Thermal Storage Solution for the Organic Rankine Cycle

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Contents

Table of Figures

Tables

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Abstract- Our group has partnered with Verdicorp, a company that produces and sells Organic Rankine Cycle (ORC) power systems, to build a thermal storage unit to extend the running time of their ORC system. Group 17's current process to accomplish this task has been laid out in this finalized report. Up until this point our team has met with Verdicorp many times to better understand what they need from a thermal storage unit. Our sponsor informed us that our thermal storage unit will be used in the town of Birdsville, Queensland in Australia. In addition to this information we have selected a heat source with a maximum temperature of 275^{o}C will be provided from solar power or from the waste heat of diesel power generators that are already installed in the town. Once our group discussed which direction and concept we were leaning toward, we were able to research material properties, mainly thermal conductivity and heat capacity of the minerals in the surrounding areas of Birdsville. A final design, including a customized heat conducting brick containing the mineral bauxite, was chosen and drawn up using ProE. These bricks will form four long collection cells and will surround a pipe with a working fluid of mineral oil. These collection cells will each be 25 meters long and have an outer diameter of 2 meters. Many calculations were performed to determine the appropriate mass of each material in order to store the amount of energy needed. The total amount of energy needed is 860GJ allowing for 200MJ of energy escaping through losses. In the next couple of weeks our group will begin to order materials and continue to perfect the necessary drawings. Further modeling will be performed to ensure any possible reactions from heat addition are accounted for.

Introduction

Verdicorp has tasked us with creating a thermal storage device for use in conjunction with their Organic Rankine Cycle power generation device. An Organic Rankine Cycle is similar to a typical vapor cycle, however, rather than producing the heat, the Organic Rankine Cycle accepts waste heat as its heating source. Our device will retain excess heat from topping cycle for later use within the Organic Rankine Cycle which is the bottoming cycle. Contained within this report is the selected thermal storage concept and the reasoning behind this selection. This includes the reasoning behind why a sensible heat storage concept was chosen over its latent counterpart, the selection of the sensible materials to will be implemented within this concept, and the scale by which the full size device will be reduced by. These decisions were made with strong consideration of the customer’s needs and goals in order to provide Verdicorp Inc. with a commercially viable product. The temperature range from inputs to outputs will also be presented alongside the parameters that led the team to these choices. The report will also discuss the details of the interior design of the storage. This includes the testing and eventual proof of concept evaluation.

Background

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. 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. 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.

In relation to this project, Verdicorp has asked for the team to develop a thermal energy storage solution to help increase their production time and efficiency. They implement their Organic Rankine Cycle (ORC) units all over the world, particularly 3rd world areas to better production costs where resources are not readily available. By improving efficiency and allowing for extended running times, the company is able to increase the commerciality of the product and ultimately increase profits. The project location has been set to Birdsville, Australia. This is a small town in the state of Queensland with only a population of 283 people and is pretty much in the middle of the desert. To put it in perspective, Birdsville is roughly 29 driving hours away from Sydney which lies on the Eastern coast of the country. As you can imagine, trucking resources to Birdsville is not only a headache, but quite costly as well and so the need for energy independence is crucial to the electricity cost for the locals. This project has real world implications and if successful will be sold to the areas that desperately need it.

Need Statement

Thermal storage is needed to increase the operation time and thus the overall feasibility of Verdicorp's existing Rankine Cycle. By using heat, that might otherwise be wasted, to continually power the cycle the ORC is able to take advantage of a greater portion of the heat produced from intermittent sources thus requiring less fuel for power production. This trait also lends to the Organic Rankine Cycle's ability to function as a bottoming cycle. As a result the end user saves in fuel costs and reduces their environmental impact. By using less fuel the production of any potentially harmful emissions from the system is also decreased.

Goal Statement

Our aim is to produce a commercially viable thermal storage solution for Verdicorp's Organic Rankine Cycle using environmentally friendly and locally available materials.

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
- Specifically applicable to Birdsville, Au
- Ability to supply extra power during times of peak operation

Selected Design Concept and Parameters

Previously, sensible storage was chosen to be the most applicable form of storage for this particular application. Below in Fig. 1 is a schematic of the updated sensible concept. Although sensible storage will reach higher temperatures for the same amount of energy stored thus requiring more insulation, sensible storage was selected over latent storage because of its monetary savings in initial cost but also in consideration of future maintenance costs caused by the corrosive properties of the phase change materials that are used in latent storage. The availability of sensible storage materials also played a large role in this decision. Verdicorp's targeted markets for this device often include isolated areas such Birdsville Australia, located in the Australian outback, so it was a priority that replacement parts & materials should be easily portable or locally available. It was also determined that this was infeasible with phase change materials since no local sources were available in the surrounding area of Queensland Australia.

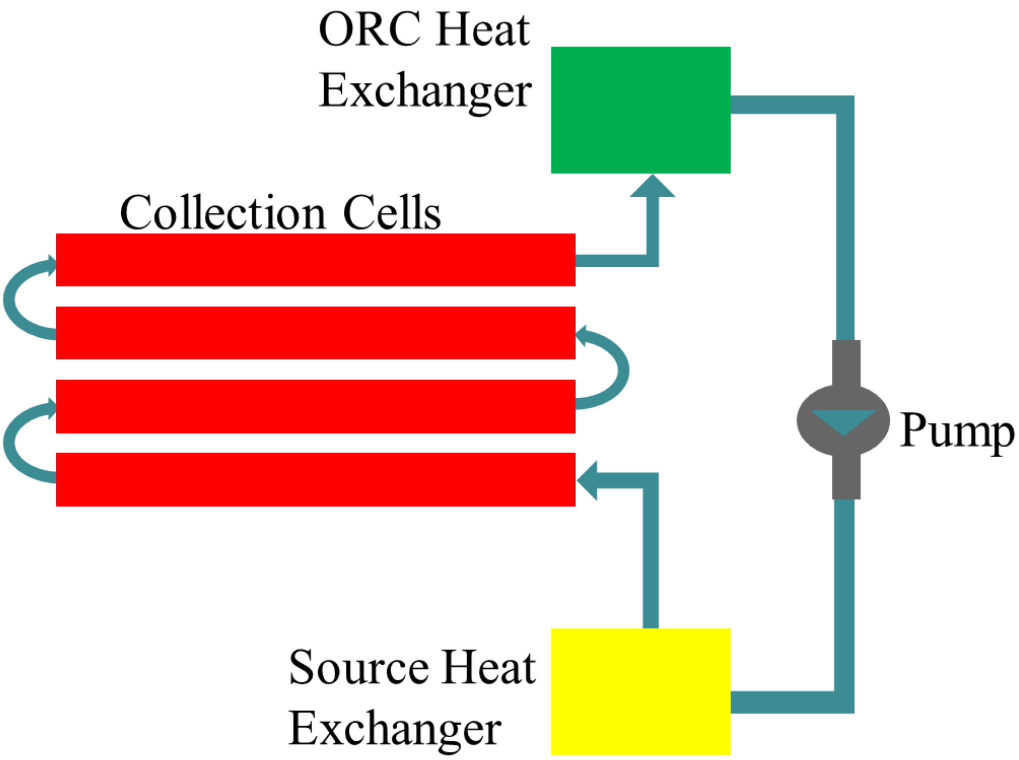


Fig. 1 Selected Concept Schematic

The selected concept in Fig. 1 was inspired by a solar parabolic trough heat addition system, the heat transfer fluid passes through blue pipe in Fig. 1 gaining waste heat from the heat source in yellow box representing the sources heat exchanger. The heat transfer fluid leaves the source at after reaching a max temperature of 275°C. The fluid then enters a system of collection cells shown in red. There the fluid sheds its excess heat into the four well insulated 25m long cells and drops the temperature of the fluid to an acceptable 200°C before entering the Organic Rankine Cycle heat exchanger. The excess heat is stored in the cells for later use. Flow through the system is controlled by the pump on the right. The flow of heat during the charging cycle is represented by the block diagram in Fig. 2.

