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Salt River Project (SRP) Thermal Mass

Final Design Report

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EXECUTIVE SUMMARY

This senior mechanical engineering capstone project was funded and sponsored by Salt River Project (SRP). This team consists of Courtney Hiatt, Janelle Peña, Steven Galloway, Aaron Espinoza, Maciej Ziomber. Salt River Project is a power company covering much of the Phoenix metropolitan area. SRP faces challenges with high electricity demand during peak hours (4 PM to 8 PM) when energy costs were at their highest. This project addresses the need for affordable, user-friendly thermal energy storage systems to help residential customers reduce their electricity bills and improve home cooling efficiency. The primary objective was to design and develop a thermal energy storage unit that was accessible for everyday households. By leveraging energy stored during off-peak hours, the system aimed to alleviate peak-load demands on SRP's grid, offering both economic and environmental benefits. The unit was designed to integrate seamlessly into existing or new build household setups, providing efficient cooling during peak hours while reducing reliance on traditional air conditioning systems.

The team adopted a systematic approach, including extensive benchmarking, mathematical modeling, and prototyping. The design concepts explored ranged from PCM-based systems integrated into HVAC setups to standalone units utilizing innovative materials and configurations. Compliance with relevant safety and building codes was prioritized to ensure practical and scalable solutions. The concrete bar was able to generate a heat transfer rate of 30W and the water bars didn't produce the heat transfer rate that was hoped for. The water produced a consistent heat transfer of 3.0E-4 W. The prototype of the water bars could not produce a flow that was turbulent, and the heat transfer traveled along the walls of the copper tube. The heat another way to produce the heat transfer that was wanted is to force a turbulent flow by using an inline static mixer. The copper tube used to maximize the amount of water that is smaller than any inline mixer made leading to the future work of designing a new heat exchanger outside of the scope of this project.

This project had a budget of $5,000 and only $1,832.63 was used. The results of the proof of concept that were obtained through testing, demonstrating the feasibility of the proposed design. Specifically, the new build validated key performance metrics, including cooling capacity, energy efficiency, and compatibility with household systems. The prototype was tested under simulated peak conditions. These results supported the economic and technical viability of the system, aligning with SRP's goals to optimize energy usage and reduce costs for customers. The proof-of-concept prototype was successfully developed and demonstrated, marking a significant step toward implementing thermal energy storage solutions in residential settings. This initiative not only supported SRP's mission but also contributed to advancing sustainable energy practices.

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Chapter 1: Background

1.1 Project Description

The project's goal is to develop thermal energy storage systems to reduce peak-load air conditioning expenditures for Salt River Project (SRP) customers in central Arizona. SRP, a community-based, non-profit organization, serves more than 2 million people in the Phoenix metropolitan region. With a peak load of over 8,000 MW in the summer, SRP faces difficulty in satisfying demand, especially during peak hours (3 PM to 8 PM), when electricity rates are highest.

In response to these problems, SRP intends to investigate the viability of thermal energy storage systems, which might potentially lower consumers' electricity rates during peak hours. The initial focus on conducting state-of-the-art research exposed the limitations of cooling with thermal mass. The examination of typical electricity uses patterns during peak months developed an understanding of the potential cost savings. Coupled with the study of SRP’s consumer rate packages, both with and without customer-sited solar PV generation the modes of development became clear. The systems would have to be created for different new structures and pre-existing structures.

The project's goals included presenting a variety of energy storage systems with technical and economic details. In collaboration with the client the two concepts to compare against an industry standard device we would develop. Based on the test results, a full-scale design and a preliminary techno-economic analysis will be suggested. Despite its ambitious goals, the project remained well within the $5,000 budget. The team fundraised 5% of the budget to ensure the project’s success.

1.2 Deliverables

The primary project deliverables included.

- A comprehensive report evaluates thermal energy storage methods and their costs.
- Analysis of SRP customer electricity usage during peak months, assessing possible cost savings with thermal energy storage options.
- Proposal describing various energy storage technologies, including technical and economic requirements.
- Design, build, and two thermal energy storage solutions and a datum at which to compare.
- A full-scale design proposal is based on test results, including an initial techno-economic analysis.

These deliverables are critical to achieving the project's objectives and offering significant insights into the feasibility and effectiveness of thermal energy storage in lowering peak load air conditioning expenses for SRP customers.

1.3 Success Metrics

Our project's success will be measured using several important metrics consistent with client and engineering criteria. First, user-friendliness and functionality will be evaluated based on our thermal energy storage system's ease of use and effectiveness in cooling the house when activated. The system's capacity to survive as long as needed during peak hours will define its reliability, assuring continuous performance and comfort for residents. Safety is vital; thus we will assess whether the system poses minimum threats such as explosion, fire, or freezing, assuring the safety of all inhabitants.

Technical Performance: The chosen thermal energy storage solution's ability to successfully store and release thermal energy to counter air conditioning power use during peak hours will be assessed. Technical performance criteria include energy storage capacity, efficiency, dependability, and scalability. Engineering requirements will also be critical in determining the success of our project. The materials and systems used in our thermal energy storage solution will be analyzed to determine efficiency to achieve optimal performance and energy savings. Thermal performance will be evaluated using various methods, including transient heat analysis and thermodynamic modeling, to ensure that our system efficiently stores and releases thermal energy as needed to maintain a comfortable interior atmosphere.

Economic viability: The selected thermal energy storage solution's techno-economic analysis will determine its financial feasibility and long-term viability. The upfront costs, payback period, return on investment, and possible revenue streams (for example, demand response programs) will all be examined. Cost will be an important consideration, and we will ensure that our system is cost-effective, considering both pre-built and pre-existing structures. Net Present Value (NPV) and Internal Rate of Return (IRR) assessments will be performed to ensure favorable financial results and long-term viability.

Cost Savings: The degree to which thermal energy storage systems lower electricity bills for SRP customers during peak periods will be a key success metric. Cost savings will be determined by comparing pre- and post-implementation electricity bills, considering various customer rate plans and situations. Affordability will be evaluated by determining whether the system is feasible for the average house buyer, whether for an existing structure or a new construction. In addition, we will analyze whether our solution saves consumers energy and money, meets customer needs, and improves marketability.

Safety will be prioritized, and the team will ensure the system complies with all applicable safety requirements and standards, thereby reducing dangers to occupants and property. The ease of maintenance and access will be assessed to ensure that the system is user-friendly and handy for homeowners.

Chapter 2: Requirements

2.1 Customer Requirements

The customer requirements from our client SRP were mostly related to user ease and affordability. The customer requirements listed below are explained in further detail in the points and measures that we take into consideration during each part of the development of the thermal energy storage device.

- Safety
    - Categorized as how likely will the design develop a lawsuit from injury. Based on the FMEA. The use of ethylene glycol proved to be the most dangerous aspect of the device and safety improves greatly using propylene glycol with some loss to heat transfer and additional maintenance. (CR)
- Reliability
    - Does it cool down the house when turned on? (4 hours CR)
    - Does it prepare for use during the correct time? (10 hours)
- Affordability
    - Can the cost of the product be offset by incentives
    - Will the return on investment be within a feasible time frame (5 years CR)
- Material Access
    - The availability of parts on the standard market (parts on open Market CR)
- Risk
    - Will the product provide a business opportunity (CR)

2.2 Engineering Requirements

The engineering requirements are related to the customer requirements but go more in-depth. The engineering requirements also require an analysis of each aspect that uses calculations and numerical data to support them. If the concept doesn’t have numerical calculations, we also use theory and content from engineering textbooks, research and professionals. One important value we are aware of is battery storage. The device needs to have 4 hours' worth of storage. One example of this would be the Net Present Values calculated for each part. The parts must have a positive value to be beneficial to the device, the larger, the better even.

- Safety
  - The same as the customer requirements
- Ease of Access
  - Availability to install or build on site (part availability, ER)
- Initial cost (Monetary)
  - If a buy receives “sticker shock” from the price they will not buy it.
  - Compared to the state of the art how much does it cost? (ER $15000)
- Energy Demand
  - Will the proof of concept provide cooling to a standard size home in the valley (found to be the average of 1600 sq. ft.)
  - ASHRAE calculation (37000 BTU ER)
- Heat Transfer (ER adjacent)
  - Transient Heat Analysis
  - Thermodynamic analysis
  - Thermodynamic Models
  - Radiation Heat Analysis
  - ANSYS Models

All the engineering requirements have engineering calculations. Often alternative systems such as MATLAB, ANSYS, IT, and SOLIDWORKS help accomplish these too. These calculations have been completed in parts through the semester and will continue as the project progresses.

As the design coalesced, it was important to categorize the safety factors for the materials and their uses. For example, refrigerants can cause blindness, brain damage, and death, but they are considered safe to use as product in a product. What makes these substances we use dangerous is when they are being administered, so much of the safety factor is calculated in the manufacturing process and not considered in our engineering requirements.

Ethylene glycol is considered an HTF and a product in a product. If it can be demonstrated in a future experiment to modify the properties of water to produce a more effective thermal mass, the team will have to re-evaluate what is unreasonably poisonous. Ingesting 4 ounces of ethylene glycol may be enough to kill an average-sized man. [50] This

One of the materials of interest initially was a paraffin called N-tetradecane (C14), originally the study's most promising material. Due to the flammability and toxicity, it was eliminated as a candidate. N-tetradecane (C14) proved costly and has now been removed from our candidate list.

The factor of safety for candidate materials of thermal mass is on a “go-no-go" basis. If they are unreasonably flammable or poisonous, they are instantly rejected.

Once the designs were manufactured and tested, we considered eight important elements to create spider charts using MATLAB, which are represented in figures 1,2,3,4. On a scale of 0% to 100%, where 0% denotes the worst possible result and 100% the best, each factor was assessed. These elements were chosen to guarantee a thorough examination of our concepts by matching engineering and client requirements.

Two of our designs, Water Bars and Concrete, were evaluated against these eight aspects in order to develop the charts: Safety, Reliability, Monetary, Material Availability, Risk, Return on Investment (ROI), Energy Demand, and Ease of Access. Every element was assessed to show how well the designs satisfy prospective clients' expectations while upholding important engineering principles. Data and computations unique to the performance and application of each design were used to support the evaluations.

A third design, which acted as our datum, was then used to compare the outcomes of our two designs. We were able to objectively evaluate each design's advantages and disadvantages thanks to this comparison method. We provided a clear foundation for decision-making by visualizing the trade-offs and performance measures by charting these evaluations on spider plots. Below are the explanations for the particular scores given to each factor.

- **Safety**
  Safety was assessed based on the product’s potential impact on the household and its residents. Key considerations included the risk of leaks that could cause slip injuries or structural damage, the possibility of collapses leading to health hazards or structural compromise, and the potential spread of hazardous substances.
- **Reliability**
  The reliability metric measures the trustworthiness of the product to perform as intended. It reflects the accuracy of calculations and data used to ensure that the system can fully cool a home during peak energy demand hours.
- **Monetary**
  The monetary scale evaluates the financial investment required to initiate the project. A lower percentage on the scale indicates a higher initial cost associated with the design and implementation of the product.
- **Material Availability**
  This factor assesses the accessibility of materials required for manufacturing the product. For example, if 90% of the necessary materials can be procured within a few business days, the scale would reflect a 90% availability score.

- **Risk**
  Risk evaluates the likelihood of project success in relation to the initial investment. For instance, manufacturing 20,000 units of a water bar product may pose greater risk compared to installing a single concrete wall in a newly constructed home. For new thermal energy storage systems, the risk is estimated at approximately 45%.
- **Return on Investment (ROI)**
  The ROI metric analyzes whether the project is financially viable, considering the initial investment and potential profit.
- **Energy Demand**
  This metric measures the ability of the project to meet energy requirements during peak demand periods. Scaled-up versions of the proposed designs are projected to cover one-third of energy demand during these hours.
- **Ease of Access**
  Ease of access evaluates the practicality of implementing the product. For example, water bars can be purchased and easily installed by customers, whereas concrete solutions require specialized equipment and a structured installation process.

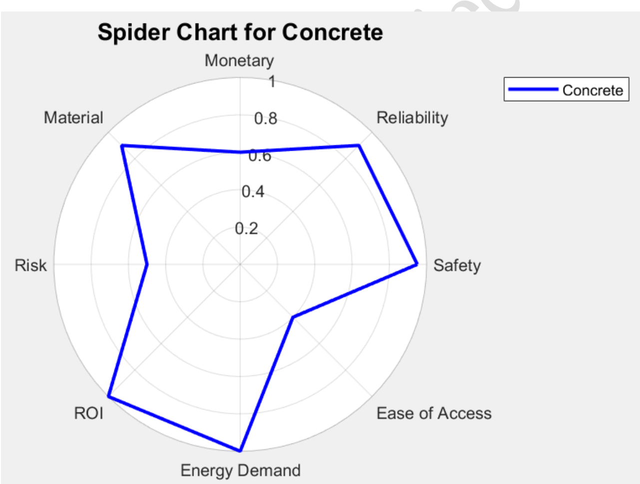


Figure 1

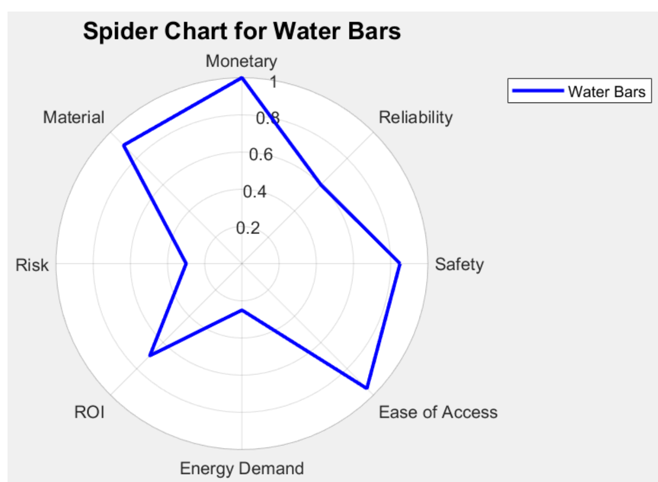


Figure 2

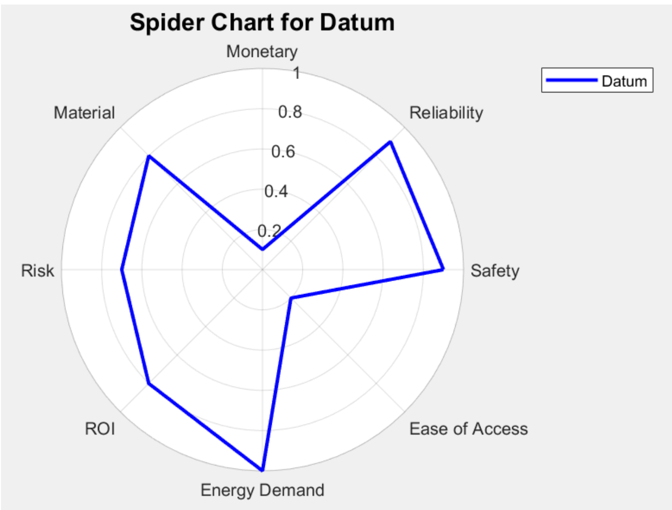


Figure 3

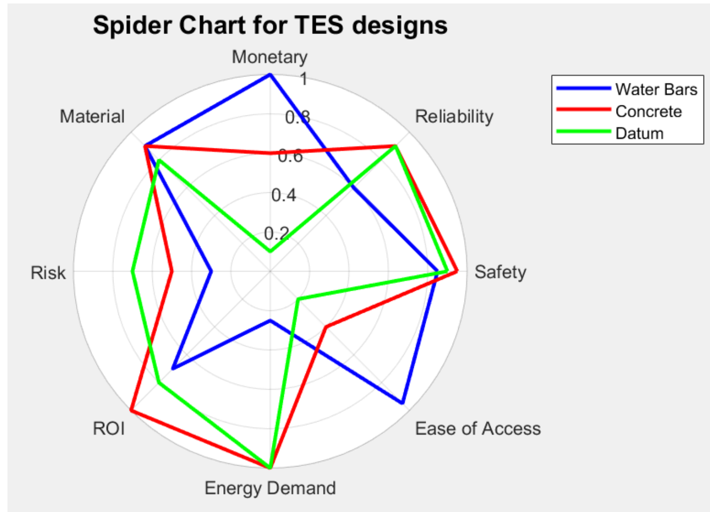


Figure 4

2.3 House of Quality (QFD)

The QFD has been updated to reflect the customer requirements in the burnt orange section of the QFD and the engineering requirements can be seen in the light blue section of the QFD.

