Thermal Storage Solution for the Organic Rankine Cycle

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Restated Project Definition and Project Plan

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Abstract

As a customer, Verdicorp, a company that produces and sells Organic Rankine Cycle power systems, has asked us to build a thermal storage unit to extend the running time of their ORC system. It was requested that our design specifically take into account the location of the end user with regards to raw material procurement. This led us to pursue a sensible thermal storage method that could be tailored to the location by changing material mediums. Later in the project, our customer acquired a new patent on phase change material encapsulation and decided to refocus our efforts on a latent heat storage device that was previously considered in earlier reports. We have been tasked with developing an efficient way to take advantage of the geometry and thermal properties of the phase change material properties. In response our team chosen a new storage medium called Dynalene MS-1 and heat transfer fluid Duratherm HF. We've also chosen to use existing Shell-and-Tube heat exchanger technology to store and transfer energy by applying several variations.

I. Introduction

Presented In this report is our current understanding of the Thermal Storage Solution project. The goal of this project is to produce a functional scaled down version of a thermal storage device. Objectives for the final model include that the device display the potential to power Organic Rankine Cycle for up to four hours, ability to respond to energy needs as they're demanded of it, and produces costs at or below the target of 23 cents per kilowatt hour.

The need for thermal storage solutions is currently within a time of growth. As the use of intermittent sources such as solar increases so does this need. When these sources are no longer available power companies need thermal storage devices to continue producing energy. VerdiCorp's ORC is in need of such a device to continue providing the heat needed to produce electricity.

II. Project Definition

Background Research

With the human population growing at an exponential rate, energy demands will soon follow. As resources become scarcer it becomes apparent that energy demands cannot rely on fossil fuels. The world needs to simultaneously find ways to efficiently use the remaining fossil fuel deposits and develop renewable resources for future generations to rely on. Strides have been made to relieve ourselves from the grips of fossil fuels by building solar power plants, wind farms, using natural gas, bio mass, and even marketing electric cars. However, these sources are often intermittent in nature. For example solar plants are unable to produce energy at night. This implies a need for some type of energy storage so that plants can maintain consistent operation. Thermal storage stores excess energy while the renewable source is available and provides energy when the conventional energy source is no longer available.

The idea of thermal energy storage is simple and has been around for some time. No matter the method of thermal storage, the cycle is the same. The system is charged with thermal energy, the energy is stored for some time, and finally the energy is released. The earliest units may be dated to the 1890s when people used compressed air, flashing high temperature water into steam, and implementing water or steam storage tanks [1]. The problem with water is that it cannot retain the heat for very long, even in an insulated tank. Also, there is only so much heat the water can absorb. Therefore, if more heat needs to be stored more water is needed which means more space is needed. So by using water as a thermal medium the storage device is constrained in almost every way including space, amount of heat absorbed, and duration.

Phase change materials (PCM), is another common thermal storage medium. As heat is added the material approaches its melting temperature. As the material begins to change phase it is able to store more heat without increasing the temperature, given that the pressure doesn't go up in the enclosure due to the volume change. Additional heat also increases the amount of energy stored even after the melting process is complete [2]. What makes the process so unique is the fact that lots of heat may be stored in a material without much change in the material's temperature. This has benefits in areas where temperature control is critical. Many classes of phase change materials exist including inorganic, organic, and bio-based. The organic class stems from petroleum bi-products which are manufactured by major petrochemical companies [2]. For that reason, their availability could be limited and prices could vary. While these materials may be toxic, flammable and expensive they have a potentially infinite number of life cycles. The bio-based class contains organic materials that are naturally existing fatty acids such as vegetable oil. These products are non-toxic, non-corrosive and have infinite life cycles. However, they may be expensive and the risk for flammability increases with high temperature [2]. The inorganic class includes salts which are an engineered hydrated salt solution and deemed to be non-toxic, non-flammable and economical [2].

Recently, molten salts have become quite popular amongst the solar industry for its ability to be pumped as a liquid when hot enough and retaining heat for extended periods of time. Some estimate that solar thermal plants can keep running for six hours after the sun goes down [3]. The process is simple as stated before. The salts are melted or charged, stored in an insulated container

and when energy is needed again, pumped through a heat exchanger to warm the working fluid.4 These salts must be heated by an incredible amount before they turn to gas so the potential to store heat dwarfs that of water and also surpasses many oils. However, it still faces some of its own challenges, at least in the solar industry. The main challenge is optimization in this technology.