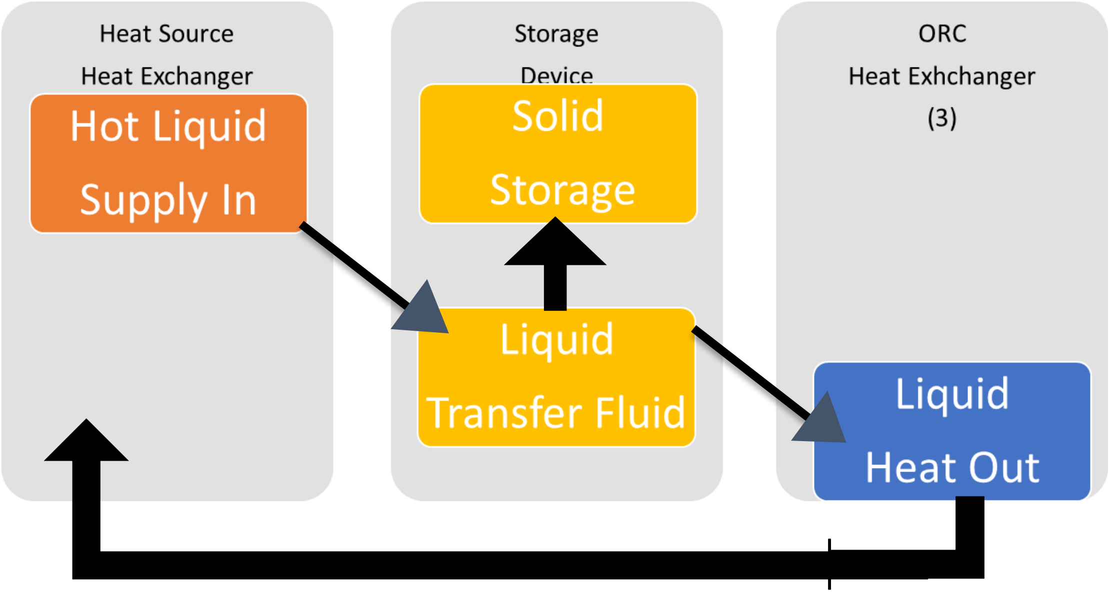


Fig. 2 Heat Flow Block Diagram

When the heat source is exhausted, the pump continues to circulate the fluid. The cold fluid enters the cells and gains heat from the excess heat stored earlier that day until reaching 200°C. After choosing the form of storage and concept, the team moved on to solid storage material selection i.e. the materials used in the collection cells. Table 1 below shows the decision matrix used to select the appropriate heat transfer fluid and input output selection.

Thermal Storage Material Selection

Table 1. Liquid Storage materials

Liquids	**Cost**	**Corrosivness**	**Temperature Range**	**Thermal Conductivity**	**Specific Heat**	**Total**
Mineral Oil	5	5	1	1	5	**157**
Synthetic Oil	2	5	2	1	5	**136**
Silicone Oil	1	3	4	1	5	**124**
Nitrate Salts	4	2	2	2	3	**118**
Carbonate Salts	2	1	5	3	3	**123**
Liquid Salts	2	1	3	5	3	**121**
Weight	**10**	**10**	**9**	**8**	**8**	

The heat transfer fluid at least twice the cost of the solid storage materials that will be discussed later. They are also the limiting factor on the range in operation temperatures since they are easily susceptible to degradation from high temperatures. Table 1 shows the basis by which Mineral Oil was chosen. Despite having higher temperature application ranges the salts corrosive abilities under minded the reliability of the system. The salts also came with higher costs. What set Mineral Oil apart from the other oils was its relatively inexpensive it was. Cost analysis placed Mineral Oil at $0.30 per kg while its closest competitor was over three times the price at $1.00 per kg. Having chosen the heat transfer fluid the temperature range during system operation could be determined.

Temperature Range Selection

Selected temperature output: 200°C
The selected temperature input to the Organic Rankine Cycle (ORC) was chosen to be 200°C. This temperature was chosen because the higher proposed temperatures may have caused part degradation within the ORC. The working fluid of the ORC was designed to vaporize at 150°C so parts were not designed to withstand temperatures in considerable excess to this temperature. Higher operation temperatures also put limitations on liquid storage materials that could be implemented in the thermal storage unit and led us to specifying the maximum inlet temperature of our storage device.

Selected temperature input: 275°C
Increasing the upper limit of the temperature input to the storage unit has significant benefits such as decreasing the amount of material needed for storage, but the drawbacks to increasing this temperature cannot be ignored. Like the output temperature selection the input selection plays a large part in determining the liquids that can be implemented within the storage device. As the temperature is increased the options for heat transfer fluid becomes limited to expensive and often corrosive heat transfer fluids such as liquid sodium. Ultimately, the output temperature was based on the liquid heat transfer fluid medium, Mineral Oil. By setting the upper inlet temperature to 275°C, a temperature well within the operational temperature of the Mineral oil, we were able to safely use the most cost effective liquid available among our list of considered choices. After choosing the liquid we moved on to selection of the solid storage mediums.

Table 2. Solid Storage Materials

Sensible Minerals	**Cost**	**Thermal Cycling**	**Thermal Conductivity**	**Specific Heat**	**Environmental Friendliness**	**Volume**	**Total**
Granite	4	2	2	3	4	2	**124**
Clay	1	1	1	4	4	2	**87**
Limestone	5	2	1	4	4	3	**137**
Iron Ore	3	3	5	2	2	3	**128**
Nickel	1	5	5	2	3	5	**134**
Bauxite	4	5	4	5	4	1	**174**
concrete	5	3	1	4	4	3	**144**
Weight	**10**	**7**	**8**	**8**	**6**	**3**	

Table 2 is comparison of several solids that were found to be readily available in Birdsville. This means that all of these solids are either excavated in the Queensland area or easily transportable to the area. Based on our criteria presented in Table 2 above, we have selected bauxite and concrete. Certain secondary costs will be considered in later evaluation but the material abundance of bauxite and its desirable thermal characteristics have placed this material as the front runner, while the low cost of concrete and its ability to be easily formed into complex geometries makes it a close second. To avoid the incursion of secondary costs in producing complex shapes with the raw bauxite it was decided that the two materials would be used in conjunction with one another. The two solid materials are shown side by side in Fig. 3. In the Brick Design section of this report, the specifics of how the solids will be combined will be presented.

Fig. 3 Raw Bauxite & Concrete Structure

Brick Designs

As shown in the material selection section of the report, it was decided that bauxite and concrete will be used in conjunction with one another to avoid the extra cost of creating complex shapes of bauxite alone. Compared to other mined minerals found deep in the Earth's crust like diamond, bauxite ores are usually found a little under Earth's surface as solid rocks and are sold in the form of pellets with a diameter close to an inch. Concrete should serve as the matrix to hold bauxite pellets together since it is easily formed. Many questions now remain as to how the two will be combined.