Table 1

	Customer Importance (1=Low, 5=High)	Percent of Customer Importance Rating	Safety	Cost	Level of Maintenance	Weight	Heat Transfer	Boston Air Coil	Mass Flow Rate	NPV ($$$)	Thermal Efficiency	Latenet Heat	Sensible Heat	Specific Heat
SRP Clientel Satisfaction		+	++	++		++								
User Friendly		(- +)	-	-		--								
Reliability		++	(- +)	+		--								
Safety		++	+	+		-								
Affordability		(- +)	+	+		+								
Aluminum	3	3	9	5	6	8	7			7	6		2	5
Copper	5	5	9	7	6	6	8	8		8	7		2	1
Concrete	5	5	6	8	6	3	2	7		7	1		5	
Water	5	5	9	8	2	5	5	6	9	8	6	5	10	9
Ethelyne Glycol	4	4	7	6	6	6	5	6	8	7	5	1	8	
			40	34	26	28	27	27	17	37	25	6	27	15
Percent of Importance		%	22.86	22.08	23.21	23.73	23.28	20.93	22.08	22.56	23.15	20.69	21.95	23.08

House of Quality (QFD)

Chapter 3: Research within your Design Space

3.1 Benchmarking

Here, the state-of-the-art cold thermal energy storage (CTES) will be identified. The technological categories of the CTES are substance, management, and methods. The benchmark substance for CTES is water, which has the highest specific heat, but expansion at freezing can damage containers. For management, ice or ethylene glycol chilling chambers are proven technologies that get results. A passive method for temperature regulation is to place a phase change material (PCM) into a structure to maintain a temperature at the melting point of the PCM.

Many of the breakthroughs in CTES are a direct result of research and development of substances developed for heat transfer in sub-zero conditions or for long term cold storage. [1] Organic paraffin compounds have shown promise because of their general abundance. Research has produced exotic materials that sacrifice chemical stability to achieve remarkable results. N-tetradecane (C14) is one such material with a melting point of 6 Celsius, and a latent heat of 228 kJ/kg, which is as close to the thermal characteristics of water as available. [2] This is an expensive and less safe option that does not justify the mitigation of the expansion, but it does show the limits of this technology that can still be challenged. Other substances that come from this material science approach lend to the next benchmark of management.

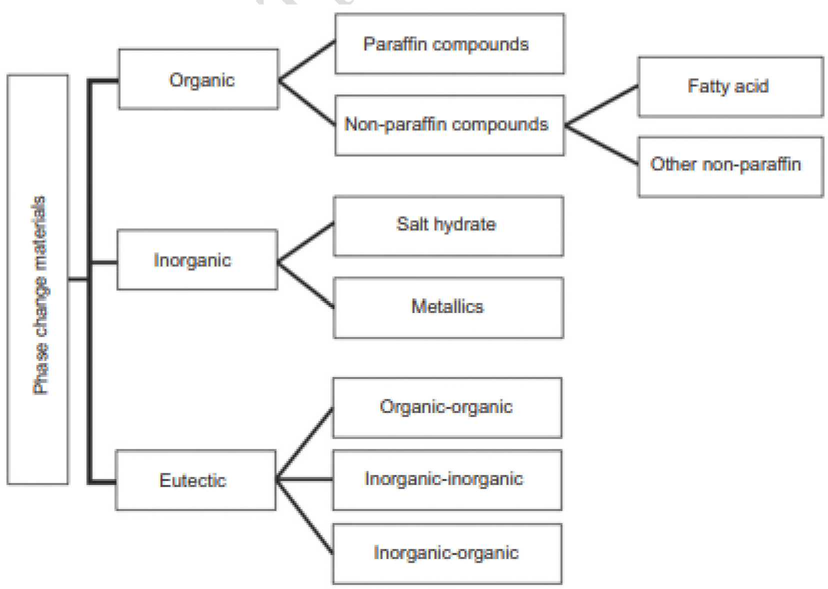


Figure 3

Thermal Energy Storage pg.110 [3]

The Baltimore Aircoil Company TSU-M ice chiller is an example of the pinnacle of CTES technology. [4] By chilling water to freezing in containers created to control the expansion of ice and circulating ethylene glycol through it as the heat transfer fluid they create a low maintenance and efficient management system. These are large systems that are made to provide apartment complexes and commercial buildings. This is not the target of the Thermal Mass team but is a functional management system to compare to.

The passive method used to maintain the temperature of a structure is some form of building material that doubles as a CTES. Armstrong World Industries capitalizes on this market using ceiling tiles and wall replacement panels. [5] Using Ultima Templok (PCM) these tiles phase change at 66 to 81 Fahrenheit and maintain a structures internal temperature with latent energy. Other passive methods do not need to be building materials, they can be simple stand-alone devices that require little to no maintenance or assembly. The Viking Cold Solutions cold storage system for commercial refrigeration warehouses. [6] The substance used is not disclosed but whether it is a eutectic or a paraffin the method is the same, a passive phase changing material that maintains a temperature. These substances, management schemes, and were compared against all our concept and cost models.

3.2 Literature Review

Courtney –

1. Paraffin: Thermal Energy Storage Application (book) *[7]*

This article presents pros and cons of storage systems, including sensible storage is best if the operating temperature is higher, latent is best at narrow operating ranges. This will be useful for research and concept generation for everyone.

2. ***Economic Analysis of a Novel Thermal Energy Storage System Using Solid Particles for Grid Electricity Storage (Conference Paper)*** *[8]*

This paper includes images of the mechanical systems used for thermal energy storage. Equations for calculating the economic efficiency of thermal energy storage systems. This will be useful for financial analysis done by Maciej.

3. ***Advances in Thermal Energy Storage System (Book)*** *[9]*

Comprehensive analysis of thermal energy storage systems using water, molten salts, concrete, aquifers, boreholes, and phase-change materials. This will be useful for prototyping/manufacturing done by Steven and Aaron.

4. Seasonal thermal energy storage with heat pumps and low temperatures in building projects – A comparative review (Article) *[10]*

Research article that compares the coefficient of performance (COP) of different heat pumps used for thermal energy storage. This would be useful for research/data collection done by Janelle.

5. Thermal conductivity measurement techniques for characterizing thermal energy storage materials – A review (Article) *[11]*

This article develops methods for testing materials and systems for their thermal conductivity. Useful during the prototype testing phase by Maciej and Courtney.

6. Thermal Energy Storage (Government Website) *[12]*

Provides website links to specific thermal energy storage projects. This will be useful during concept generation production.

7. Who Said Thermal Storage Has to be Only in Tanks? Thermal Storage in the Building Envelope (Presentation) *[13]*

This source provides useful graphs showing average daily load using solar panels used to heating and cooling. It also provides an overview of methods to storing thermal masses in buildings.

8. 1997 ASHRAE Handbook (Book) *[14]*

This source provides information about how to perform a transient heat analysis on a house that can be used to calculate the energy needed to keep the house cool.

9. Cooling Load | hand calculation example | HVAC 13 (Video) *[15]*

This source provides an example of how to use the 1997 ASHRAE handbook to find the load calculation. It is useful to follow along with and determine which information in the book is most important.

10. Ethylene Glycol Heat-Transfer Fluid Properties (Engineering Toolbox) *[16]*

This source provides information on one of the materials we are using, ethylene glycol. This toolbox is also used to perform calculations about other materials and provides information such as the specific heat and heat of fusion.

Janelle –

1. ***Fluid Mechanics: Fundamentals and Applications*** **(Textbook)** [17]

   This textbook provides information on how fluid mechanics works. This is important because there are many different fluid mechanic applications that are being used in this project. The portion of the textbook specifically that is useful is the portion about transition of fluids for transient heat. As well as how it provides useful equations on fluid mechanics.

2. ***Fundamentals of Heat and Mass Transfer*** **(Textbook)** [18]

This textbook provides information on heat transfer fundamentals and applications. This textbook gets referred to often. Some specific applications of when this reference is used is for the transient heat calculations, the heat exchanger calculations, and the radiation calculations.

3. ***Fundamentals of Engineering Thermodynamics*** **(Textbook)** [19]

   This textbook provides information on thermodynamics and thermodynamic systems. This is useful in calculating heat exchangers and analyzing an actual AC compression vapor system. This textbook is also useful for the material properties tables in the back of the textbook. This textbook is also useful for learning to use Interactive Thermodynamics Software (ITS). As well as of course it provides useful equations on Thermodynamics.

4. ***Storing energy : with special reference to renewable energy sources*** **(Book)** [20]

   This is a textbook that Carson referred to us for assistance on this project. It has been useful for information on phase change materials and for phase change material equations. It is also useful for information on latent and ambient temperature. It also is useful for heat storage in general.

5. ***Energy Storage*** **(Book)** [21]

   This textbook talks about the specifics of heat storage. It talks about and explains the importance of heat storage and heat exchange devices. It explains the different ways to analyze heat storage and heat exchange devices. It has useful graphs and figures as well. It is a great reference for storage and similar systems as well.

6. ***Air Conditioning with Thermal Energy Storage*** **(Journal Article)** [22]

   This engineering document was surprising and very useful. It talks about and refers to aspects almost exactly related to what this project is about. It also addresses materials, PCMs, construction materials, ASHRAE figures, and similar prototypes. This was a useful paper.

7. ***Hybrid HVAC with Thermal Energy Storage Research and Demonstration*** **(Website)** [23]

   This was a useful research project that another college team set out to complete for the Department of Energy. In this project, another college team set out to create a Thermal Energy Storage Device to support the grid. One thing they did was compare chemical analysis with thermal analysis. They also had a comparable functionality report, which was useful for comparing results and doing a sanity check. The Black Box model is useful and comparable, too.

8. ***Storing Thermal Heat in Materials*** **(Website)** [24]

    This website has many useful equations and data tables to use for reference. It has a table with the important thermal heat storage values for different materials we plan to test. It also has links to other information that will be useful and information to reference.

9. ***Energy & Buildings: Experimental and numerical investigation of the thermal performance of phase-change module using built-in electrical heating*** **(Journal Article)** [25]

    This research talks about the usefulness of latent heat in thermal energy storage. It also breaks down information on complex materials, specifically different complex phase change materials. Also, the tables 1-3 in the paper and figures 4&5 were useful. This paper also talks about PCMs and electric energy storage.

10. ***Energy & Buildings: Component-level analysis of heating and cooling loads in the U.S. residential building stock*** **(Journal Article)** [26]

    This article talks about how residential homes use most of the energy in the US, and heating and cooling systems use most of the energy that they use. This article then talks about how to reduce the demand on the load. It also goes through specific materials in a home and how heat transfers through them.

Steven-

1. ***Energy & Buildings: Component-level analysis of heating and cooling loads in the U.S. residential building stock*** **(Journal Article)** [26]

    This article talks about how residential homes use most of the energy in the US, and heating and cooling systems use most of the energy that they use. This article then talks about how to reduce the demand on the load. It also goes through specific materials in a home and how heat transfers through them.

2. ***Heat and cold storage containers, systems, and processes*** (Patent) [27]
    Proposes CTES devices that are buried underground in flexible tubes. A flexible tube allows the PCM to occupy more space around a home without using a large, hard-to-create hole that would require special permits. This is an undeveloped patent but references the creation of polymers that function in the same way. This is proposed as a supplement to geothermal as well.
3. ***Eutectic salt cold-storage material*** (Patent) [28]
    Explains applying an organic-inorganic cold storage device using a newly constructed eutectic salt. This method is a novel way to overcome the issue of

water expansion that causes cracking and leakage and uses a higher working temperature. The inefficiency caused by condensate depression of other eutectics is discussed.

4. ***Armstrong World Industries BUILDING PANEL SYSTEM Patent Application (Patent Application)*** [29]

   A method of installing a PCM in existing structures with minimal intrusion into the existing building. The unintrusive method is important here regarding failure caused by installation mitigation. This passive system requires a large amount of whatever PCMs are used.

5. ***Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage – A review (Journal Article)*** [30]

   A short discussion of previous methods stabilizes organic phase change materials. The authors categorize and use experimental data to justify the current industrial uses of these materials. Of particular interest is using microencapsulation and nanomaterials to stabilize the PCMs and prevent leakages.

6. ***Phase change materials for thermal energy storage – (Journal Article)*** [31]

   Another large study of PCMs specifically focused on stabilizing and creating safe ways to use them. Many of the organic PCMs are dangerous to ingest or corrosive to containers. The discussion of how PCMs fail is enlightening as well.

7. ***Effect of Ethylene glycol as Phase Change Material in a Cold Storage Unit on retention of cooling (government-supported study)*** [32]

   A government agency in India performed and funded a cold storage containment unit study, which shows how to replicate the experiment. Empirical data for using ethylene glycol as a PCM instead of using it solely as a heat transport fluid is presented. This inspires more experimentation but does not deliver a comprehensive list of data from the experiment.

8. ***Advanced Strength and Applied Elasticity (Textbook)***[33]

   Systematic Exploration of real-world stress analysis. Shows the derivations and application for buckling stress analysis. The equations and boundary conditions are discussed here.

9. ***A First Course in Finite Elements (textbook)*** [34]

   Finite element methods for numerical heat transfer approximations and failure mode analysis. Developing numerical methods to approximate the values

10. ***Ansys Learning Resources (website)*** [35]

Resources about how to use and understand ANSYS. Specifically, Workbench (Mechanical and Fluent) to complete the analysis.

Maciej-

1. ***Air Source Heat Pumps Tax Credit | ENERGY STAR*** (government website) [36]

    Lays out the requirements for a company to apply for ENERGY STAR. How to create a device that is ENERGY STAR compliant.

2. ***2018 International Fire Code (IFC)*** (government website) [37]

    The requirements for wiring and spacing. Also discusses the safety requirements for some products like air conditioners.

3. ***2018 International Building Code (IBC)*** (government website) [38]

    Identifies the rules about the sizes and shapes of objects on residential properties.