The problem with using molten salts as of now lies in the process for heating and storing the salts. Halotechnics is currently working on developing salts to store energy from any source of electricity [4]. Rather than building long expensive troughs as the only way to heat the salts, electricity may be used as a supplement which cut capital cost down. Terrafore Technologies is also trying to cut the price on molten salts by redefining how the heat is stored and dissipated all together. They plan on combining multiple materials together, all with different melting temperatures to cut the number of tanks needed, essentially leaving one tank for heat storage and one for the cold salts.[3] This would cut the initial capital cost of building a ecofriendly plant such as a solar one, which is always more appealing to investors.

Need Statement

A thermal energy storage solution is needed to increase the operation time, efficiency, and overall feasibility of Verdicorp's Organic Rankine Cycle power generator. Using waste or excess heat, the ORC is able to take advantage of a greater portion of the heat produced from intermittent sources to continually generate power. This process will reduce the required fuel needed for the same amount of energy production; after an input source has been depleted or turned off. This produces savings for the customer in fuel and energy costs, as well as reducing the production of any potentially environmentally harmful emissions from the system. The main storage component of the device will be provided by Verdicorp. This component is a patented encapsulated PCM storage cell. The optimal configuration using these cells must be designed to maximize the functionality of the overall system.

Goal Statement

Our aim is to produce a commercially viable thermal energy storage solution for Verdicorp's Organic Rankine Cycle using their patented PCM, environmentally friendly materials, and cost effective manufacturing.

Objectives

- To design and construct a functioning thermal energy storage unit prototype by April 2015, under the present day constraints specified below.
- Insure that said prototype is easily serviceable
- Produce power at 23cent per kilowatt hour
- Applicable in developing markets such as China
- Ability to supply extra power during times of peak operation
- Optimize the heat transfer and energy storage using the latent heat method provided

Project Challenges

While our overall goal remains the same, our project has undergone several changes since it began in August of 2014. The first of which was a change in location from Brazil to the Australian Outback. At the time our team was pursuing a sensible heat storage concept based on materials locally available at the location of the end user. This change to Queensland, AU forced us to reevaluate the materials that would be used in our design. While studying the mineral resources of the Outback we found an ore called bauxite that was commonly available throughout the region and possessed desirable thermal properties like such as high thermal conductivity compared to similarly priced options like concrete and granite. In our sensible storage concept, Bauxite would be used as our storage medium. Then in early December the project was subject yet another change. After acquiring a patent in phase change encapsulation Verdicorp directed the team to refocus on developing a latent heat storage concept. To address this change the team once again reevaluated the available storage materials. Our research led us to Dynalene MS-1 a molten salt that exhibited low corrosion on stainless steels unlike other options and a redesign of our storage device to take advantage geometry of the phase change capsules. The team has chosen to accomplish this by creating a variation of Shell-and-Tube Heat Exchanger, a pre-existing design.

While facing the challenges that come regularly in a dynamic industrial environment, the team has refined its process to pool our individual resources to gather and learn new research material. The team has also improved its design process by communicating design issues and discussing solutions as a group, while leaving individuals to specialize in specific areas of the design.

III. Constraints

A key to the success of the project will be the management of the various constraints that are inherent in the design, or that may arise during the design process. In order to optimize the productivity of the team these constraints must be constantly analyzed and reevaluated. The present constraints of the project are categorized by full and prototype scale:

For Thermal Storage Unit (Full Scale):

- Stores Heat for a minimum of 14 hours after heat input.
- Robust system-Corrosive resistant
- Resistant to high thermal cycle fatigue
- Serviceable and cost-effective maintenance
- Design must generate power at or below 23 cents per hour of power.