Although concrete is easily formed it is also very brittle. Cracks tend to occur frequently under the right conditions. Because the working fluid will be under some amount of pressure and high temperature, the fear is that cracks will form and repairs will become frequent. The overall collection cells will be approximately 25m in length and so having one solid piece of concrete wouldn't make any sense from a maintenance standpoint. In an effort to reduce maintenance costs and downtime, it was decided to design bricks of concrete that would connect together along the length of the cell as well as around the circumference of the cell. Therefore, in the event of a crack somewhere along the pipe, rather than replacing the entire collection cell only a few bricks would be replaced saving time and money.

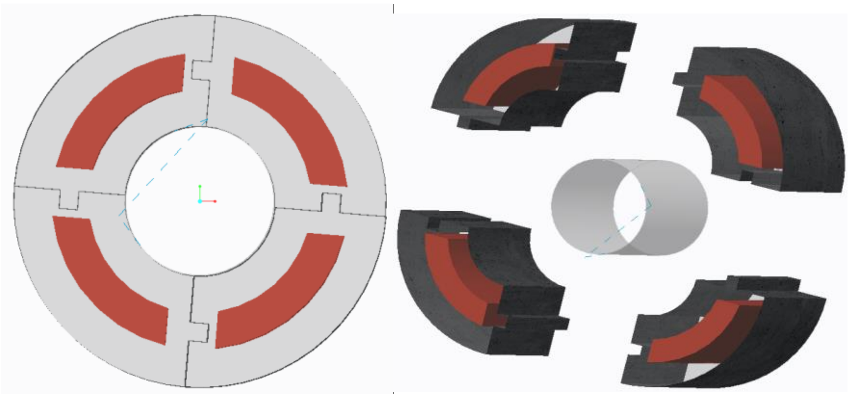


Fig. 4 Solid Material Storage Bricks composed of Bauxite & Concrete

Fig. 4 depicts a proposed brick design. The red shown in the Fig. symbolizes bauxite while the surrounding gray symbolizes concrete. The inner circle where the working fluid is projected to flow is designed to be 0.2 meters in diameter while the outer circle is approximately 2 meters in diameter. Bauxite has great conductivity and specific heat compared to other solids so the idea of concentrating that heat is quite appealing. However, this design has its flaws. Because the bauxite is in the form of pellets it needs to be contained. Having the bauxite sandwiched between two layers of concrete poses the threat of impeding heat transfer to the bauxite since concrete has relatively low conductivity. The charging time would take much longer compared to the bauxite coming into direct contact with the working fluid which may cause problems on days where charging time is limited. However, for those days where there is a long period of heat supply, it would be better to have this resistance layer to slow the heat transfer process because if the rate was too high and there wasn't proper temperature and valve control, the rocks could get dangerously hot, changing the properties of the material or worse, causing rapid degradation of the working fluid. Perhaps an alternative to having the bauxite concentrated in the middle of the concrete brick would be to disperse it throughout the entire brick. In the process of mixing the cement, the bauxite pellets could be used as an aggregate to the cement solution which would ultimately lead to a brick with the conductivity between that of concrete and bauxite. This is something that has not been done before to anyone's knowledge and so the properties and benefits of such concrete cannot be theorized and would need physical experimentation. It could, however, be the answer to a more thermally conductive concrete that the world is looking for.

The right of Fig. 4 exploits the bricks geometry and how they would all come together. The idea came from Lego blocks where one shape can make a museum of designs. By having one shape be the basis of the entire pipe, manufacturability and assembly of the system becomes much faster. The faster it goes up, the faster it can make money. One mold would be all that's needed and because its only cement, no real technical knowledge is needed to complete the mold. Remember this type of system would be implemented in rural third world areas. The ability to hire locals to create these molds is a major commercial selling point for many reasons. For one, the area is more welcoming of your product because it aids in creating jobs which is beneficial to the immediate economy of that area and the overall well-being of the locals. For two, Verdicorp wins because they won't have to pay these workers as much allowing them to hire more to get the job done faster. So you see there is a win-win for both parties. One flaw in this design is that the bricks would need to be connected in the axial direction which poses a maintenance problem after completion. Say for example a crack was found in a brick which happens to lie in the middle of the collector cell. There would need to be a more complex process for replacing that brick rather than simply plugging a new brick in that spot and moving on. There would need to be enough clearance space to allow room for a new brick to slide into the empty slot. The bricks themselves would also need to be light enough for removal by hand using one to two workers.

Overall, the materials make sense to choose for testing. The question is how will they perform together as a unit? To better the chances of success it was decided to test the two different configurations previously discussed. One as shown in Fig. 4 where the bauxite is concentrated in the middle of the brick and the other with the bauxite dispersed throughout the entire brick. The results will be compared with the conclusion of testing.

Analysis

Energy Requirements

A Major requirement of any energy storage device is that it be capable of storing the energy required of it. Taking the sum of energy added to storage from Table 4 in the Appendix provided by Verdicorp and multiplying it by the duration of time by which this rate of energy was added It was found that this device should be capable of storing up to 860GJ of energy. To evaluate whether or not our design was capable of storing this energy without reaching temperatures in excess of 200^{o}C Equation 1 was used. Where the excess energy stored was equal to difference between the amount stored and the amount required for storage.

Eq. 1 $E_{excess} = E_{Stored} - E_{Required}$

Eq. 2 $E_{Stroed} = m_{Bauxite} C_{pB} \Delta T + m_{concrete} C_{pC} \Delta T$

Equation 2[5] was defined as the amount stored energy stored in the Concrete and Bauxite combination. Energy stored is a solid sensible material is defined as the mass of that material times the specific heat of that material multiplied by its change in temperature. The change in temperature was from 23^{o}C to 200^{o}C. The upper temperature was set to 200^{o}C to prevent the fluid from reaching temperatures in excess of 200^{o}C when the charging cycle ended. Analysis found that our design yielded 200MJ in excess energy that could be lost to the environment.

Major Dimensions

The dimensions of solid portions of the collection cells were found based on the need to have enough mass to hold the required energy and have a thermal resistance low enough to dissipate the heat even when the heat added to the storage is at its highest rate to insure that the heat transfer fluid does not reach the Organic Rankine Cycle above the correct temperature. The inner pipe was set to be 0.2 meters in diameter and the subsequent layers of concrete, bauxite and concrete to be 0.3m, 1.6m, and 0.1m thick respectively. The overall resistance was modeled as the equivalent resistance of convection and conduction and assumed perfect contact. Sample Calculations can be found in the appendix. To reduce requirements on the thermal resistance, the heat transfer process was complimented by the systems pump system which is capable of controlling the exposure time between the heat transfer fluid and solid storage materials.

Pipe Requirements

In order to properly size the pump for the heat transfer fluid (mineral oil) the minimum pressure difference (head loss) through each collection cell must be computed. Using the designed material radius and volume dimensions, the minimum and maximum mass flow rate needed was computed, and approximated linearly with the use of Eq.3. Which is the ration of the heat transferred divided by the specific heat of the fluid times the temperature of the fluid. Where the minimum and maximum heat transfer was 310 kJ/s and 3613 kJ/s, respectively. Also considering the minimum and maximum temperatures of 423 K and 573 K, respectively. The approximated range of the mass flow rate is between 0.235 kg/s to 3.71 kg/s; using the maximum heat transfer and minimum temperature to get the maximum mass flow rate, and using the minimum heat transfer and maximum temperature to get the minimum mass flow rate of the working fluid.

