. The TEG cost for 14,400 would be $250,000. The total cost for the build comes to $292,450.

Table 1: Cost Estimate Breakdown

Part	Unit Price	Quantity	Cost
1-Hp Pump	$ 730.00	6	$ 4,380.00
Square Piping	$ 189.84	6	$ 1,139.04
Additional Piping	-	1	$ 22,500.00
Ice Block	-	1,200,000	$ 15,000.00
TEG	$ 17.31	14,400	$ 249,264.00
Total cost			**$ 292,283.04**

Discussion of the Product

The designed system pumps water out of the SFP, through a block of ice then back into the pool. Inside the ice block, the square piping is covered in TEGs. The ice block is used as a heat sink for the pool water and as the cold side for the TEGs. The water inside the pipes serves as the hot side of the TEG. Based on the temperature difference between the pool water and the ice block, each TEG would be able to produce 0.5 W of power. By covering the entire length of the piping inside the ice block in TEGs, each pipe would be able to produce 1.2 kW of power.

In total, the system is designed to have six pipes to flow water between the pool and the ice block, based on the mass flow rate required to achieve the desired amount of cooling in the pool. Each pipe would be covered in TEGs inside the ice block, producing 7.2 kW in total.

The TEGs along each pipe would be wired in series, and then the pipes would each be wired in parallel to each other. This would allow for some flexibility in the power use. If an issue were to arise with one pipe's worth of TEGs, then the other five pipes would still continue to operate without issue, continuing to cool the SFP. All of the wiring would go to a central hub, so as to prevent the malfunction of one set of TEGs to prevent an entire pump from being able to operate. This wiring configuration would then allow the entire system to be self-sufficient and not require additional resources to maintain cooling to the SFP.

Conclusions and Future Work

The design and calculations of this project prove to be realistic from a physical perspective, while using conservative parameters. Future work on this project would require site-by-site logistics to be established. The location of the ice block, along with the piping lengths will all vary based on the plant-specific implementation of the system. No two systems would be identical from an appearance standpoint, but the physics and calculations of the system do not change.

In future analysis, the refrigeration system required to maintain the ice during normal operation would be designed. Some of the conservatives and assumptions used in this analysis could also be verified or refined to ensure the system is still able to meet all requirements.

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