For Thermal Storage Unit (prototype):

- Maximum operating pressure: 50 psi
- Construction material: 80-20 alloy
- Must be mobile
- Design must be marketable
- Maximum budget for parts and materials: $2000

Performance specifications

- Must not heat the working fluid, R245, of the ORC to temperatures in excess of 170^{0}C
- Ability to deliver energy as demand dictates
- Extends the ORC's operation time by 14 hours when primary fuel source is no longer available (assuming the device is fully charged)

Prototype Design specifications

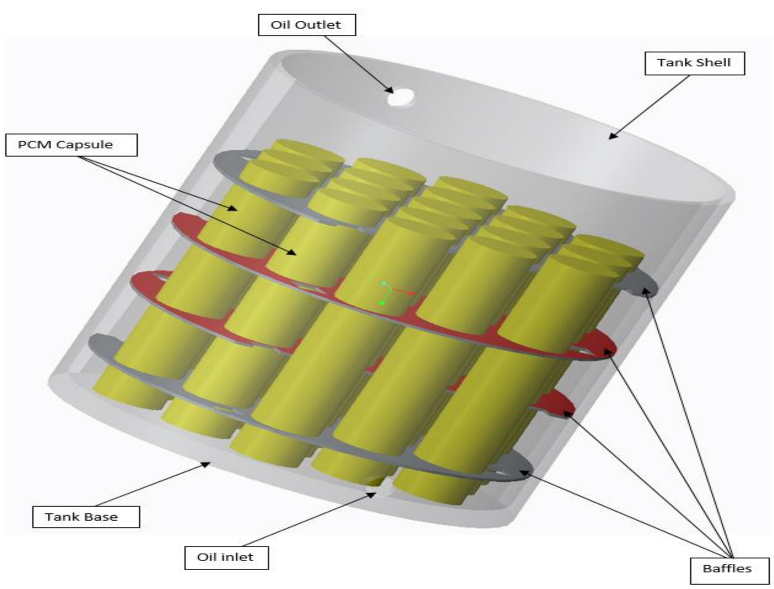

Figure 1: Shell and Tube concept

The energy storage material is a key component to the design, and after careful consideration and talks with our sponsor, it has been decided to implement phase change material as our storage medium. This material must be contained in an insulated environment and be capable of transferring energy with minimal losses and maximum heat transfer. The heat exchanger configuration and piping must be designed to optimize the energy control to and from the system. An example of a possible design is presented in Figure 1. The type of material and heat transfer configuration selected will determine the amount of heat that can be stored and the duration. The device must be capable of storing the thermal energy for at least 14 hours and consistently deliver the heat needed to generate power in the ORC system.

As previously stated in the prototype section, the PCM material will be contained in approximately 2" ID (inner diameter) & a 2.375" OD (outer diameter) cylindrical tubes about 1ft tall placed throughout the tank with baffles incorporated to allow the tank to act as a shell and tube heat exchanger. Shell and tube heat exchangers are often employed in industry in part for their serviceability but also because they maximize surface area while minimizing floor space which ultimately saves money. The idea is simple, one fluid flows through the tubes while another flows around the tubes in a direction dictated by baffles. Heat transfers from one fluid to the other by modes of conduction and convection. However, when it comes to actually designing the system it becomes quite complex as there are many variables to consider, each of which directly impacts strength of heat transfer, serviceability, and pump requirements. Examples of these variables include tube configuration, baffle cuts, and baffle spacing.

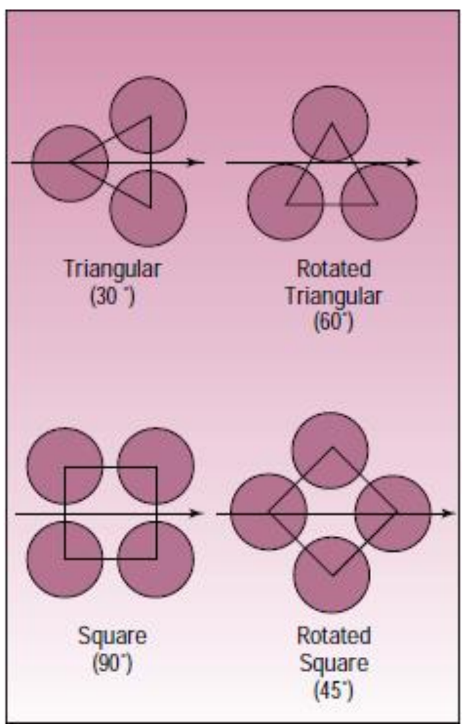

Figure 2: Pipe Configuration

Tube configuration is the most important when it comes to strength of heat transfer and serviceability. There are generally four types of configurations as seen in Figure 2. Keep in mind the space between each tube is dictated by the tube pitch. The tube pitch for triangular geometry is 1.25 times the OD of the tube while for square geometry it is 1.25 times the OD or the OD plus 6 mm, whichever is closer [5].