Eq.3 $\dot{m} = \frac{\dot{q_{in}}}{C_P * T}$

Once the mass flow rate was approximated the velocity of the fluid through the pipes was calculated with the use of Eq.4, which multiplies the mass flow rate by the cross sectional area of the pipe by the density of the working fluid. This velocity is pivotal to controlling the heat transfer rate to and from the working fluid to the storage medium in the collection cells. With the velocity known, the dimensionless parameter of the Reynold's number can be computed, which tells if the flow of the fluid is laminar or turbulent. Fig. 5 shows a plot of the Reynold's number versus mass flow rate. A mass flow rate of around 2.5 kg/s is desired in order to keep the flow turbulent and increase the heat transfer rate. Fig.6 shows the relation between the temperature of the heat transfer fluid with mass flow rate, as the temperature of the fluid decreases the mass flow rate must be increased to maintain the energy input to and from the storage.

Eq.4 $\vec{V} = \dot{m} * A * \rho$

Eq.5 $R_e = \frac{\rho * \vec{V} * D}{\mu}$

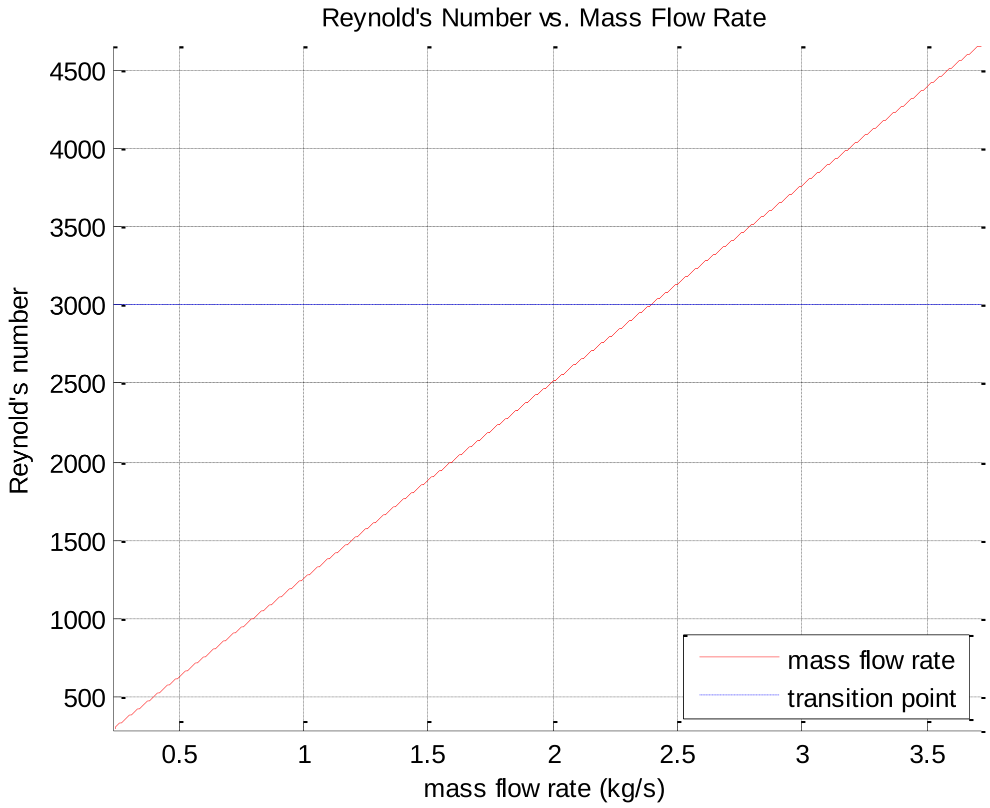


Fig. 5 Depicts the transition point from laminar to turbulent flow for the heat transfer fluid.

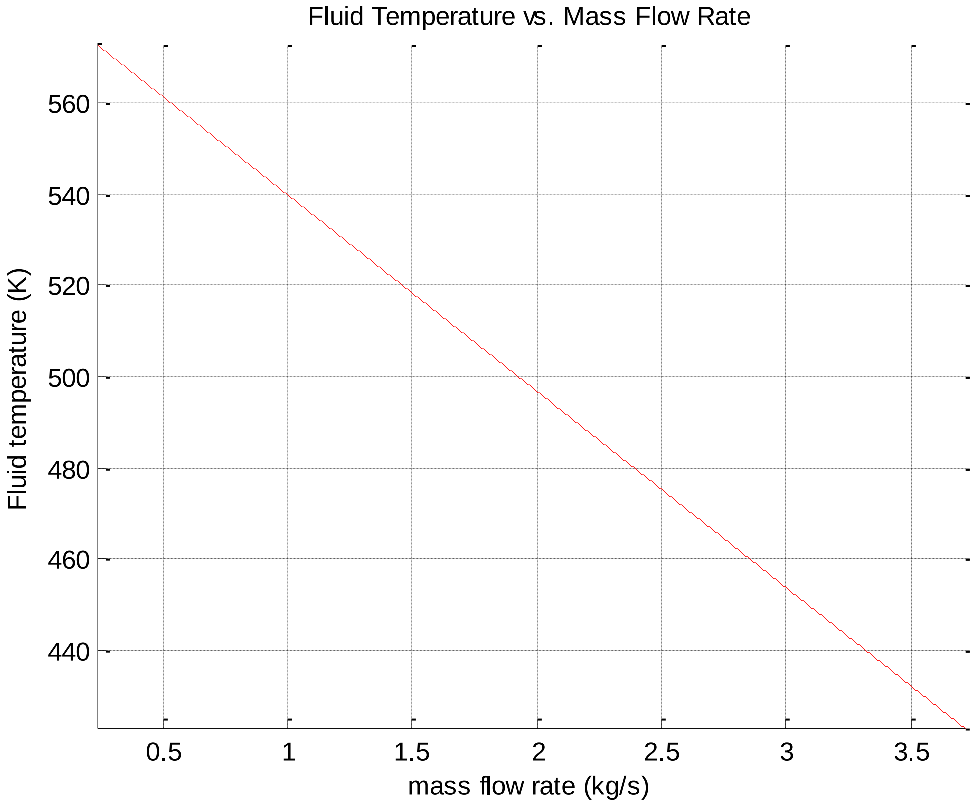


Fig. 6 A linearized relationship between the heat transfer fluid temperature and mass flow rate.

With the Reynold's number known, the next step in computing the head loss is the determination of the friction factor. The friction factor relation changes with the flow properties of the fluid. Eq.6 and Eq.7 shows the relation for laminar and turbulent flow, respectively. Since the flow changes with the collection cells the friction factors for each flow property is summed together. Using this approximated friction factor and an effective length of the collection cell piping the head loss was computed with Eq.8, which is plotted versus the mass flow rate. A maximum head loss of 1.8 Pa per unit length of the collection cell piping.