4. ***2018 International Mechanical Code (IMC)*** (government website) [39]

    All the rules for ducting and air handling for a structure. Hints at digging holes and how and why regulations apply to burning things.

5. ***2018 International Plumbing Code (IPC) | ICC Digital Codes*** (government website) [40]

    The rules and regulations for geothermal devices. Hints back to the IMC and digging holes and points to the swimming pool and Spa Code.

6. ***2018 International Swimming Pool and Spa Code (ISPSC)*** (government website) [41]

    The rules about digging shallow holes. Give the ways to classify the use of a hole.

7. ***The Consumer Product Safety Improvement Act (CPSIA)*** (government website) [42]

    A list by category of every type of product. Every category has rules about how to create and injury-proof a device safely. Led to the discussion about what this device does in an earthquake or tornado.

8. **Engineering Economy** (book) [43]

    Through solved examples, problems, and case studies, the book addresses contemporary engineering challenges in areas such as energy, ethics, the environment, and evolving economics, providing practical insights and solutions for real-world scenarios. The book retains its extensive coverage of engineering economy principles even with the addition of new features and themes like ethics and staged decision making, guaranteeing that readers will gain a comprehensive understanding of the subject.

9. **Engineering Economics: Problems and solutions** (book) [44]

   Examples of problems and solutions for different engineering problems and applications.

10. **Essentials of Engineering Economics** (book) [45]

    Explores economic analysis methods such as cash flow analysis, cost estimation, and decision making under uncertainty. Provides practical examples, case studies, and problems to illustrate the application of economic concepts in real-world engineering scenarios.

Aaron –

1. ***Armstrong World Industries | Armstrong Ceiling Solutions*** (website)[5]

   A building material that uses a salt hydrate PCM in ceiling tiles to regulate temperature passively. Data is provided from testing and of application of these tiles used in New Hampshire High School. Their products can be purchased on a website.

2. ***Phase Change Materials | PCMs | Ceiling Systems*** (website) [46]

   Ceiling tiles using the passive method and a different PCM that is not listed. They advertise a PCM that is a cable to distribute in a building. They also offer wall panels with the same PCM to increase room thermal mass. The PCM is said to be inside the panel as a microencapsulated metal fiber composite that the panels are made of.

3. ***Hybrid HVAC with Thermal Energy Storage Research and Demonstration*** (government website) [23]

   Government research into a working model of CTES for a small commercial or residential structure. Simulations demonstrate expected results since testing was not yet conducted when published. Models are shown to demonstrate the system, including investment and material costs.

4. ***PCM Products*** (website) [47]

Products with PCMs into the range of refrigeration or freezer usage. A very wide range of items for heating and cooling applications are described and offered. There is deep research for many PCM and their intended uses. Energy saving designs are listed systems are shown and explained.

5. ***Cold Storage - Viking Cold Solutions™*** (website) [6]

    A PCM built simply for refrigerators and freezers is used in warehouses. The simple design lowers cost and maintenance due to higher efficiency and temperature stability. Eutectic PCM is packed into many small Cells that are used to increase the thermal mass of warehouse-size freezers.

6. ***Paratherm- Low Temperature Heat Transfer Fluids*** (website) [48]

    Specialized heat transfer fluids are purchasable on the website. These incredibly low-temperature fluids could be used as working fluids in a heat exchanger. Specialized fluid would allow efficient and safe heat transfer through a system to freeze a Eutectic PCM.

7. ***SRP Time-of-Use (TOU) Price Plan | SRP*** (website) [49]

    The chart of on-peak and off-peak hours for SRP members started to discover the number of cooling hours. This led to the discovery of the cooling value and the baselines of the project. Pricing of kWh is used for energy cost calculations.

8. ***Green Building Advisor - Storing Heat in Walls with Phase-Change Materials*** (website) [50]

    Drywall made from the PCM 'Micronal' and Gypsum Crystals for mold resistance is held together by fiberglass. The product is not on the market, but there is information on the exact PCM, a paraffin-based material. Website leads to the use of PCM in building materials in homes.

9. ***Portland Cement Association – Thermal Mass*** (website) [51]

    Covers the use of concrete as a thermal mass/ energy storage in homes. Provides info on peak loads and peak shifting using concrete. This led to the interest in using concrete since it is already used in home buildings.

10. ***Microtek Laboratoires – MICRONAL® DS 5039 X*** (Document) [52]

    The Material data sheet covers the Micronal PCM properties used in the ThermalCore drywall panels. The material is paraffin-based and made to melt at 23 °C, allowing the material to sit around that temperature. Gives details of processing and incorporating the material into other composites and applications. Using a PCM with a melting point at the desired temp will help regulate the temperature of the rooms.

3.3 Mathematical Modeling

Janelle- Resistive Heat Network

For this project it was important to conduct an analysis of the resistive heat network of the water bars. To complete this calculation, it was necessary to calculate specific numbers in relation to the flow of liquid and heat transfer. The values that were important to calculate were the Reynolds number (Re), Prandtl number (Pr), the convective heat transfer coefficient (h). These values are either calculated or can be looked up in table A.3 from the heat transfer textbook [18]. Other important calculations that were completed were finding the change in temperature and the conductive resistance at each part. A visual of this process can be seen in the appendix as well as in figure 8.11. [18] Figure 5.24 is a visual of what a general resistive heat network functions, were Fig 8.11 is an example of a concentric bars network. [18] All of the equations listed below can be found and referenced from the Heat Transfer textbook. [18] Convective heat transfer is modeled based on Reynolds and Prandtl numbers, emphasizing the importance of fluid flow dynamics, as discussed in Chapter 8 on internal flow and concentric tube annulis. [18] Conductive resistance calculations through materials like copper and PEX rely on their thermal conductivities (k), which align with Fourier's law, emphasizing the transfer from high to low temperature regions as detailed in Chapter 1. [18] These calculations provide a comprehensive thermal resitive network. This is critical for optimizing the performance of the TES units.

The inputs that are needed for the code is the geometry of the PEX pipe and the properties of the fluid. The ethylene glycol and water.

$$Re = \frac{\rho v D}{\mu}$$ Reynolds Number **(1)**

- ρ: Fluid density (kg/m³)
- v: Velocity of the fluid (m/s)
- D: Characteristic length (pipe diameter or equivalent, m)
- μ: Dynamic viscosity (Pa·s)

$$Pr = \frac{C_p \mu}{k}$$ Prandtl Number **(2)**

- Cp: Specific heat capacity at constant pressure (J/kg·K)
- k: Thermal conductivity (W/m·K)

$$Nu = 0.023 * Re^{0.8} * Re^{0.4}$$ Nusselt Number Flow **(3)**

$$h = Nu * \frac{k}{D}$$ Convective Heat Transfer Coefficient **(4)**

$$R_{total} = R_{conv1} + R_{cond1} + R_{conv2} + R_{cond2}$$

Thermal Resitance (Conductive and Convective) **(5)**

$$R_{conv} = \frac{1}{hA}$$ Convective Resistance **(6)**

$$R_{cond} = \frac{\ln\left(\frac{r2}{r1}\right)}{2\pi kL}$$ Conductive Resistance **(7)**

$$q = \frac{\Delta T}{R_{total}}$$ Heat Transfer Rate **(8)**

The outputs generated from the code to calculate the thermal resistivity of the water bars can be seen below.

Total Thermal Resistance: 1.1541 K/W

Heat Transfer Rate: 69.3194 W

The calculation of the total thermal resistance was important because it allowed the team to have values to compare the calculated results to versus the actual experiment results. The proof-of-concept testing, backed by the code's predictions allowed for validation of the calculated total thermal resistance and the heat transfer rate. The code's ability to simulate thermal behavior under varying operational conditions ensures that the TES system's ability to store energy efficiently during off-peak hours and release it during peak demand. The code also ensures that the ehanced understanding of how design variations (pipe dimensions, flow velocities) impact overall performance.

Courtney- Transient Heat Model

Calculating the amount of heat that enters the house during the time that the thermal mass is discharging is necessary to determine the amount of energy that should be removed from the mass. These calculations are made using the 1997 ASHRAE handbook method with all of the formulas and values taken from there, then Excel is used to apply to method to our project. [14]

To find the amount of heat entering the house, the heat entering from windows, walls, and roofs is added together for each hour that the mass is discharging. This is calculated by multiplying the subsequent area by the heat transfer coefficient and a variable CLTD which is determined through the ASHRAE handbook based on location and material.

$$Q_{window} = U * A * CLTD_{corrected} \quad (1)$$

$$Q_{walls} = U * A * CLTD_{corrected} \quad (2)$$

$$Q_{roof} = U * A * CLTD_{corrected} \quad (3)$$

$$Q_{total} = Q_{window} + Q_{walls} + Q_{roof} \quad (4)$$

To find the CLTD corrected value, the CLTD is found in the tables of the ASHRAE handbook using the correct latitude and longitude of phoenix and the material of the building. Those values are then plugged into the following formula. In this report, the average roof and wall CLTD values are shown, however our calculations also include the roofs and walls with the highest and lowest CLTD values.

$$CLTD_{corrected} = CLTD + (78 - TR) + (TM - 85) \quad (5)$$

TR = Indoor Room Temp **(6)**

TM = Max Outdoor Temp (Dry bulb) – Daily Range/2 (7)

Table 2

Initial Data		
Latitude	33.43	
Longitude	112.02	F
Outdoor Dry Bulb	110	F
Outdoor Wet Bulb	80	F
Daily Range	23	F
Area of Wall - North Facing	395	ft^2
Area of Wall - South Facing	395	ft^2
Area of Wall - East Facing	395	ft^2
Area of Wall - West Facing	395	ft^2
Area of Roof	1700	ft^2
Area of Windows	100	ft^2

U Walls Max	1	Btu/h*ft^2*F
U Roof Max	0.2	Btu/h*ft^2*F
U Walls Min	0.05	Btu/h*ft^2*F
U Roof Min	0.04	Btu/h*ft^2*F
U Windows	0.55	Btu/h*ft^2*F

Table 3

Min Roof - Assume Roof 14			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	32	45.5	3094
15	36	49.5	3366
16	39	52.5	3570
17	42	55.5	3774
18	44	57.5	3910
19	45	58.5	3978
20	45	58.5	3978
Total			25670

Table 4

Min North Wall - Assume Wall 16			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	9	22.5	444.4
15	10	23.5	464.1
16	11	24.5	483.9
17	13	26.5	523.4
18	14	27.5	543.1
19	16	29.5	582.6
20	17	30.5	602.4
Total			3643.9

Table 5

Min East Wall - Assume Wall 16			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)

14	26	39.5	780.1
15	28	41.5	819.6
16	30	43.5	859.1
17	31	44.5	878.9
18	31	44.5	878.9
19	32	45.5	898.6
20	32	45.5	898.6
Total			6013.9

Table 6

Min South Wall - Assume Wall 16			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	11	24.5	483.9
15	14	27.5	543.1
16	17	30.5	602.4
17	20	33.5	661.6
18	23	36.5	720.9
19	25	38.5	760.4
20	27	40.5	799.9
Total			4572.1

Table 7

Min West Wall - Assume Wall 16			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	11	24.5	483.9
15	12	25.5	503.6
16	14	27.5	543.1
17	17	30.5	602.4
18	20	33.5	661.6
19	25	38.5	760.4
20	30	43.5	859.1
Total			4414.1

Table 8

Windows (Conduction Load)			
Hour	CLTD	CLTD corrected	Q (Btu/hr)
20	8	21.5	1182.5
21	6	19.5	1072.5
22	4	17.5	962.5
23	3	16.5	907.5
24	2	15.5	852.5
1	1	14.5	797.5
2	0	13.5	742.5
3	-1	12.5	687.5
4	-2	11.5	632.5
5	-2	11.5	632.5
6	-2	11.5	632.5
Total			9102.5

Table 9

Max Q Values (Btu)		Max Q Values (kJ)		Max Q Values (kWh)	
Roof	188870	Roof	199258	Roof	55
Windows	9817.5	Windows	10357	Windows	3
Walls	278475	Walls	293791	Walls	82
Total	477163	Total	503406	Total	140
Min Q Values (Btu)		**Min Q Values (kJ)**		**Min Q Values (kWh)**	
Roof	25670	Roof	27082	Roof	8
Windows	9818	Windows	10357	Windows	3
Walls	18644	Walls	19669	Walls	5
Total	54132	Total	57109	Total	16

Courtney- Heat Equation and Phase Change Diagram Applications

An important project component is understanding phase change diagrams and the difference between latent and sensible heat. A phase change diagram is shown below, demonstrating the difference between latent and sensible heat.

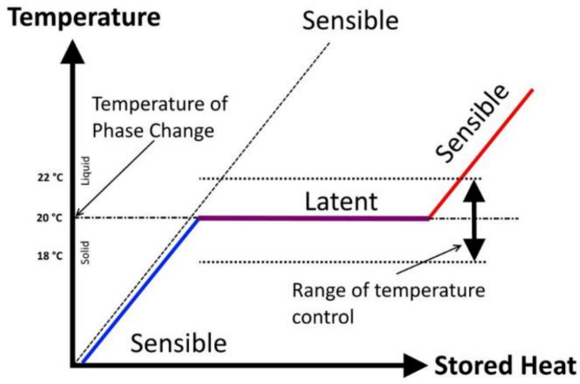


Figure 4 Phase Change Diagram [53]

An important aspect of the project is determining which material takes up the least space. To calculate this fact, a series of calculations are made in MATLAB using the equations for latent and sensible heat to determine the heat energy density of the materials and compare that to the energy requirements. The formulas for latent and sensible heat are given below.

$$\boldsymbol{Latent\ Heat = Q = m * c} \tag{8}$$

$$\boldsymbol{Sensible\ Heat = Q = m * C * \Delta T} \tag{9}$$

$$\boldsymbol{D = \frac{m}{V}} \tag{10}$$

Where

m = mass

c = heat of fusion

C = specific heat

T = temperature

V = volume

D = density

The volume of material needed is calculated by rearranging the above equations and including the additional variables of energy needed to cool the house through the night calculated in the transient heat analysis done previously in Excel. This is inputted in MATLAB in the code that can be found in the appendix, and the following graphs are created for water and concrete.