It should be noted that in Figure 2, the black arrow depicts fluid flow. According to this fluid flow, the triangular pattern offers the highest amount of turbulence and therefore the highest heat transfer coefficient. Not only that, but it also accommodates the greatest amount of tubes within a given space compared to the square pattern due to its geometry, which reduces space required which reduces capital cost. However, the downfall with the triangular geometry is that it is not easily serviceable due to the reduction of space between each tube. Square configurations are necessary when cleaning and serviceability is a major concern. The rotated square layout is used when Re<2000 to help increase turbulence and therefore heat transfer [5] Because of limited serviceability, triangular pattern is limited to applications where there is expected to be clean shell side operation or an operation that can employ chemicals to do the cleaning. As for the rotated triangular configuration, it does not offer as high a heat transfer coefficient as normal triangular and still possess the same problem when it comes to serviceability so therefore rarely employed.

For our application in particular, the shell side fluid will be the Duratherm HF heat transfer oil. The main concern when using oil as far as serviceability is the buildup of sludge. However, oil sludge can be treated with a variety of chemicals without the need of manual labor the same way it is treated in an automobile engine. After consideration of the pros and cons of each configuration and the materials of our design, it was decided that the triangular configuration would suit our needs best. It offers the best heat transfer coefficient, the smallest footprint, and manageable serviceability considering oil sludge can be treated with chemicals. For the sake of comparison, we will also test the rotated square configuration and compare charging/discharging times, space

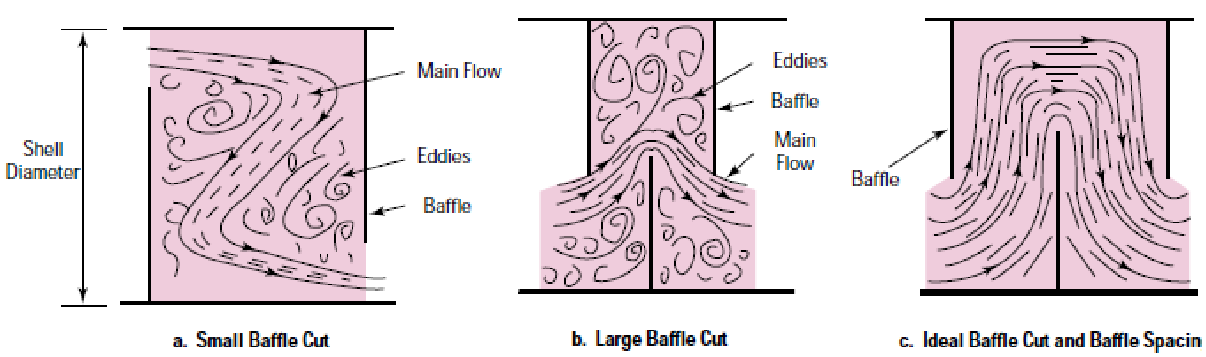

Figure 3: Examples of projected fluid flow for various baffle cuts and spacing.

required, and exit temperatures. The expectation is that the exit temperature for the triangular configuration will be higher than that of the square layout because the triangular layout offers a higher heat transfer coefficient. Now with a deeper understanding of how the fluid will interact with the tubes, it is now necessary to develop how the oil will flow through the entire tank. Fluid direction is dictated by the use of baffles, how they are cut, and how they are spaced. Baffles are vital in shell and tube design because the allow fluid to flow across tubes rather than parallel which increased heat transfer coefficient and cuts the length of the system down which reduces costs. Baffles are also important for supporting tubes so they don't sag and also to minimize vibrations induced on the tubes which become increasingly important as fluid velocity is increased. Figure 3 showcases examples of baffle cuts and spacing to demonstrate what works and what doesn't work.