Eq.6 [5] $f_R = \frac{64}{R_e}$

Eq.7 [5] $f_R = (0.79 * \ln(R_e) - 1.64)^{-2}$

Eq.8 [5] $h_l = \frac{f_R * L_{eff} * \rho * 0.5 * \vec{V}^2}{D}$

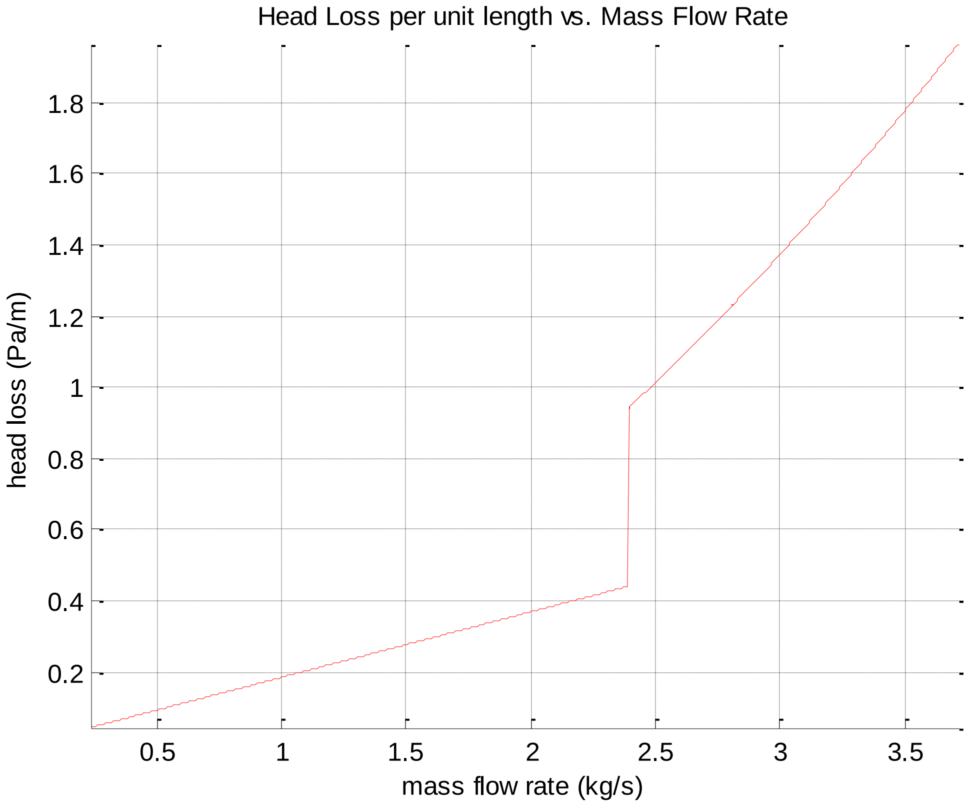


Fig. 7 An optimal mass flow rate of 2.5 kg/s must be maintained to keep the flow turbulent.

Cost Analysis

The cost of the raw storage materials including the heat transfer fluid were calculated and presented in Table 3. These calculations were based on bauxite costing $016/kg, Concrete $0.18/kg, and Mineral Oil for $0.3/kg. Further optimization is expected to lower the initial cost and thus allow to surpass our goal of $0.23/kWh. The energy used to calculate these values was taken as the energy stored per cycle time the number of cycles.

<u>Table 3. Raw Material Cost Estimation</u>

Storage Mediums	**Initial Cost**	**Cost per Cycle**	**9yr Life Cycle Cost**
Cost	$830,000	$0.29/kWh	$1e^{-4}/kWh

Scaled Prototype

The scaled prototype will be 1/25 the scale of the full scale solution. This means that each of the four collection cells will be 1 meter in length and of thickness 16cm. the pump will also be sized accordingly. All other flow parameters such as non-dimensional Reynolds and Nusselt numbers will be maintained as close as possible to validate our concept. The heat source will be modeled by an electric resistance heater and the success will be measured by the ability of the prototype to produce a consistent outlet temperature. This will be gauged by placing a thermocouple at a point where the flow leaves the collection cells. Another thermocouple will be placed at the inlet to the cells and flow of the heat transfer fluid will be changed accordingly by adjusting the pump.

Procurement

There are many countries that export bauxite, unfortunately the United States is not one of them. Although the mineral is very abundant in Australia, it is not available locally and must be imported to build a scaled down model. Suppliers all over the world were considered in order to minimize shipping costs and to compare different prices. All suppliers require a minimum order amount which was also considered during the selection process. A supplier in China was chosen because their minimum order requirement was only 1 ton as compared to other suppliers which ranged from 50,000 to 300,000 tons. Because this is for a small scale model, the amount of bauxite needed does not even come close to 1 ton. At $150 per ton this supplier was the best choice. The supplier will be contacted and questioned about shipping and handling costs in the next couple of weeks in order to ensure the arrival of the mineral is soon enough to build and test the model. The concrete will be purchased as needed from a local manufacturer. As tests are performed more and more concrete will be needed and therefore a total amount is unknown. By purchasing as needed we can assure that we will not spend more than necessary keeping the budget in mind. The mineral oil used as the working fluid will be purchased by the drum from a supplier in the United States. The same process was performed to select the mineral oil supplier, taking in to account the price, minimum order, shipping cost, and quality of the product. By using the suppliers chosen, the total amount of money spent on materials, shipping, and handling from the supplier to the location of assembly will be well under the $2,000 budget. Having this extra flexibility within the budget will allow for unexpected costs when testing and overcoming other obstacles that arise.