Table 10

Energy Requirmenets (kJ)	Mass Required (kg)	Volume Required (m^3)	Latent Heat Storage (kJ)	Sensible Heat Storage (kJ)
		Mass and Volume Requirements for Energy Requirements Water		
57109	135.35	0.14769	45208	11901
3.1907e+05	756.23	0.82516	2.5258e+05	66493
5.8104e+05	1377.1	1.5026	4.5995e+05	1.2108e+05
8.43e+05	1998	2.1801	6.6732e+05	1.7568e+05
1.105e+06	2618.8	2.8576	8.7469e+05	2.3027e+05
1.3669e+06	3239.7	3.535	1.0821e+06	2.8486e+05
1.6289e+06	3860.6	4.2125	1.2894e+06	3.3945e+05
1.8908e+06	4481.5	4.89	1.4968e+06	3.9404e+05
2.1528e+06	5102.3	5.5674	1.7042e+06	4.4863e+05
2.4148e+06	5723.2	6.2449	1.9116e+06	5.0322e+05
2.6767e+06	6344.1	6.9224	2.1189e+06	5.5782e+05
2.9387e+06	6965	7.5998	2.3263e+06	6.1241e+05
3.2007e+06	7585.8	8.2773	2.5337e+06	6.67e+05
3.4626e+06	8206.7	8.9548	2.741e+06	7.2159e+05
3.7246e+06	8827.6	9.6323	2.9484e+06	7.7618e+05
3.9866e+06	9448.4	10.31	3.1558e+06	8.3077e+05
4.2485e+06	10069	10.987	3.3632e+06	8.8536e+05
4.5105e+06	10690	11.665	3.5705e+06	9.3996e+05
4.7724e+06	11311	12.342	3.7779e+06	9.9455e+05
5.0344e+06	11932	13.02	3.9853e+06	1.0491e+06

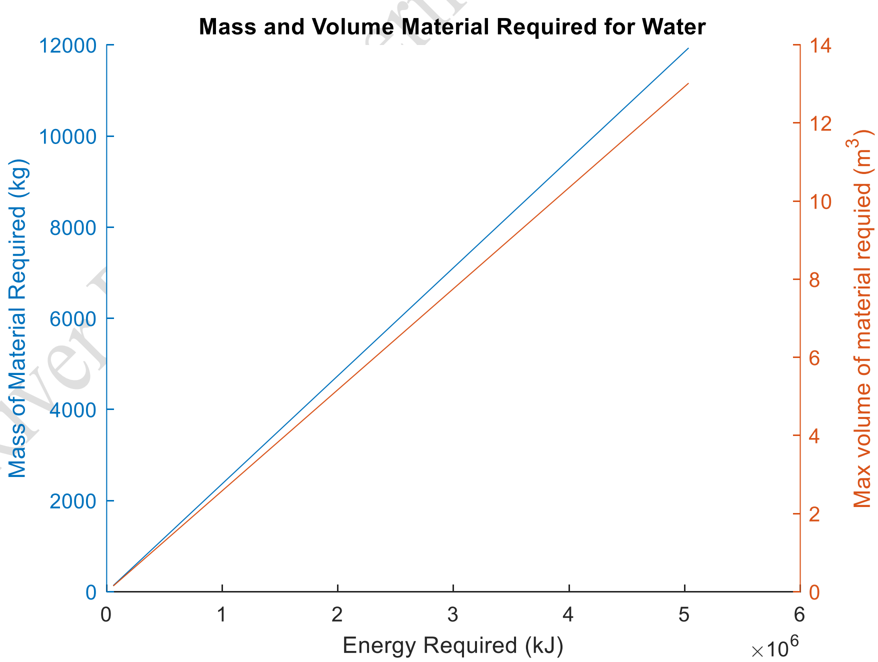


Figure 5

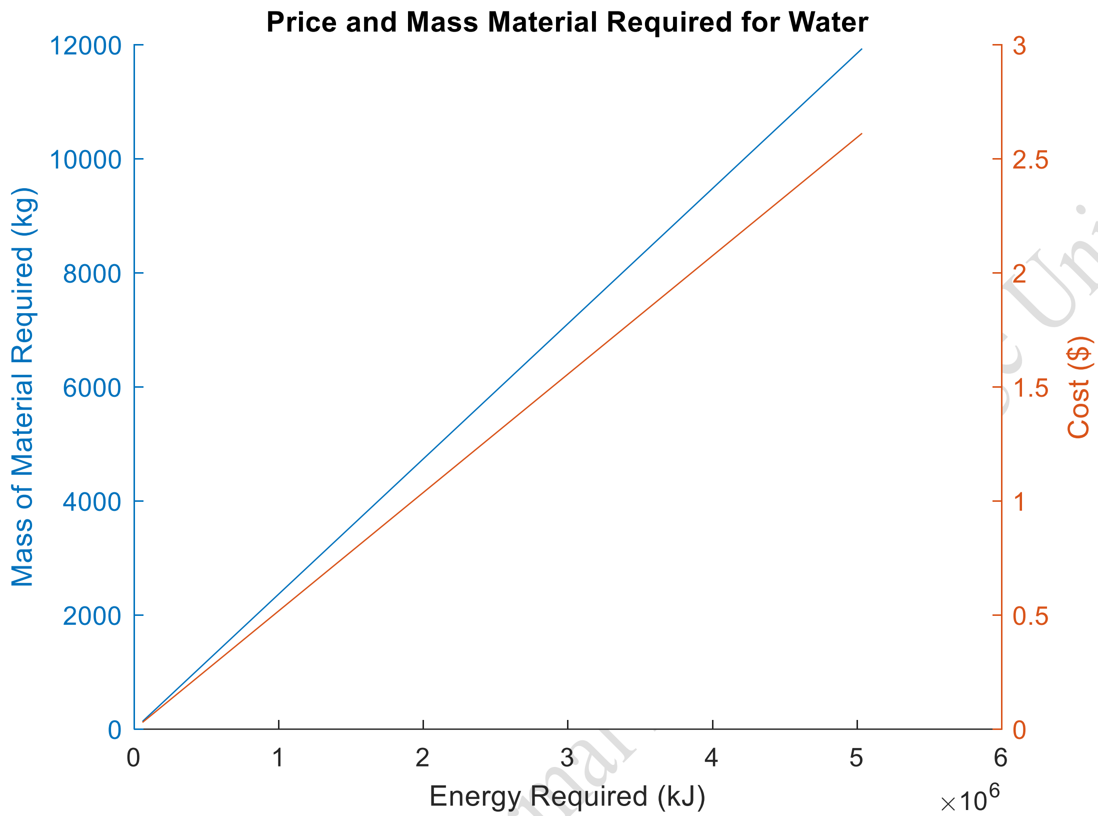


Figure 4

Table 11

Volume Requirements for Maximum Energy Requirements Water

Temperature (C)	Volume
-1	13.02
0.10526	12.899
1.2105	11.933
2.3158	11.933
3.4211	11.932
4.5263	11.933
5.6316	11.933
6.7368	11.934
7.8421	11.934
8.9474	11.935
10.053	11.936
11.158	11.937
12.263	11.939
13.368	11.94
14.474	11.942
15.579	11.944
16.684	11.946
17.789	11.949
18.895	11.951
20	11.953

'olume Requirements for Minimum Energy Requirements Water

Temperature (C)	Volume (m^3)
-1	0.14769
0.10526	0.14633
1.2105	0.13537
2.3158	0.13536
3.4211	0.13536
4.5263	0.13536
5.6316	0.13537
6.7368	0.13537
7.8421	0.13538
8.9474	0.13539
10.053	0.13539
11.158	0.13541
12.263	0.13543
13.368	0.13545
14.474	0.13547
15.579	0.13549
16.684	0.13552
17.789	0.13554
18.895	0.13557
20	0.1356

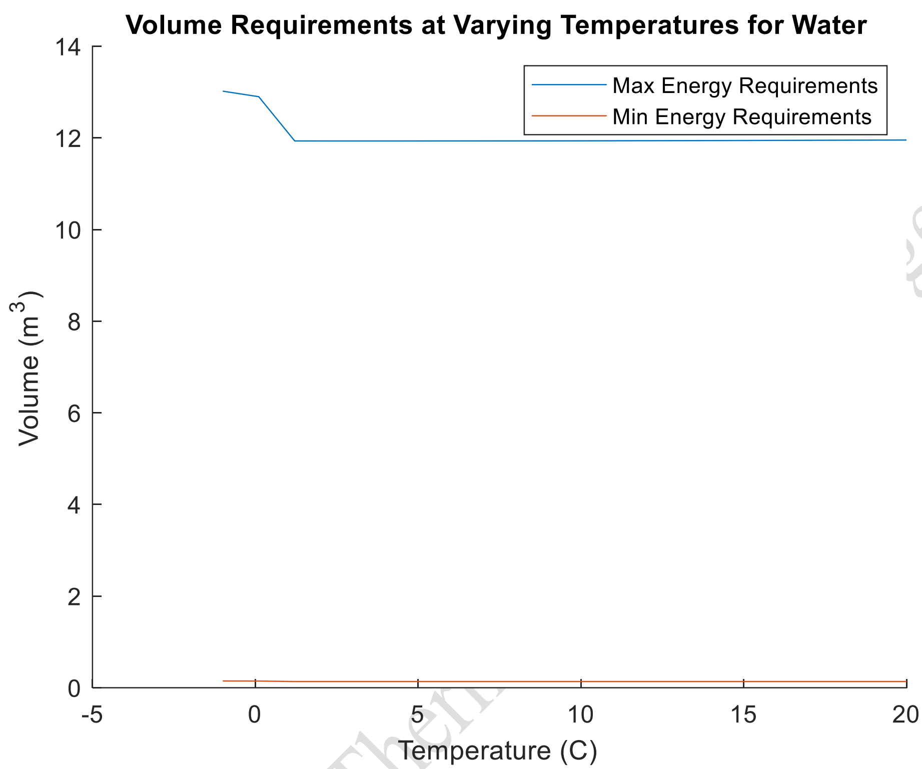


Figure 6

Table 12

Mass and Volume Requirements for Energy Requirements Concrete

Energy Requirmenets (kJ)	Mass Required (kg)	Volume Required (m^3)	Latent Heat Storage (kJ)	Sensible Heat Storage (kJ)
57109	2719.5	1.1824	0	57109
3.1907e+05	15194	6.606	0	3.1907e+05
5.8104e+05	27668	12.03	0	5.8104e+05
8.43e+05	40143	17.453	0	8.43e+05
1.105e+06	52617	22.877	0	1.105e+06
1.3669e+06	65092	28.301	0	1.3669e+06
1.6289e+06	77566	33.724	0	1.6289e+06
1.8908e+06	90040	39.148	0	1.8908e+06
2.1528e+06	1.0251e+05	44.572	0	2.1528e+06
2.4148e+06	1.1499e+05	49.995	0	2.4148e+06
2.6767e+06	1.2746e+05	55.419	0	2.6767e+06
2.9387e+06	1.3994e+05	60.843	0	2.9387e+06
3.2007e+06	1.5241e+05	66.266	0	3.2007e+06
3.4626e+06	1.6489e+05	71.69	0	3.4626e+06
3.7246e+06	1.7736e+05	77.114	0	3.7246e+06
3.9866e+06	1.8984e+05	82.537	0	3.9866e+06
4.2485e+06	2.0231e+05	87.961	0	4.2485e+06
4.5105e+06	2.1478e+05	93.385	0	4.5105e+06
4.7724e+06	2.2726e+05	98.808	0	4.7724e+06
5.0344e+06	2.3973e+05	104.23	0	5.0344e+06

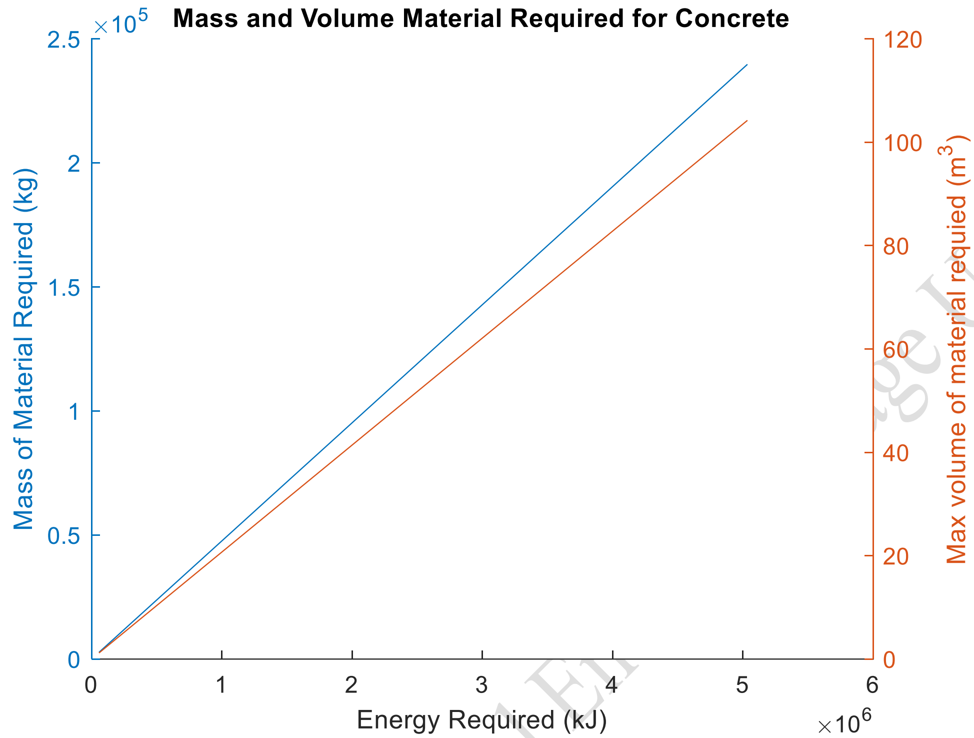


Figure 7

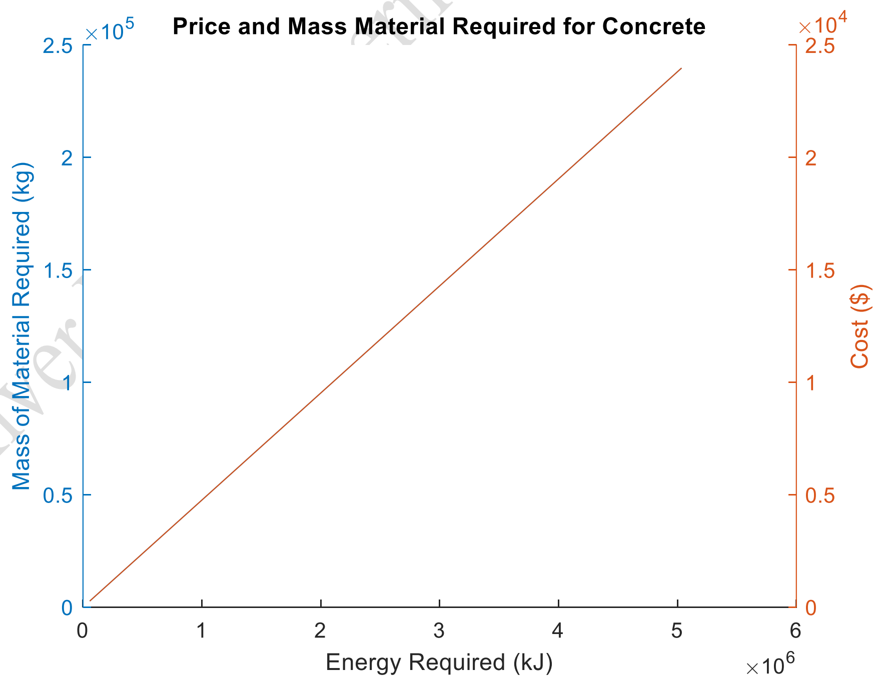


Figure 8

Steven- Morphological calculations

Now that the energy calculations can produce a value that pertains to the volume of the product, some morphology can be derived. Using SolidWorks to model a general geometry prototype is created, which can be used to gain preliminary measurements. SolidWorks will conveniently provide all the values required for the morphology of a prototype in any units required. Because the Pex-A pipe is in imperial units, the volume of the material is converted 0.1621 $m^3$is 5.724 ft^3. According to the SolidWorks model, per foot of 1-inch Pex-A with a .25-inch copper pipe inserted inside is 0.00371185 ft^3 means that our prototype will require 1542.1 feet of the prototype.