As seen in Figure 3, pushing for small baffle cuts may increase heat transfer coefficient but will result in poor fluid distribution. The same may be said for having baffle cuts too big in an attempt to decrease pressure drop. The objective is seen in Figure 3(c). The more fluid moves, the better the overall heat transfer. The formation of eddies will lead to a less than satisfactory system with a lower efficiency than expected. Also having a disproportionate cut will lead to repeated acceleration and deceleration of fluid flow which is not as effective as constant motion in terms of pressure drop to heat transfer. It is recommended the baffle cuts are between 20% and 35% of the shell inside diameter [5]. We will employ a 30% to push for a balance of pressure reduction without sacrificing much heat transfer loss.

As far as baffle spacing, the Tubular Exchanger Manufacture's Association (TEMA) sets the minimum spacing to be a fifth of the shell inside diameter or 2 in, whichever is bigger [5]. Setting the spacing too small leads to more difficult cleaning and poor fluid distribution while spacing too large will lead to primarily parallel fluid flow which is less effective at transferring heat than cross flow. It is shown in a study that as baffle spacing is reduced, the pressure drop increases more rapidly than does the heat transfer coefficient. The optimum spacing is 30% to 60% of the shell inside diameter. We will employ a 40% spacing to balance pressure drop and heat transfer. In summary, our prototype will stand vertically with cylindrical PCM capsules oriented in a triangular patter for one test and a square pattern for a separate test with baffles cut to 30% of the shell inside diameter.

Prototype Sensors and Control

In order to determine if our system is working, temperature sensors will be placed before and after the thermal storage tank. Based on the outcome temperatures, modifications to the pump can be made to pull the oil through the tank slower or faster. Changing the flow of the oil will change the amount of time it is exposed or in contact with the PCM capsules. A flow meter will be used directly after the thermal storage tank and will be used with the temperature sensors to find the appropriate speed to successful transfer the correct amount of heat from the oil to the PCM and vice versa. All of these components must have a max temperature range of at least 200 ^{0}C. The typical flow in the system will be between 0.01 and 1.0 gallons per minute (gpm) and therefore a flow meter with these characteristics will be used. Finding controls and sensors that can operate at such high temperatures has been a challenge with the remaining budget.