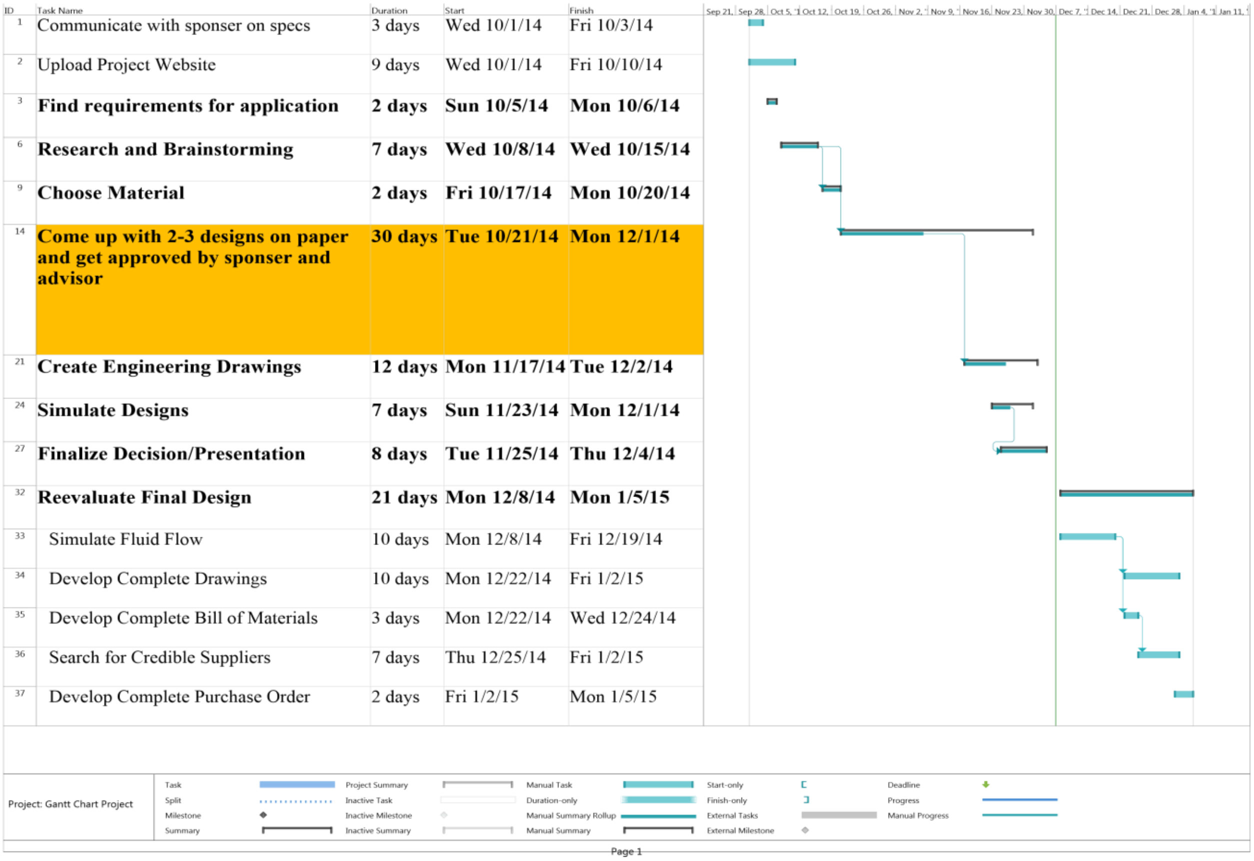
Communication

Communication between the team, faculty, and Verdicorp has been crucial to keeping this project on track for success since this project has been prone to numerous changes throughout its development. From location changes to priority changes that depend on the customer’s perceived needs and suggestions pushed by the involved faculty the project has evolved to fit new requirements as they’re introduced. To ensure a balance between time spent working and time spent in meetings, Communication with our sponsor has been on has been on a regular bi-weekly basis along with deliverables on our progress during the weeks that we do not meet. Meetings with our faculty advisors has been less formal because of their close proximity and many suggestions have been taken from in-class deliverables and presentations. Good communication between the three parties involved allowed the team to respond to location changes and this process is will be maintained through completion of the thermal storage prototype.

Future Goals

Moving forward from this point poses a few challenges for this group. Up to this point we have decided on a design scheme including the design of the bricks involved, however, proper drawings still need to be created in order to create the mold we need for those bricks. This is the priority for the group in the next few weeks before Christmas and more importantly before the beginning of the new semester. A huge chunk of time, approximately 3 to 4 weeks were lost this semester due to the confusion on the actual project description from the sponsor. It took some time to get a hold of our schedules and the sponsor at the beginning of the semester and when we did meet with them they weren't sure where our project was going since Brazil was on the fence whether or not they wanted Verdicorp's services and then about 4 weeks in opted out. This left us having to come up with ideas based on many assumptions. With the change of location from Brazil to Australia, many of those assumptions, such as input/output temperature and materials, had to be changed. The group did a good job of scheduling and put in a little more effort and ultimately were able to overcome this challenge. Sponsor meetings were scheduled every two weeks while team meeting were held every week. Upon submitting our new designs described in the Midterm I report the sponsor advised us to take a different approach and come up with a new design which is why the concept generation task is highlighted in the Gantt chart shown below in Fig. 5. It took quite some time to be in agreement with the sponsor and their expectations and so the following tasks suffered a little and required the team to work through the break. Fig. 6 below displays the outlook for the coming weeks his group wishes to accomplish.

The team will begin the winter break examining the pipe design on a deeper level, specifically in simulating the flow of the fluid within the pipe. The fluid flow is critical in applications involving fluid transfer. The more turbulent, or the more mixing achieved by the fluid the better heat transfer because that introduces better convection rates, increasing the overall heat transfer to the surrounding solid. As mentioned by an advisor of this team, oil is a lubricant and so it is difficult to mix due to its ability to absorb a high amount of shear stress. The fear is the middle of the profile remains the hotter than the edges which is ultimately what touches the solid and conducts the heat. This challenge needs to be fully understood and predicted before moving on and creating drawings and a bill of materials. It is allotted 10 days in the event that the fluid flow is unsatisfactory and requires small changes in the brick design. This will later change the drawings and the amount of material necessary for the design which is why the drawing task and final ordering tasks are contingent upon the results of this stage. Once complete, however, the plan is to immediately begin to create drawings and looking for suppliers to not waste any more time.



ID	Task Name	Duration	Start	Finish
1	Communicate with sponser on specs	3 days	Wed 10/1/14	Fri 10/3/14
2	Upload Project Website	9 days	Wed 10/1/14	Fri 10/10/14
3	**Find requirements for application**	**2 days**	**Sun 10/5/14**	**Mon 10/6/14**
6	**Research and Brainstorming**	**7 days**	**Wed 10/8/14**	**Wed 10/15/14**
9	**Choose Material**	**2 days**	**Fri 10/17/14**	**Mon 10/20/14**
14	**Come up with 2-3 designs on paper and get approved by sponser and advisor**	**30 days**	**Tue 10/21/14**	**Mon 12/1/14**
21	**Create Engineering Drawings**	**12 days**	**Mon 11/17/14**	**Tue 12/2/14**
24	**Simulate Designs**	**7 days**	**Sun 11/23/14**	**Mon 12/1/14**
27	**Finalize Decision/Presentation**	**8 days**	**Tue 11/25/14**	**Thu 12/4/14**
32	**Reevaluate Final Design**	**21 days**	**Mon 12/8/14**	**Mon 1/5/15**
33	Simulate Fluid Flow	10 days	Mon 12/8/14	Fri 12/19/14
34	Develop Complete Drawings	10 days	Mon 12/22/14	Fri 1/2/15
35	Develop Complete Bill of Materials	3 days	Mon 12/22/14	Wed 12/24/14
36	Search for Credible Suppliers	7 days	Thu 12/25/14	Fri 1/2/15
37	Develop Complete Purchase Order	2 days	Fri 1/2/15	Mon 1/5/15

Fig. 6 Gantt chart projecting assignments up until the new semester

The goal is to be ready by the beginning of next semester in order to begin purchasing as soon as possible to avoid Murphy's Laws. There's always the possibility orders will get mixed up, parts will get destroyed, and things will be assembled wrong, all which lead to lost time the team cannot afford. Scheduling throughout the next semester was not included here for the simple reason that some individuals have not finalized their schedule for the next semester. Once everyone has finalized their class/work schedule for next semester, a meeting will take place to develop a Gantt chart for the remainder of the year.

Conclusion

After taking the needs of our customer, Verdicorp, and the suggestions of our faculty advisors into account the team has decided to produce a sensible heat storage device that implements inexpensive and transportable materials as actual storage mediums. A heat transfer fluid will exchange excess heat with the solid storage materials in an effort to constantly output from the system a temperature of 200^{o}C. The chosen heat transfer fluid is Mineral Oil, thus our maximum temperature input is 275 ^{o}C. The full scale design will be scaled down by 75% to produce our final working model. Each collection cell will be downsized accordingly along with the final pump selection. We believe our sensible storage device which estimated to cost about $0.29 per kWh is reliable, scalable, economically feasible solution to our customer’s needs.