Using this method as a template and executing the rest of the materials, the calculations can inform the team how they apply to the customer and engineering requirements. It is already understood that this would be 161.7 kg of water or 356.5 pounds. Paraffin in the prototype means 2852 feet of Pex-A (10.6 ft^3 and 661.4 pounds). Concrete is 33.956 ft^3 and 5088 pounds in our prototype would be 4232.8 ft. Interestingly, in concrete, the temperature of the prototype can be decreased to values of -40 degrees Celsius or if the prototype required is cut in half. Given that concrete would not require a container like water, it can give a distinct advantage in the cost of the device.

Courtney- Arduino Temperature Sensors

During the project's testing phase, we may need to use an Arduino and temperature sensors to determine how well our design stores thermal energy. Depending on the type of sensor we use, we will need to convert the input voltage or current into temperature.

To prepare for this, the online simulation tool TinkerCad was used to model an Arduino and temperature sensor. This tool only has a TMP temperature sensor, so the modeling is based on that. To convert a TMP sensor voltage to temperature, the following equation is used: [54]

$$\boldsymbol{Temp\ (C) = (V - 0.5) * 100} \tag{11}$$

In Tinkercad, the code (found in the appendix under Figure 9) and the equation above was used to calculate the temperature using the Arduino. The values were then sent to the serial monitor.

Maciej- Net Present Value (NPV)

Net Present Value (NPV) is a crucial financial metric used to evaluate the profitability and cost-efficiency of investment projects over time. When it comes to renewable energy technologies, such as home thermal energy storage systems, net present value (NPV) analysis offers important information on how feasible these projects are. To calculate net present value (NPV), all project-related future cash flows are discounted using a predefined discount rate to their present value. When referring to a single-household thermal energy storage system, this includes:

- Initial investment: The initial outlay needed to buy and install the thermal energy storage system.
- Cash Flow: The total net cash inflows and outflows that result from the system's lifetime operation. This includes any applicable charges as well as money from energy savings and maintenance.
- Annual Discount Rate: This rate, which takes into account both the investment risk and the time value of money, is used to discount future cash flows to their present value. Usually, this rate takes into account variables like opportunity cost, inflation, and project-specific risk.

The NPV formula is expressed as:

$$NPV = \frac{Cash\ Flow}{(1+r)^t} - Initial\ Investment \tag{12}$$

Where:

r = annual discount rate

t = number of periods

With other financial data and qualitative considerations, decision-makers should evaluate the net present value (NPV) of a thermal energy storage system for a single-family household. A positive net present value (NPV) suggests that the investment may be profitable and could support moving forward. It is imperative, nonetheless, to assess net present value (NPV) in tandem with sensitivity analysis, taking into account fluctuations in critical factors, including discount rate, energy costs, and system longevity.

The team evaluated two of their thermal energy storage final designs, Water Bar, and Concrete wall made of concrete blocks. Water Bar design is expected to be manufactured. The team performed their NPV and ROI calculations based on a price of manufacturing 20,000 units. Therefore, the price of each single unit is estimated to be $367. Multiplying this number by 20,000 the total manufacturing price is estimated to be $7,333,500.00. It is assumed to sell 4,000 units annually for 5 years for the price of $700/unit. The present value is therefore calculated in table 18. The discount rate of 4.75% is being considered regarding this project. Using the Net Present Value and all of the assumptions it is calculated that the project will bring a profit of $4,873,270.52 after 5 years. The Return on Investment is estimated at 13%, that is because 5 water bar devices are needed to cool off a 1,600 ft^2 house. Therefore, the ROI value was divided by 5 units.
As for the Concrete blocks, the team decided to apply it only to a new built house. It is calculated that our design can cover 1/3 of a electricity load during on-peak hours. This design consists of

45 units of 4x4x84 inch concrete blocks. Therefore, the team came up with a design to put a wall of concrete blocks while designing and building a house. The estimated cost of materials and labor of this design is $5,416.40 as shown in table 16. Additionally, a customer is charged a $500 engineering fee and 40% mark up on materials. That brings the company a $2,292.40 profit for each project performed. It is assumed to perform 5 projects annually for 5 years. The present value is therefore calculated in table 18. Using the Net Present Value and all of the assumptions it is calculated that the project will bring a profit of $32,624.92 after 5 years. The ROI is estimated at 24%.

Below are tables supporting the NPV calculations.

Table 13

Thermal Energy Storage		
Net Present Value Calculator		
Your NPV is:	H2O Bars	Concrete
	$4,873,270.52	**$32,624.92**
Dicount Rate:	4.75%	
Period (#years):	5	

Table 14

Initial Ivestment							
H2O Bars (Manufactured Product)					Concrete (Installation at 1600ft^2 home)		
Item	Unit Needed	Cost			Item	Unit Needed	Cost
PEX-A (1")	15	$ 18.60			PEX-A (3/8") (ft)	600	$ 210.00
PEX-A Plug (1")	20	$ 54.00			PEX-A Sleeve (3/8")	600	$ 132.00
PEX-A Sleeve (1")	20	$ 13.80			Elbow Fittings (3/8")	300	$ 864.00
Copper Tube (ft)	16.5	$ 84.98			Cast Iron drain (12")	15	$ 1,275.00
Additional Fittings	6	$ 16.20			Pump & Freezer (System)	1	$ 2,000.00
Fan	1	$ 15.00					
Outer Shell	1	$ 20.00			Fan Celling	1	$ -
R&D	1	$ 0.10			Labor (hour)	32	$ 640.00
Control	1	$ 10.00			Propylene Glycol	5	$ 75.00
Propylene Glycol	2	$ 30.00			Concrete (m^3)	1.16	$ 220.40
Labor	8	$ 44.00					
Pump + Freezer	1	$ 60.00					
Total (1 unit)		$ 366.68	<- what we pay	what -> cust. Pay	Total		$ 5,416.40
Total (20,000 units)		$ 7,333,500.00			Total (25 units)		$135,410.00

Table 15

Cash Flow				
H2O Bars (#units sold)			Concrete (1600^ft Installation)	
Number of units sold	Price		Number of units sold	Price
4000	$ 2,800,000.00		5	$ 38,544.00
			Engineering Fee	$ 500.00
			Materials Coverege	$ 5,416.40
			Mark-up	$ 1,792.40
			Total	$ 7,708.80
			Profit Margin	30%

Table 16

Initial Inevstment	
H2O Bars	**Concrete**
$ 7,333,500.00	$ 135,410.00

Table 17

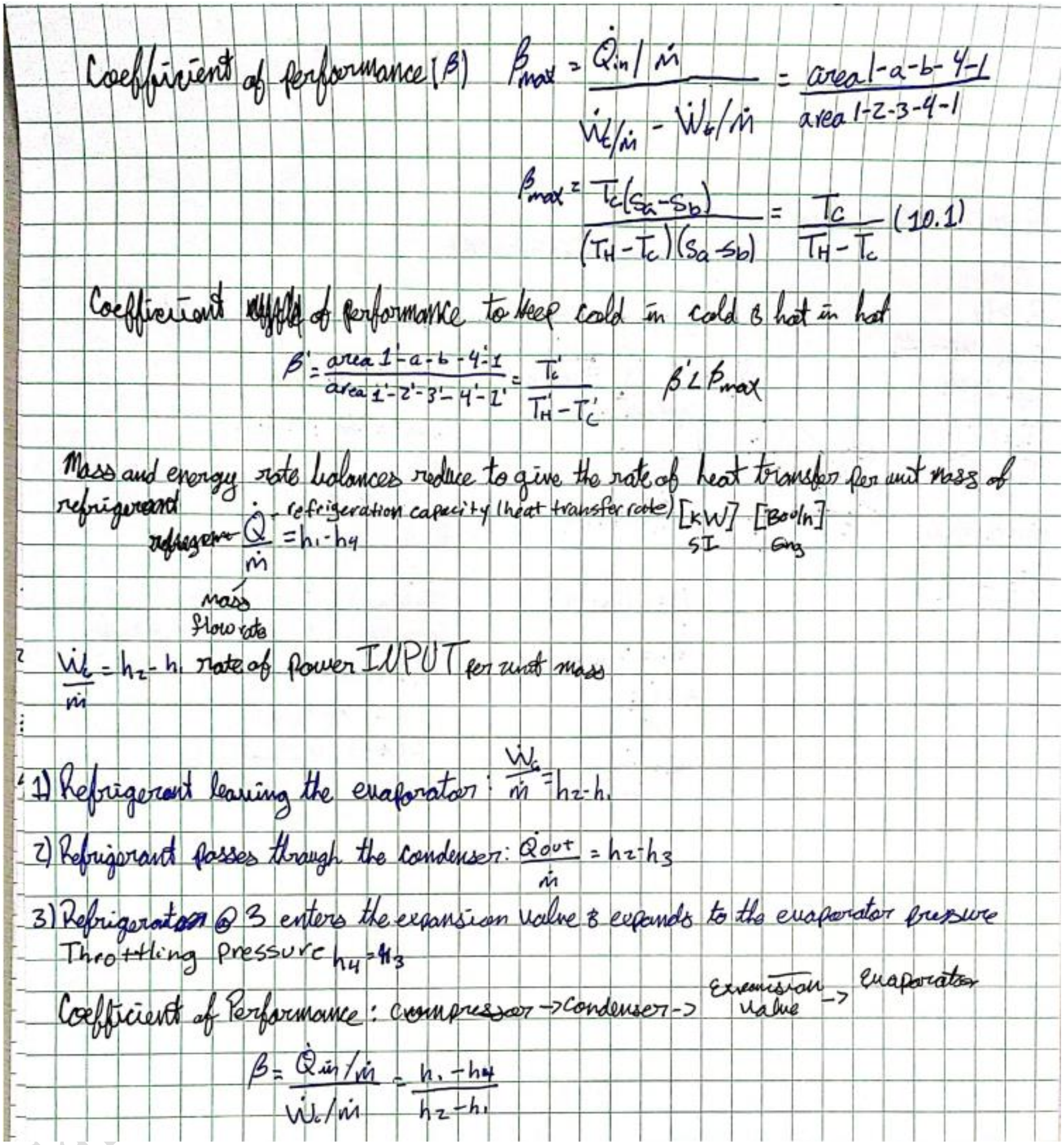
Present Value			
H2O Bars		Concrete	
Period	Cash Flow	Period	Cash Flow
1	$ 2,673,031.03	1	$ 36,796.18
2	$ 2,551,819.60	2	$ 35,127.62
3	$ 2,436,104.63	3	$ 33,534.72
4	$ 2,325,636.87	4	$ 32,014.05
5	$ 2,220,178.40	5	$ 30,562.34
Total	$ 12,206,770.52	Total	$ 168,034.92

Table 18

ROI Calaculations	
H2O Bars	Concrete
13%	24%

Janelle- Analyzing a Vapor-Compression Refrigeration Cycle

Having an analysis of the Vapor-Compression cycle of this system is crucial. This is essentially what we are doing with our device. To accomplish this I read chapter 10 of *Fundamentals of Engineering Thermodynamics (Textbook)* [19] to learn about vapor compression refrigeration cycles. From there I went through different examples of compression cycles until I was able to create one for our system. I did this in conjunction with finding the mass flow rate. I used excel to calculate some values from tables, and after that I completed the rest of the calculations by hand. The hand calculations can be seen in the figures below. The heat transfer rate (Q_dot) for the system is Q_dot= 1.310664 kJ. Refer to the figures 11 and 12 below to see the worked-out calculations.


Coefficient of performance (β) $\beta_{max} = \dfrac{\dot{Q}_{in}/\dot{m}}{\dot{W}_t/\dot{m} - \dot{W}_c/\dot{m}} = \dfrac{\text{area } 1\text{-}a\text{-}b\text{-}4\text{-}1}{\text{area } 1\text{-}2\text{-}3\text{-}4\text{-}1}$

$$\beta_{max} = \frac{T_C(s_a - s_b)}{(T_H - T_C)(s_a - s_b)} = \frac{T_C}{T_H - T_C} \quad (10.1)$$

Coefficient of performance to keep cold in cold & hot in hot

$$\beta' = \frac{\text{area } 1'\text{-}a\text{-}b\text{-}4'\text{-}1'}{\text{area } 1'\text{-}2'\text{-}3'\text{-}4'\text{-}1'} = \frac{T_C'}{T_H' - T_C'} \qquad \beta' < \beta_{max}$$

Mass and energy rate balances reduce to give the rate of heat transfer per unit mass of refrigerant

$\dfrac{\dot{Q}}{\dot{m}} = h_1 - h_4$ — $\dot{Q}$: refrigeration capacity (heat transfer rate) [kW] SI, [Btu/h] Eng; $\dot{m}$: mass flow rate

$\dfrac{\dot{W}_c}{\dot{m}} = h_2 - h_1$ rate of power INPUT per unit mass

1) Refrigerant leaving the evaporator: $\dfrac{\dot{W}_c}{\dot{m}} = h_2 - h_1$

2) Refrigerant passes through the condenser: $\dfrac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$

3) Refrigerant @ 3 enters the expansion valve & expands to the evaporator pressure

Throttling pressure $h_4 = h_3$

Coefficient of Performance: compressor -> condenser -> Expansion valve -> Evaporator

$$\beta = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m}} = \frac{h_1 - h_4}{h_2 - h_1}$$