IV. Project Schedule for January 1, 2015 – May 5, 2015

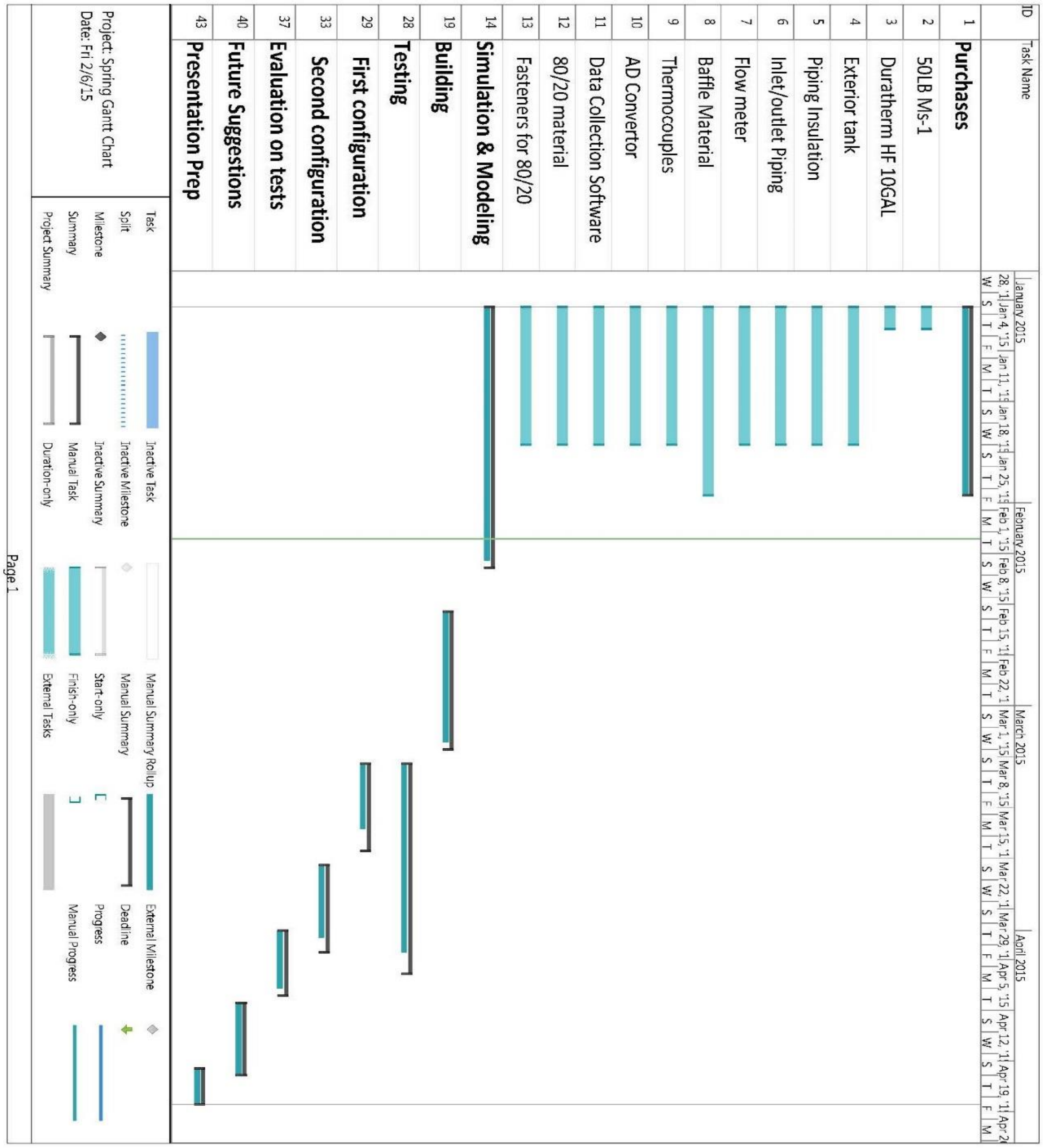

Figure 4: Gantt Chart

By setting short term goals our team will be able to assure our client of a product that meets their needs and is finished by the appropriate deadline. The Gantt chart, Figure 4, will help us complete these short term goals throughout the semester. It will also help us manage unforeseeable obstacles since our overall timeline for the project will be laid out. Any new tasks that need to be added will be done immediately in order to give our team as much time as possible to adjust to the changes. It is critical to the project to manage our time wisely and the Gantt chart will be our guide.