References

[1] Google Books. (2014, September 22). *Thermal Energy Storage (1st ed.)* [Online]. Available: http://books.google.com/books?id=EsfcWE5lX40C&pg=PA93&lpg=PA93&dq=methods+of+thermal+energy+storage&source=bl&ots=7XQn2Ozyuw&sig=vw4lHt7F0F3BKmzDdWgtIAq-dcY&hl=en&sa=X&ei=qEwcVKuAL8-YyATlsYHACw&ved=0CE8Q6AEwBDgK#v=onepage&q=methods%20of%20thermal%20energy%20storage&f=false

[2] Heat and Cold Storage with PCM. (2014, September 22). *Reinhart & Gupta Energy Efficiency Systems (1st ed.)* [Online]. Available: http://rgees.com/technology.php

[3] IEEE Spectrum. (2014, September 22). *Terrafore Looks to Cut Molten Salt Energy Storage Costs in Half (1st ed.)* [Online]. Available: http://spectrum.ieee.org/energywise/green-tech/solar/terrafore-looks-to-cut-molten-salt-energy-storage-costs-in-half

[4] MIT Technology Review. (2014, September 22). *Molten Salts May Be An Alternative to Batteries for Electricity Storage | MIT Technology Review (1st ed.)* [Online]. Available: http://www.technologyreview.com/news/525121/molten-salts-might-provide-half-price-grid-energy-storage/

[5] Cengel Yunus, Cimbala John, Turner Robert. *Fundamentals of Thermal Fluid Sciences*. (New York, New York 2011) 4th ed.

Appendix

Table 4. Energy Requirements provided by Verdicorp

Time of Day	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Electrical Load	35.00%	30%	30%	30%	30%	35.00%	40.00%	50.0%	65.00%	80.00%	85.00%	90.00%	95.00%	100.00%	100.00%	100.00%	100.00%	100.00%	90.0%	80.0%	70.0%	50.0%	45.00%	40.00%	35.00%
Required - kWe	123	105	105	105	105	123	140	175	228	280	298	315	333	350	350	350	350	350	315	280	245	175	158	140	123
Reserve Capacity - kWe	278	295	295	295	295	278	260	225	173	120	103	85	67	50	50	50	50	50	85	120	155	225	243	260	278
ORC Efficiency	9.60%	9.60%	9.60%	9.60%	9.60%	9.60%	9.60%	9.20%	9.00%	8.80%	8.60%	8.40%	8.20%	8.00%	7.80%	7.80%	7.80%	7.80%	7.80%	8.00%	8.40%	8.80%	9.20%	9.60%	9.60%
Thermal Requirements - kW	1,276	1,094	1,094	1,094	1,094	1,276	1,458	1,902	2,528	3,182	3,459	3,750	4,055	4,375	4,487	4,487	4,487	4,487	4,038	3,500	2,917	1,989	1,712	1,458	1,276
Daily Requirements	1,276	2,370	3,464	4,557	5,651	6,927	8,385	10,288	12,815	15,997	19,456	23,206	27,261	31,636	36,124	40,611	45,098	49,585	53,624	57,124	60,040	62,029	63,741	65,199	66,475
Collection	0%	0%	0%	0%	0%	0%	0%	10%	40%	70%	100%	100%	100%	100%	100%	100%	100%	70%	40%	10%	0%	0%	0%	0%	0%
Collection Capacity	-	-	-	-	-	-	-	707	2,829	4,950	7,072	7,072	7,072	7,072	7,072	7,072	7,072	4,950	2,829	707	-	-	-	-	-
Cumulative Collected Energy	-	-	-	-	-	-	-	707	3,536	8,486	15,558	22,630	29,702	36,774	43,846	50,918	57,990	62,941	65,770	66,477					
Energy Used from or added to Storage	(1,276)	(1,094)	(1,094)	(1,094)	(1,094)	(1,276)	(1,458)	(1,195)	301	1,769	3,613	3,322	3,017	2,697	2,585	2,585	2,585	463	(1,210)	(2,793)	(2,917)	(1,989)	(1,712)	(1,458)	(1,276)
Thermal Storage Requirements	8,306	7,212	6,118	5,025	3,931	2,655	1,197	2	301	2,070	5,682	9,004	12,021	14,718	17,303	19,888	22,473	22,936	21,726	18,934	16,017	14,028	12,316	10,858	9,582
Thermal Energy Reserves - kWe	14,040	12,946	11,852	10,759	9,665	8,389	6,931	5,736	6,035	7,804	11,416	14,738	17,755	20,452	23,037	25,622	28,207	28,670	27,460	24,668	21,751	19,762	18,050	16,592	15,316

Time of Day	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Electrical Load - kWe	123	105	105	105	105	123	140	175	228	280	298	315	333	350	350	350	350	350	315	280	245	175	158	140	123
Thermal Requirements - kWt	1,276	1,094	1,094	1,094	1,094	1,276	1,458	1,902	2,528	3,182	3,459	3,750	4,055	4,375	4,487	4,487	4,487	4,487	4,038	3,500	2,917	1,989	1,712	1,458	1,276

Time of Day	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Thermal Collection - kWt	-	-	-	-	-	-	-	707	2,829	4,950	7,072	7,072	7,072	7,072	7,072	7,072	7,072	4,950	2,829	707	-	-	-	-	-
	-	-	-	-	-	-	-	707	3,536	8,486	15,558	22,630	29,702	36,774	43,846	50,918	57,990	62,941	65,770	66,477	-	-	-	-	-

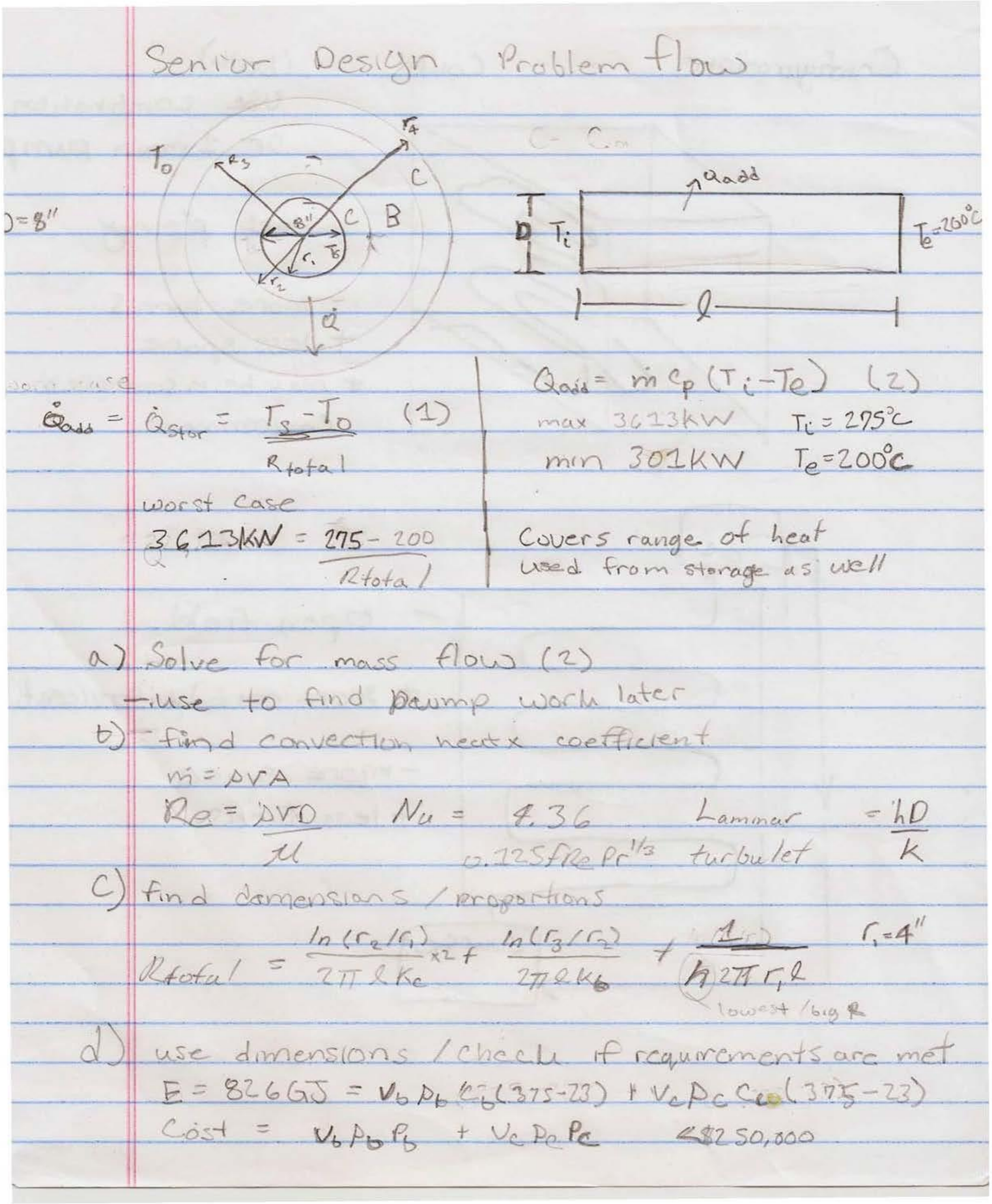
								7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00					
Energy Collected								707	2,829	4,950	7,072	7,072	7,072	7,072	7,072	7,072	7,072	4,950	2,829	707					
Cumulative Energy Collected								707	3,536	8,486	15,558	22,630	29,702	36,774	43,846	50,918	57,990	62,941	65,770	66,477					