Figure 9

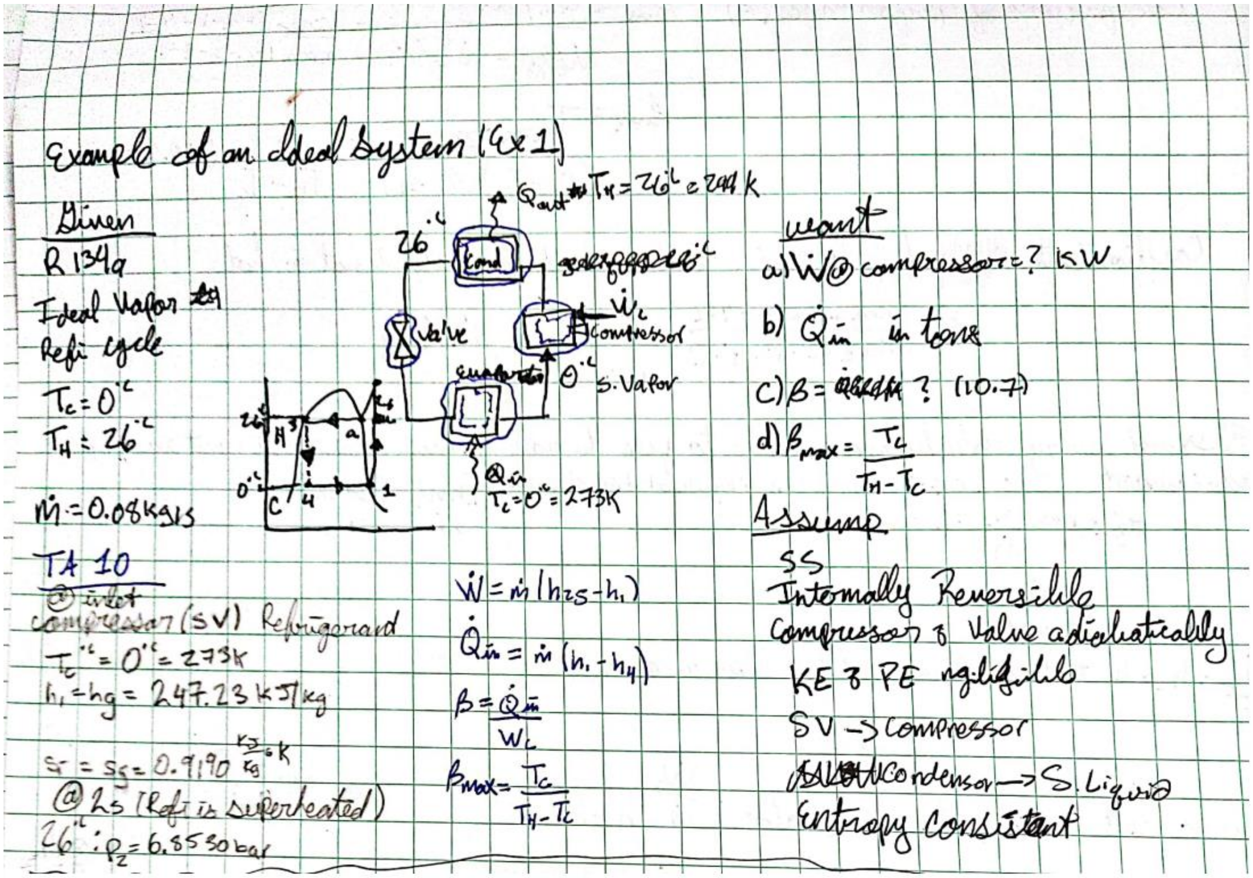

Example of an Ideal System (Ex 1)
Given
R134a
Ideal Vapor
Refi cycle
Tc = 0°C
TH = 26°C
ṁ = 0.08 kg/s
TA 10
@ inlet
compressor (SV) Refrigerant
Tc = 0°C = 273K
h1 = hg = 247.23 kJ/kg
s1 = sg = 0.9190 kJ/kg·K
@ 2s (Refi is superheated)
26°C : P2 = 6.8530 bar
Qout TH = 26°C = 299 K
26°C
Cond
Valve
Compressor
evaporator
0°C
S. Vapor
Qin
Tc = 0°C = 273K
Ẇ = ṁ (h2s - h1)
Q̇in = ṁ (h1 - h4)
β = Q̇in / Ẇc
βmax = Tc / (TH - Tc)
want
a) Ẇ @ compressor = ? kW
b) Q̇in in tons
c) β = ? (10.7)
d) βmax = Tc / (TH - Tc)
Assump
SS
Internally Reversible
Compressor & Valve adiabatically
KE & PE negligible
SV -> Compressor
Condensor -> S. Liquid
Entropy consistant

Figure 10

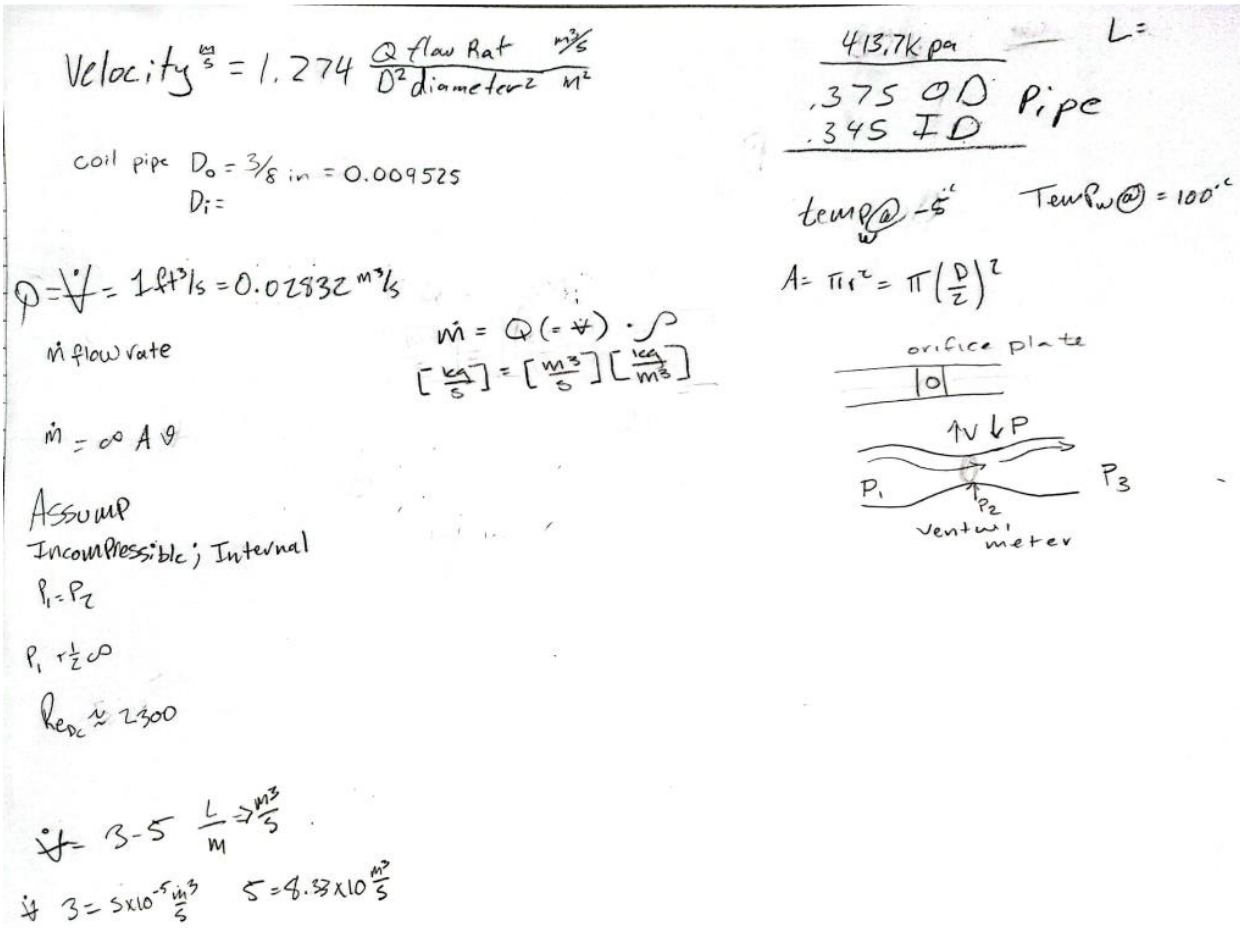


Figure 11

Table 19

Temperature (°C)	Absolute Pressure (bar)	Density Liquid (kg/m³)	Density Vapor (kg/m³)	Enthalpy Liquid (kJ/kg)	Enthalpy Vapor (kJ/kg)	Entropy Liquid (kJ/(kgK))	Entropy Vapor (kJ/(kgK))				
-60	0.15935	1472	0.9291	24.491	261.491	0.68772	1.8014				
-50	0.29477	1444.9	1.6526	36.302	267.779	0.74358	1.7809				
-40	0.51225	1417	2.773	48.631	274.068	0.79756	1.76448				
-30	0.84379	1388.2	4.4307	61.13	280.324	0.84995	1.75142				
-20	1.32719	1358.4	6.7903	73.833	286.513	0.901	1.74113	*m (kg/s)	0.05	Aveage mass flow rate of R134a	
-10	2.00575	1327.4	10.047	86.777	292.598	0.95095	1.73309	Temp	-40	50	0
0	2.,92769	1295.1	14.433	1000	298.536	1	1.72684	*V (m^3/S)	3.52858E-05	4.53638E-05	3.86071E-05
10	4.14571	1261.2	20.226	113.54	304.276	1.04834	1.72196				
20	5.71665	1225.5	27.773	127.437	309.756	1.09613	1.71806				
30	7.70132	1187.5	37.517	141.736	314.892	1.14354	1.71473				
40	10.1648	1146.7	50.055	156.491	319.575	1.19073	1.71152				
50	13.1773	1102.2	66.234	171.778	323.652	1.23794	1.70792				
60	16.8156	1052.9	87.346	187.715	326.896	1.28548	1.70325				
70	21.1668	996.49	115.564	204.515	328.941	1.3339	1.6965				
80	26.3336	928.78	155.13	222.616	329.095	1.38434	1.68585				
90	32.4489	838.51	216.936	243.168	325.655	1.43978	1.66692				
100	39.7254	649.71	367.064	273.641	309.037	1.5198	1.61466				

Aaron – Biot Number Calculation and Lumped Capacitance

```
%Lumped Capacitance ahe

Ti = -40;          % Initial temperature of the TES (°C)
T_inf = 36;        % Ambient temperature (°C)
h = ;            % Convective heat transfer coefficient (W/m^2.K)
A = 0.00262903663;        % Wetted surface area of the TES (m^2)
rho = 1000;        % Density of the material (kg/m^3)
V = 0.0056613;     % Volume of the TES (m^3)
cp = 4182;          % Specific heat capacity of the material (J/kg.K)
k = 0.6;           % Thermal conductivity of the material (W/m.K)
tmax = 14400;       % Time in seconds (1hr=3600s, 4 hr=14400s)

% Calculate the characteristic length
L_c = V / A;

% Calculate the Biot number
Bi = h * L_c / k;

% Check if lumped capacitance method is valid
if Bi >= 0.1
    error('Biot Number is too large (Bi = %.3f). Lumped Capacitance method is not valid.', Bi);
else
    disp(['Biot Number: ', num2str(Bi)])
    disp('Lumped capacitance method is valid. Proceeding with the solution...')
end
% Time vector (seconds)
t = linspace(0,tmax, 100);  % Time from 0 to tmax

% Lumped capacitance solution
T_t = T_inf + (Ti - T_inf) * exp(-h * A * t / (rho * V * cp));

% Plot the results
figure;
plot(t, T_t, 'LineWidth', 2);
xlabel('Time (s)');
ylabel('Temperature (°C)');
title('Temperature vs. Time using Lumped Capacitance Method');
grid on;
```

Figure 12

The calculation for the Biot number was necessary to determine if the lumped capacitance method would apply to our system. I wrote a MATLAB script seen in figure 12 that would compute a simple calculation and check to see if it meets the parameters being if the Biot number is calculated to be less than 0.1 then if the lumped capacitance method applies it can be used to determine how the concrete thermal mass or the Waterbars would cool/heat over time. The script needs the user to input the temperatures of the thermal mass and the ambient as well as the heat transfer coefficient, the surface area, density, volume, specific heat capacity, thermal conductivity, and time that the mass will be subjected to these parameters.

After the parameters for the calculations are set the next thing, the script does is calculate for the characteristic length. That is the last variable needed to solve for the Biot number. The next calculation which is for the Biot number uses the equation used in the Heat transfer textbook [18]. After running this code for the parameters for the water thermal mass which can be seen in appendix B, the Biot number was calculated and was not less than 0.1. The same was done for the concrete thermal mass and the Biot number led us to determine that the lumped capacitance *would not apply to either of the thermal energy storages designed by the team because the assumption of the materials thermal resistance being negligible could not be made.*

Steven- External flow and bank of tubes external flow

The external flow of air over the device is the method of delivery of cold air. In the fashion of the datum is to pump glycol and operate a fan. Ours is only to operate a fan over the chilled surface. To obtain the theoretical model Matlab was employed.

To solve the external flow over the water bars a Matlab lab code was created. Simulating a bank of tubes with five bars in staggered rows.

Chapter 4: Design Concepts

4.1 Functional Decomposition

The following models demonstrate the function of the system. The color codes correlate the varying graphs to demonstrate which functions happen in their corresponding component.