ID	Task Name	Duration	Start	Finish
1	**Purchases**	**20 days**	**Mon 1/5/15**	**Fri 1/30/15**
2	50LB Ms-1	3 days	Mon 1/5/15	Wed 1/7/15
3	Duratherm HF 10GAL	3 days	Mon 1/5/15	Wed 1/7/15
4	Exterior tank	15 days	Mon 1/5/15	Fri 1/23/15
5	Piping Insulation	15 days	Mon 1/5/15	Fri 1/23/15
6	Inlet/outlet Piping	15 days	Mon 1/5/15	Fri 1/23/15
7	Flow meter	15 days	Mon 1/5/15	Fri 1/23/15
8	Baffle Material	20 days	Mon 1/5/15	Fri 1/30/15
9	Thermocouples	15 days	Mon 1/5/15	Fri 1/23/15
10	AD Convertor	15 days	Mon 1/5/15	Fri 1/23/15
11	80/20 material	15 days	Mon 1/5/15	Fri 1/23/15
12	Fasteners for 80/20	15 days	Mon 1/5/15	Fri 1/23/15
13	**Simulation & Modeling**	**26 days**	**Mon 1/5/15**	**Mon 2/9/15**
14	Vertical Configuration	1 day	Sun 2/8/15	Sun 2/8/15
15	Horizontal Configuration	1 day	Sat 2/7/15	Sat 2/7/15
16	CAD Modeling	25 days	Mon 1/5/15	Fri 2/6/15
17	Submit Drawings to Verdicorp to begin cutting	1 day	Fri 2/6/15	Fri 2/6/15
18	**Building**	**14 days**	**Mon 1/19/15**	**Thu 2/5/15**
19	Create Capsules	14 days	Mon 2/16/15	Thu 3/5/15
20	Create Heat Exchanger	14 days	Mon 2/16/15	Thu 3/5/15
21	Weld bottom to tank	1 day	Mon 2/16/15	Mon 2/16/15
22	Cut Baffels	1 day	Mon 2/16/15	Mon 2/16/15
23	Frame for baffels	3 days	Mon 2/16/15	Wed 2/18/15
24	Connect pipes	1 day	Thu 3/5/15	Thu 3/5/15
25	Place capsules/oil in tank	1 day	Thu 3/5/15	Thu 3/5/15
26	Screw top on tank	1 day	Thu 3/5/15	Thu 3/5/15
27	**Testing**	**21 days**	**Mon 3/9/15**	**Mon 4/6/15**
28	**First configuration**	**10 days**	**Mon 3/9/15**	**Fri 3/20/15**
29	Test 1	2 days	Mon 3/9/15	Tue 3/10/15
30	Test 2	2 days	Fri 3/13/15	Mon 3/16/15
31	Test 3	2 days	Mon 3/16/15	Tue 3/17/15
32	**Second configuration**	**10 days**	**Mon 3/23/15**	**Fri 4/3/15**
33	Test 1	2 days	Mon 3/23/15	Tue 3/24/15
34	Test 2	2 days	Thu 3/26/15	Fri 3/27/15
35	Test 3	2 days	Tue 3/31/15	Wed 4/1/15
36	**Evaluation on tests**	**7 days**	**Wed 4/1/15**	**Thu 4/9/15**
37	Performance of first configuration	3 days	Wed 4/1/15	Fri 4/3/15
38	Performance of second configuration	3 days	Mon 4/6/15	Wed 4/8/15
39	**Future Suggestions**	**7 days**	**Sat 4/11/15**	**Mon 4/20/15**
40	Brainstorm how to improve	5 days	Sat 4/11/15	Thu 4/16/15
41	Present suggestions to sponser	1 day	Mon 4/20/15	Mon 4/20/15
42	**Presentation Prep**	**5 days**	**Mon 4/20/15**	**Fri 4/24/15**
43	Prepare board	3 days	Mon 4/20/15	Wed 4/22/15
44	Present	1 day	Fri 4/24/15	Fri 4/24/15

Figure 5. Project Schedule

As seen in Figure 5, our team will wrap up any final purchases by the end of January. We have already ordered the items with the highest lead times including the PCM, the oil, the tank, the thermocouples, and sheet metal for the baffles. We will promptly begin building when the materials come in which is estimated to be the middle of February. We begin testing after construction is complete which is estimated to be toward the beginning of March. While we wait for the material to come in we will evaluate each configuration using CAD and COMSOL to get some approximations of what kind of flow and temperatures we should expect. The schedule in Figure represents projected deadlines and actual undertaking of certain tasks may begin earlier than reported.

Procurement

Once the constraints and volume parameters were determined, mass and volume calculations were used to find how much salt and oil would be needed. After careful research, specific salts, DynaleneMS-1, and an oil, Duratherm, were found and the suppliers were contacted. Quotes were given for our required amounts of each product and orders were placed shortly after. More research and analysis will be done to determine how much piping and which fixtures we will need to order within the next few weeks. The remaining budget will be a huge factor when determining which suppliers to order from and which sensors will be absolutely necessary. Specialized welding will be form the desired tank shape and to create the PCM capsules. Verdicorp's skilled employees will play a huge role helping us with these processes.

For our thermal storage solution a budget was set at $2,000. From this $480 was used for the Dynalene MS-1 molten salt, and $442.84 was used for the Duratherm thermal oil. That leaves us with $1077.16 to spend on piping, insulation, sensors and controls, and other unforeseen purchases. After having the tank provided for us by Verdicorp, a large chunk of the budget can now be distributed elsewhere, like purchasing metallic plates for baffle material.

V. Conclusion

Utilizing all resources available to us, our group will design, create, and present a thermal storage solution to our customer. The materials used in this scaled down model will be chosen with three things in mind, cost, effectiveness, and accessibility. Each group member will be allocated specific tasks and the scheduling of those tasks will be managed using the Gantt chart in Figure 4. In the upcoming weeks materials research will be completed and appropriate materials for the selected thermal storage unit will be chosen. The selection process of materials and parts will depend on the available budget and how well they meet the design requirements. Our design process continues to be the "funnel" methodology. Once drawings are created and materials are ordered the manufacturing process will begin.

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