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	0:00
Energy Used	1,276	1,094	1,094	1,094	1,094	1,276	1,458	1,902	2,528	3,182	3,459	3,750	4,055	4,375	4,487	4,487	4,487	4,487	4,038	3,500	2,917	1,989	1,712	1,458	1,276
Energy Requirements	8,306	7,212	6,118	5,025	3,931	2,655	1,197	2	301	2,070	5,682	9,004	12,021	14,718	17,303	19,888	22,473	22,936	21,726	18,934	16,017	14,028	12,316	10,858	9,582
Available Energy	14,040	12,946	11,852	10,759	9,665	8,389	6,931	5,736	6,035	7,804	11,416	14,738	17,755	20,452	23,037	25,622	28,207	28,670	27,460	24,668	21,751	19,762	18,050	16,592	15,316

Sample Calculations

```
%thermal storage analysis
%max energy for storage
eStored = 825699805;%(kJ)
%concrete
Cc = 0.88; %specific heat of cement kJ/kg*K
Pc = 0.18; %price of cement($/kg)
rhoC = 2300; %(kg/m3)
Kc = 1.4; % (W/m*k)
%bauxite
Cb = 2; %specific heat of bauxite k(J/kg*K)
Pb = 0.16; %price of bauxite ($/kg)
rhoB = 1281; %(kg/m3)
Kb = 30; %(W/m*K)
%synthetic oil
Cpl = 2.3; %(kj/kg*K)
Pl = 0.3; %($/kg)
rhol = 770; %(kg/m3)
Kl = 0.12; %(W/m*k)
r1 = 0.1016; %inner diameter for 8in pipe (m)
%find mass flow range corresponding to temperature drop along pipe
%final temp of liquid is 200C
Qaddition = linspace(301,3613);
MassFlow = Qaddition./(Cpl*(275-200));
Fig.(1)
plot(Qaddition, MassFlow);
title('Mass flow required of pump'); xlabel('Rate of heat addition to storage
(kW)');ylabel('kg/s')
%finding average convective heat transfer coefficeint
Velocity = MassFlow./(rhol*3.14*r1^2);% average velocity in pipe (m/s)
%Re = Velocity.*(rhol*2*r1/mew); %reynolds number if > 10^4 turbulent
Nu1 =4.36;% nusselt # for laminar flow accounting for point of largest thermal
resistance
%Nu = 0.125*f*(Re1)*Pr^(1/3) % /nusselt for turbulent flow
h = Kl*Nu1/(2*r1)
%find total thermal resistance
Rtotal = (275 -200)/3613 % (C/kW)
%manipulate material quantities to get RDesigned = Rtotal
r1 = 0.1016; %inner diameter for 8in pipe (m)
r2 = 0.4;
r3 = 2.0;
r4 = 2.1;%outermost radius of solid storage material
L = 100;% total length of pipe (m)
RDesigned = log(r2/r1)/(2*3.14*L*Kc) + log(r3/r2)/(2*3.14*L*Kb)+
+log(r4/r3)/(2*3.14*L*Kc)+(h*2*3.14*r1*L)^-1
%volume of materials present as a result of chosen dimensions
Vb = 3.14*L*(r3-r2)^2;
Vc = 2*3.14*L*(r3-r2)^2;
Vl = 3.14*L*(r1)^2;
E = Vb*rhoB*Cb*(200-23) + Vc*rhoC*(200-23); %energy stored equation
stored= E - eStored %Positve if energy storage requirements are satisfied
%check cost beneath $250,000
cost = Vb*rhoB*Pb + Vc*rhoC*Pc +Vl*rhol*Pl
%levelized cost in years
time = linspace(1,9);
dailyOp = cost./(E.*0.00278); %levelized cost per cycle($/kWh)
levCost = cost./(E.*0.00278.*time.*365); %  ($/kWh-year)conversion from
unitjuggler.com
Fig.(2)
plot(time,levCost);
```

```
title('Levelized cost est. for up to 9 years of operation')
xlabel('years of operation'); ylabel('$/(kwh-year)')
```



Senior Design Problem flow

$$\dot{Q}_{add} = \dot{Q}_{Stor} = \frac{T_s - T_o}{R_{total}} \quad (1)$$

worst case

$$3613\,kW = \frac{275 - 200}{R_{total}}$$

$$Q_{add} = \dot{m} c_p (T_i - T_e) \quad (2)$$

max 3613 kW $T_i = 275°C$

min 301 kW $T_e = 200°C$

Covers range of heat used from storage as well

a) Solve for mass flow (2)

- use to find pump work later

b) - find convection heat x coefficient

$\dot{m} = \rho V A$

$Re = \frac{\rho V D}{\mu}$ $Nu = 4.36$ Laminar $= \frac{hD}{k}$

$0.125 f Re Pr^{1/3}$ turbulet

c) find dimensions / proportions

$$R_{total} = \frac{\ln(r_2/r_1)}{2\pi l K_c} \times 2 + \frac{\ln(r_3/r_2)}{2\pi l K_b} + \frac{1}{h 2\pi r_1 l}$$

$r_1 = 4''$

lowest / big R

d) use dimensions / check if requirements are met

$E = 826\,GJ = V_b \rho_b c_b (375-23) + V_c \rho_c c_c (375-23)$

$Cost = V_b \rho_b P_b + V_c \rho_c P_c$ $< \$250{,}000$