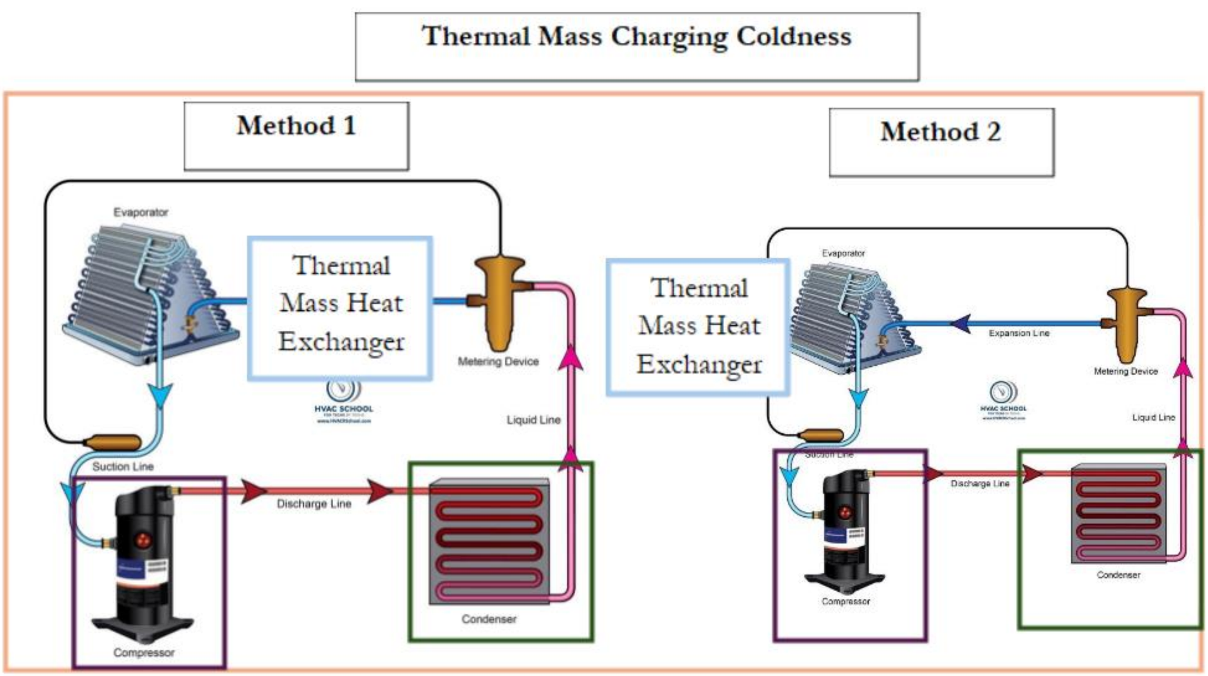


Figure 13: Removing Thermal Energy from Thermal Mass

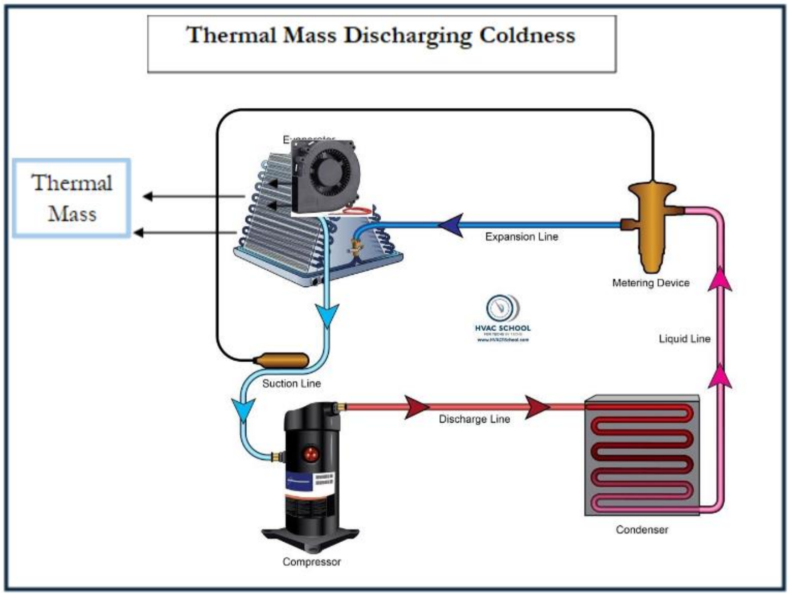


Figure 14

Black Box Model Simplified

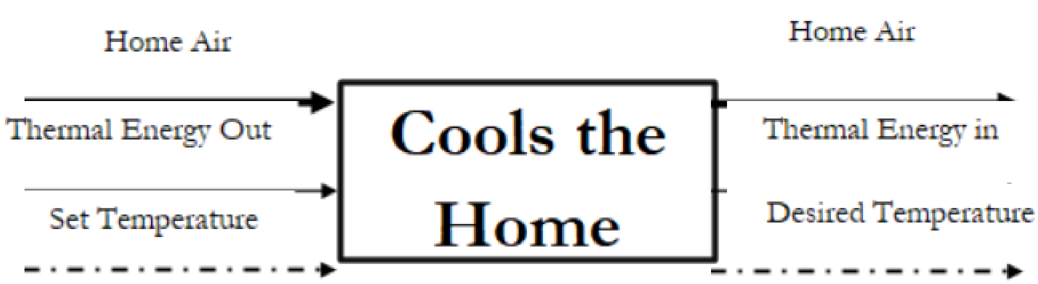


Figure 15

Black Box Model Diagram

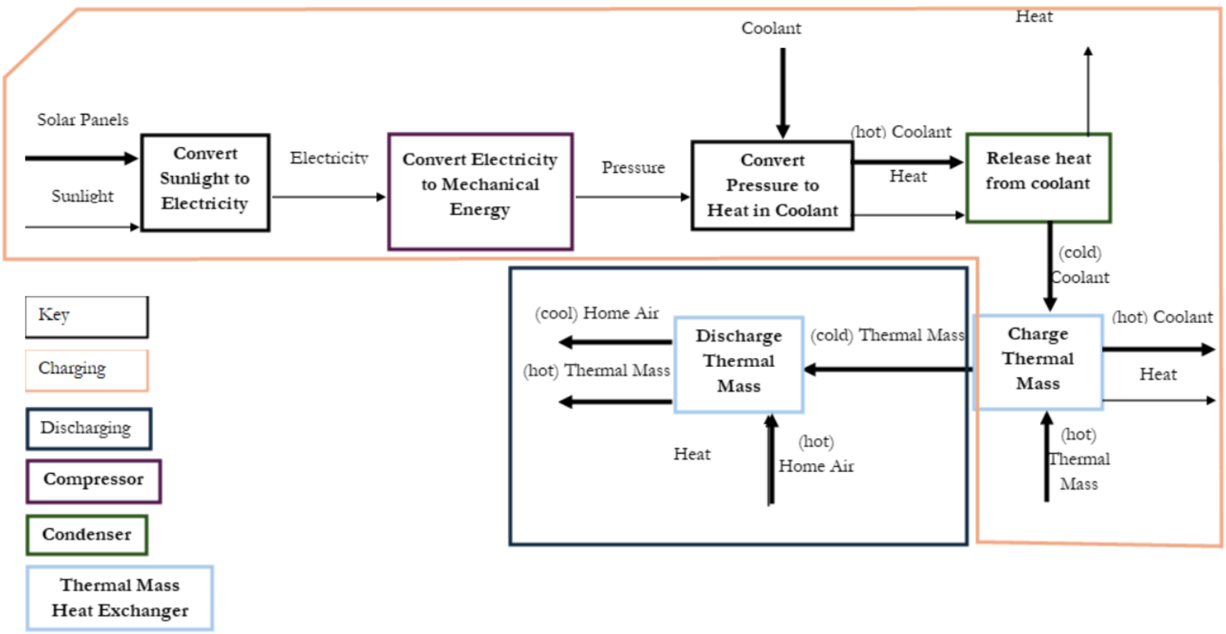
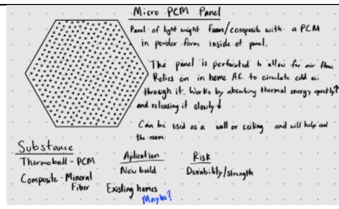
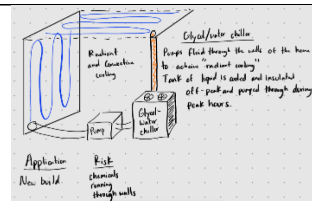
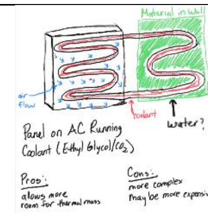
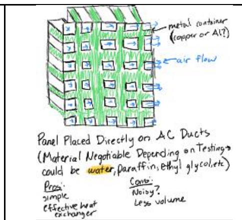
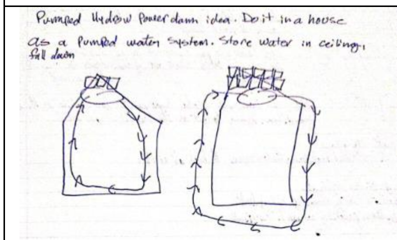
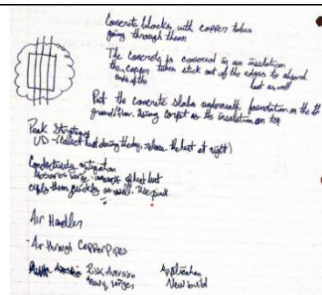
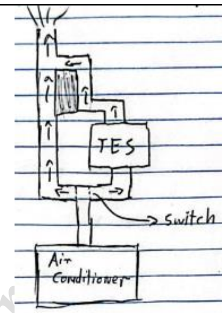
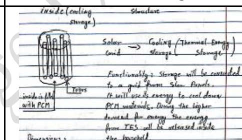
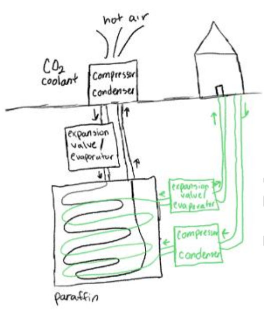
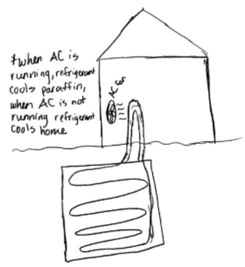


Figure 16

4.2 Concept Generation

After taking in the research and other designs we developed a method for categorizing and quantifying the ideas we generated. This is a conglomeration of design criteria, customer requirements, and engineering models. The first rounds of concepts are raw with no values that coincide with the engineering models. As more input from the client were added values for volume, energy capacity, and latent heat.

 *Figure 17* Aaron	 *Figure 18* Aaron	 *Figure 19* Courtney	 *Figure 20* Courtney
 *Figure 21* Janelle	 *Figure 22* Janelle	 *Figure 23* Maciej	 *Figure 24* Maciej

 *Figure 25* Courtney	 *Figure 26* Courtney

Initial Brainstorming Ideas

The design process began with brainstorming ideas and creating ideas for systems. Each member of the team sketched out some ideas with not many requirements and not too many. These sketches can be seen in the table above.

The first two designs were created by Aaron and the first one to the left is a PCM panel that has a microencapsulated phase change material that is inside of a composite type of panel such as a fiber panel that is perforated to allow for high airflow through the panel to ease in the phase change process. To the right of that design is a 'Radiant Cooling' design that works by having copper piping run through the walls with a mixture of Ethylene Glycol pumped through that is chilled and with the walls being cooled so much that the room encased will be cooled radiantly.

The next two designs to the right were created by Courtney and the first she made consists of filled with water that flows through a phase change material that could possibly sit inside of a wall and the piping also leads to a high air flow area such as an air vent. The next consists of a panel much like the PCM Panel mentioned above but the main improvement here is that there is more of the PCM and more surface area for there to be more heat conductivity. The idea with this design is to place the panel right at the exit of the AC vents to force more air flow and phase change the material and therefore be able to quickly use the energy stored inside.

Janelle's ideas began with 'Puffy Cement' which in theory is a block of cement which will be the material used to dump heat out of and then with insulation the block will be held at a low temperature. The insulation is where the name puffy comes from, assuming pink fiberglass insulation is used. Also, there is the idea of using solar energy to heat water and storing that energy to be used in an HVAC unit.

Maciej's ideas consist of a block of phase change material that can be incorporated into a preexisting HVAC system. The idea is to redirect the airflow into another air vent that led to the PCM when it needs to be cooled and melted to be used at that temperature. The other design is very similar to Courtneys updated design where the PCM has copper tubes running though to aid in conducting heat. The copper will allow for the temperature of the PCM to be controlled depending on the fluid that flows through.

These initial concepts were also used to develop all the sub functions of the later devices that are combined to make the final design. This process also informed the need for data about substances that still need values that will be found through experiment. This process allows us to move into the selection criteria.

4.3 Selection Criteria

4.3.1 Applying the Requirements.

Using the ideas the team generated, and the newly created sub functions the concepts are refined into 6. The requirements and models are applied to find what the 6 will look like and cost. Here every subfunction's value needs to be justified. Such that expensive paraffin's will need a morphological aspect to justify the cost. N-Tetradecane with an estimated cost of $380 per kilogram and using geometry and listed values of latent heat a value for the device is developed.[55] The team had to discuss what would cause paraffin to no longer be allowable. In that case the paraffin latent heat will need to have some way to mitigate the lag in water. If the concept cannot overcome the cost, it will be removed and the mitigation techniques for the damage caused by water expansion will become the winning concept. Along with these criteria restrictions we needed to include government regulations.

4.3.2 Government Regulations

Our team is thoroughly examining various building codes, such as the International Existing Building Code (IEBC), International Energy Conservation Code (IECC), and International Fire Code (IFC), to ensure the safety and compliance of integrating thermal energy storage systems into air conditioning units in Phoenix homes. [38], [56], [37] Understanding these standards is critical because they provide broad concepts and regulations for retrofitting, energy efficiency, and fire safety in buildings. By examining these codes, we want to acquire useful insights into building and implementing thermal energy storage solutions that optimize energy usage, improve environmental sustainability, and limit possible hazards such as flammability issues connected with phase change materials (PCMs). The team’s goal is to build integrated systems that not only fulfill high safety and performance standards, but also help Phoenix households save energy and money on utilities while maintaining their comfort and safety. Another team’s goal is to meet criteria for the energy star program that would enhance financing and marketing of our product and attract other companies and clients to partner up with our team. [36]

The International Existing Building Code (IEBC) establishes comprehensive principles and requirements for retrofitting and renovating existing buildings, assuring their safety, sustainability, and energy efficiency. [38] By studying this code, we can gain significant insights into creating a thermal energy storage system that integrates with wall-mounted air conditioning units. Incorporating thermal energy storage into these systems is consistent with IEBC's emphasis on energy conservation and sustainability. Using materials with high thermal mass, such as phase change materials (PCMs), in building walls can efficiently absorb and release heat, minimizing reliance on traditional HVAC systems during peak demand periods. Compliance with IEBC standards guarantees that these integrated systems meet safety and performance requirements, which improves overall building efficiency and environmental sustainability. Furthermore, using the IEBC rules can help with the smooth integration of thermal energy storage solutions into existing building structures, maximizing space use and improving overall building performance.

The International Energy Conservation Code (IECC) establishes critical criteria and principles for improving building energy efficiency, providing useful insights for constructing a thermal energy storage system integrated into the air conditioning unit of a single-family home in Phoenix. Given Phoenix's hot environment, thermal energy storage can help optimize energy consumption during peak demand hours. By introducing phase change materials (PCMs) or other thermal storage mediums into the air conditioning system, excess thermal energy generated during off-peak hours can be stored and released during peak periods, reducing grid load, and increasing overall energy efficiency. Compliance with IECC assures that the integrated system meets high energy efficiency regulations, resulting in reduced energy usage and lower utility costs for Phoenix homeowners while preserving comfort levels within the home. [56] Additionally, following IECC rules allows for seamless integration with current building regulations and standards, ensuring compliance and safety in the design and implementation of thermal energy storage solutions.

The International Fire Code (IFC) establishes crucial norms and standards for building fire safety and essential recommendations for constructing thermal energy storage systems that use phase change materials (PCMs) that may represent flammability risks. [37] When incorporating such materials into a single-family home in Phoenix, where fire safety is crucial, following IFC requirements is critical. Installing fire-resistant enclosures and containment measures around the PCM storage units can reduce potential fire risks. Furthermore, adding automatic fire suppression systems and using non-flammable PCM substitutes whenever available is consistent with the IFC's objective on reducing fire threats. By adhering to IFC requirements, engineers may ensure the safe integration of thermal energy storage systems using PCMs within residential constructions in Phoenix, increasing both energy efficiency and fire safety for homeowners.

The United States Environmental Protection Agency (EPA) established the Energy Star program to promote energy efficiency and sustainability in consumer products, buildings, and enterprises. Products and technologies that earn the Energy Star label meet the EPA's high energy efficiency criteria, showing that they use less energy than standard versions while providing the same or improved performance. [36] Our proposal, which involves the integration of thermal energy storage into air conditioning systems, is in line with Energy Star's objectives. Thermal energy storage allows us to optimize the energy consumption of air conditioning devices, lowering overall power consumption during peak demand periods. This meets Energy Star's requirements for energy-efficient products and technologies.

Meeting Energy Star criteria with our thermal energy storage technology can provide various advantages for our project. First, it improves marketability by highlighting our system's energy efficiency and environmental friendliness, thus attracting additional consumers and clients. Second, it can lead to cash incentives and rebates from Energy Star and other energy efficiency programs, lowering the initial expenses of implementing our solution. Furthermore, satisfying Energy Star standards may lead to new financial opportunities or collaborations with groups dedicated to sustainability and energy efficiency.

4.4 Concept Selection

Table 20

CRITERIA DESCRIPTION	Is it realizstic for the average home buyer, Pre-Build	How Hot/Cold will it make the house of the customer	How efficient is it	The expected compound annual rate of re turn that will be earned on a project or investment	between the present val ue of cash inflows and the present val ue of cash outflows over a period of	Does it need monthly/yearly/Every 5 year maintance. Refills, Parts, Repairs, Ease of Access,	Saves Power because it doesn't use prime time power/How well does it ease the load off of the grid during peak time, use power during low	Does it explode, catch fire, freeze someones hand if touched	
	Pre-Existing	Comfort Level	Efficiency	Internal Rate of Return (IRR)	Net Present Value (NPV)	Ease of Maintenance	Power Saving/Grid Assistance	Safety	WEIGHTED SCORE
WEIGHT	5	3	6	2	7	4	1	8	36
	14%	8%	17%	6%	19%	11%	3%	22%	100%

Table 21

OPTIONS									
Integrating into an AC cycle	7	4	5	8	4	6	3	6	5.444
Panel Placed Directly on AC Ducts	5	3	4	4	2	6	2	6	4.278
Material in Wall	5	3	4	2	4	5	3	6	4.472

Decision Matrix

Table 22

CRITERIA DESCRIPTION		WEIGHT		OPTIONS	Integrating into an AC cycle
Is it realizstic for the average home buyer, Pre-Build	Pre-Existing	5	14%		7
How Hot/Cold will it make the house of the customer	Comfort Level	3	8%		4
How efficient is it	Efficiency	6	17%		5
The expected compound annual rate of return tha t will be earned on a project or investment	Internal Rate of Return (IRR)	2	6%		8
The difference between the present value of cas h inflows and the present value of cas h outflows over a period of time	Net Present Value (NPV)	7	19%		4
Does it need monthly/yearly/Every 5 year maintance. Refills, Parts, Repairs, Ease of Access,	Ease of Maintenance	4	11%		6
Saves Power because it doesn't use prime time power/How well does it ease the load off of the grid during peak time, use power during low	Power Saving/Grid Assistance	1	3%		3
Does it explode, catch fire, freeze someones hand if touched	Safety	8	22%		6
	WEIGHTED SCORE	36	100%		**5.444**

Final Design Ranking

The top criteria that our design was ranked on in the decision matrix were: Listed lowest importance to highest. (8= highest,1=lowest)

1. Power Saving/Grid Assistance
    a. Saves Power because it doesn't use prime time power.
    b. How well does it ease the load off the grid during peak time, use power during low?

2. Internal Rate of Return (IRR)
    a. The expected compound annual rate of return that will be earned on a project or investment.
3. Comfort Level
    a. How Hot/Cold will it make the house of the customer?
4. Ease of Maintenance
    a. Does it need monthly/yearly/Every 5-year maintenance. Refills, Parts, Repairs, Ease of Access?
5. Pre-Existing
    a. Is it realistic for the average home buyer, Pre-Build?
6. Efficiency
    a. How efficient is it?
7. Net Present Value (NPV)
    a. The difference between the present value of cash inflows and the present value of cash outflows over a period.
8. Safety
    a. Does it explode, catch fire, freeze unexpectedly? How heavy is it? Will it fall on someone and kill them?

Since the last report there have been many designs that have been eliminated for various reasons. The underground systems would have been extremely difficult to maintain. The designs that integrated the thermal mass into the air conditioning system received positive reviews from our client, ranking them higher on the decision matrix.

After lots of deliberation, calculations, and realization of time and what is possible with the timeline and costs, we finally came to a decision of 2 high quality designs. As well as completing the calculations and deliberating as a team, we also re-ranked our designs on each of the fields, we had two final designs: Placing panels directly on AC ducts and integrating them into the air conditioning cycle. We selected these two designs because as we move into the testing and prototyping phase, we need to determine through testing if the mass stores cool energy better through the expansion line or in the evaporator. This is very important step in this process. At this point, the main and last step is to test materials within the different prototypes we have created, both physical and digital models.

A thermodynamic model of the general design is shown below, with the two designs integrated into their respective locations. We will test these designs using temperature sensors to determine the best. The final design can be found in the appendix under Figure 11.

Chapter 5: Schedule and Budget

5.1 Schedule

Spring Semester Schedule

TASK	ASSIGNED TO	PROGRESS	START	END
Presentation 1				2/5/24
Schedule	Courtney	100%	4/22/24	2/1/24
Meet with Client	Everyone/Janelle	100%	2/2/24	2/2/24
Find 3 Existing Designs	Aaron	100%	1/31/24	2/3/24
Literature Review	Everyone	100%	1/31/24	2/3/24
Mathematical Modeling	Steven	100%	1/31/24	2/3/24
Budget	Maciej	100%	1/31/24	2/3/24
QFD	Janelle	100%	2/3/24	2/3/24
PowerPoint Presentation	everyone	100%	2/4/24	2/5/24
Presentation 2				2/26/24
Update Gantt Chart	Courtney	100%	2/6/24	2/10/24
Concept Generation	Split evenly	100%	2/6/24	2/17/24
Pugh Chart	Steven, Aaron	100%	2/12/24	2/19/24
Decision Matrix	Janelle	100%	2/18/24	2/21/24
Bill of Materials	Maciej	100%	2/22/24	2/25/24

Engineering Calculations	Steven	100%	2/6/24	2/25/24
Function Flow Handout	Courtney	100%	2/6/24	2/25/24
Hypothesized Functional Models	Janelle	100%	2/6/24	2/25/24
Look for Fundraising	Maciej	100%	2/6/24	2/25/24
PowerPoint Presentation	Everyone	100%	2/26/24	2/26/24
Website Check 1				3/15/24
Team Pictures	Janelle	100%	3/5/24	3/9/24
Project Description	Aaron	100%	2/19/24	3/9/24
Team about us	Maciej	100%	2/19/24	3/9/24
Documents	Steven	100%	2/19/24	3/9/24
Gallery	Janelle	100%	2/19/24	3/9/24
Project Description Page Code	Courtney	100%	2/19/24	3/15/24
Team About Us Page Code	Steven	100%	2/19/24	3/15/24
Gallery Page Code	Steven	100%	2/19/24	3/15/24
Documents Page Code	Courtney	100%	2/19/24	3/15/24
Website Active	Courtney, Steven	100%	2/19/24	3/15/24
Report 1				3/15/24
Background	Maciej	100%	2/26/24	3/16/24
Customer/Engineering Req	Janelle	100%	2/26/24	3/15/24

Executive Summary	Janelle	100%	2/26/24	3/8/24
Format and Grammer	Courtney	100%	3/13/24	3/15/24
QFD	Janelle	100%	2/26/24	3/8/24
Literature Review	7 each	100%	2/26/24	3/15/24
Mathematical Modeling	2 each	100%	2/26/24	3/15/24
Decision Matrix	Janelle	100%	2/26/24	3/15/24
Pugh Chart	Aaron	100%	2/26/24	3/15/24
Consumer regulations	Maciej, Steven	100%	2/26/24	3/15/24
Building Codes	Maciej, Steven	100%	2/26/24	3/15/24
Functional Decomposition Chart	Courtney	100%	2/26/24	3/15/24
Concept Generation	Aaron	100%	2/26/24	3/15/24
Conclusion	Courtney	100%	2/26/24	3/15/24
Analysis Memo				3/22/24
Select Individual Topic	Everyone	100%	3/19/24	3/22/24
Write About Topic in Report	Everyone	100%	3/19/24	3/22/24
Presentation 3				4/1/24
Drawing Views of Designs	Aaron	100%	3/24/24	4/8/24
Top Level Design functions	Steven	100%	3/24/24	4/8/24
Important sub-assemblies	Aaron	100%	3/24/24	4/8/24

Flow Charts	Courtney	100%	3/24/24	4/8/24
Project Description	Courtney	100%	3/24/24	4/8/24
QFD	Janelle	100%	3/24/24	4/8/24
Engineering Calculations	Janelle, Steven, Courtney	100%	3/24/24	4/8/24
Analysis Tools (Arduino, Material Analysis)	Courtney	100%	3/24/24	4/8/24
Analysis Tools (Ansys)	Steven	100%	3/24/24	4/8/24
ER and CR's yet to be quantified	Janelle	100%	3/24/24	4/8/24
FMEA/list potential failures	Steven, Maciej	100%	3/24/24	4/8/24
Testing Procedures	Maciej, Aaron	100%	3/24/24	4/8/24
List equipment needed	Maciej	100%	3/24/24	4/8/24
Schedule for next term	Courtney	100%	3/24/24	4/8/24
Project Budget	Maciej	100%	3/24/24	4/8/24
Physical Copies of Diagrams/Drawings	Aaron	100%	3/31/24	4/8/24
Prototype Demo				4/1/24
Physical Prototype	Aaron, Maciej	100%	3/19/24	4/1/24
Virtual Prototype	Steven, Janelle	100%	3/19/24	4/1/24
Report #2				4/26/24
Project Description	Courtney	100%	4/1/24	4/23/24
Deliverables	Team	100%	4/1/24	4/23/24

Success Metrics	Team	100%	4/1/24	4/23/24
Customer Requirements	Janelle	100%	4/1/24	4/23/24
Engineering Requirements	Janelle	100%	4/1/24	4/23/24
House of Quality (QFD)	Janelle	100%	4/1/24	4/23/24
Benchmarking	Aaron	100%	4/1/24	4/23/24
Literature Review (10+ each)	Everyone	100%	4/1/24	4/23/24
Math Modeling – Vapor Compression Cycle	Janelle	100%	4/1/24	4/23/24
Math Modeling - NPV	Maciej	100%	4/1/24	4/23/24
Transient Heat Model	Janelle*/Courtney	100%	4/2/24	4/23/24
Math Modeling - Morphology	Steven	100%	4/1/24	4/23/24
Math Modeling - Materials	Courtney	100%	4/1/24	4/23/24
Functional Decomposition	Courtney	100%	4/1/24	4/23/24
Concept Generation	Maciej	100%	4/1/24	4/23/24
Selection Criteria	Aaron	100%	4/1/24	4/23/24
Concept Selection - Decision Matrix	Janelle	100%	4/1/24	4/23/24
Concept Selection - Fos	Steven	100%	4/1/24	4/23/24
Schedule	Courtney	100%	4/1/24	4/23/24
Budget	Maciej	100%	4/1/24	4/23/24
Bill of Materials	Maciej	100%	4/1/24	4/23/24

FMEA (failure analysis)	Steven	100%	4/1/24	4/23/24
Initial prototyping	Aaron	100%	4/1/24	4/23/24
Other Engineering Calculations	Team	100%	4/1/24	4/23/24
Future Testing Potential	Maciej and Aaron	100%	4/1/24	4/23/24
Final CAD and BoM				4/26/24
CAD	Aaron, Steven	100%		4/26/24
Bill of Materials	Maciej	100%		4/26/2024
2nd Prototype Demo				4/29/24
Physical Prototype	Aaron Maciej	100%		4/29/24
Virtual Prototype	Janelle, Steven	100%		4/29/24
Project Management Assignment				5/3/24
List of Successes		100%		
List of imporvements		100%		
List of action items		100%		
Remaining design efforts		100%		
Gantt chart for 2nd semester		100%		
Purchasing plan		100%		
Manufacturing Plan		100%		
Website Check #2				5/5/24

CAD and prototyping images
Update Pages
Submit live link

Fall Semester Schedule

	TASK	ASSIGNED TO	PROGRESS	START	END
	Initial Tasks				
Initial tasks	Update Gantt chart	Courtney	100%	8/1/24	8/26/24
	Submit Purchase Request	Maciej	100%	8/26/24	9/5/24
	Assign parts	Courtney	100%	8/26/24	9/5/24
	Project Management Assignment			8/31/24	
Updates from last semester	Update Header Information	Janelle	100%	8/26/24	8/31/24
	Update Gantt Chart	Courtney	100%	8/26/24	8/31/24
	Update design efforts for what was completed over summer	Steven	100%	8/26/24	8/31/24
	Update purchasing plan	Maciej	100%	8/26/24	8/31/24
	Update manufacturing plan	Aaron	100%	8/26/24	8/31/24
	Submit assignment	Courtney	100%	8/31/24	8/31/24

	Engineering Calculations Assignment			9/7/24		
Top Level Design Summary	State problem you're trying to solve/solution	Maciej	100%	8/31/24	9/7/24	
	Show image of top-level CAD/engineering drawings	Aaron	100%	8/31/24	9/7/24	
	Describe sub systems	Aaron	100%	8/31/24	9/7/24	
	Show updated QFD	Janelle	100%	8/31/24	9/7/24	
Summary of Codes and Regulations	Summarize codes and regulations that apply to your design space	Maciej/Steven	100%	8/31/24	9/7/24	
Summary of Equations and Solutions	Cooling Load/Mass of Materials Needed	Courtney	100%	8/31/24	9/7/24	
	Summarize conditions that led to your 'load cases'	Courtney	100%	8/31/24	9/7/24	
	NPV	Maciej	100%	8/31/24	9/7/24	
	Resistive Network	Janelle	100%	8/31/24	9/7/24	
	Thermo Control Volume deltaT (mdot) air	Steven	100%	8/31/24	9/7/24	
	Lumped capacitance method (dT)	Aaron	100%	8/31/24	9/7/24	
	External convective heat coefficient (hbar)	Steven	100%	8/31/24	9/7/24	
Flow Charts and Diagrams	Functional Decomposition	Courtney	100%	8/31/24	9/7/24	
Moving Forward	Write Conclusion	Janelle	100%	8/31/24	9/7/24	
	Format Document	Aaron	100%	8/31/24	9/7/24	
	Hardware Status Update - 33% build			9/25/24		
Purchasing Plan	Bill of Materials	Maciej	100%	8/27/24	9/25/24	

	Submit purchasing request to get ready for 67% build	Maciej	100%	8/27/24	9/25/24
	Top level Budget	Maciej	100%	8/27/24	9/25/24
	QFD Calcs- COST	Maciej	100%	8/27/24	9/25/24
	QFD Calcs - NPV	Maciej	100%	8/27/24	9/25/24
Design Efforts	QFD Calcs-SAFETY	Steven	100%	8/27/24	9/25/24
	~~Tap the AC unit vapor compression cycle~~	Steven	100%	8/27/24	9/25/24
	Build the TES test Box	everyone	100%	8/27/24	9/25/24
	QFD Calcs-NPV	Maciej	100%	8/27/24	9/25/24
	Factor of Safety	Steven	100%	8/27/24	9/25/24
	QFD Calcs-MAINTENANCE	Steven	100%	8/27/24	9/25/24
	QFD Calcs-WEIGHT	Aaron	100%	8/27/24	9/25/24
	QFD Calcs-LATENT HEAT	Courtney	100%	8/27/24	9/25/24
	QFD Calcs-SENSIBLE HEAT	Courtney	100%	8/27/24	9/25/24
	Lay concrete with water	Maciej, Steven, Aaron	100%	8/27/24	9/25/24
	Build water/TES	Janelle, Courtney, Aaron	100%	8/27/24	9/25/24
	CAD	Steven/Aaron	100%	8/27/24	9/25/24
	Plan for chiller	Steven/Willy	100%	8/27/24	9/25/24
Manufacturing Plan	Write out manufacturing plan	Courtney	100%	8/27/24	9/25/24
Demonstration	Bring hardware to class to demonstrate functionality	everyone	100%	8/27/24	9/25/24

	PowerPoint Presentation	Janelle	100%	8/27/24	9/25/24
Gantt Chart Update	Update Gantt Chart	Courtney	100%	8/27/24	9/25/24
	Website Check #1				10/11/24
Website	Update Pictures	Courtney	100%	9/15/24	10/11/24
	Add Resumes	Courtney	100%	9/15/24	10/11/24
	Update LinkedIn	Courtney	100%	9/15/24	10/11/24
	Update Pages	Courtney	100%	9/15/24	10/11/24
	Hardware Status Update - 67% build			10/16/24	
Purchasing Plan	Bill of Materials	Maciej	100%	9/25/24	10/16/24
	Submit purchasing request to get ready for 100% build	Maciej	100%	9/25/24	10/16/24
	Top level Budget	Maciej	100%	9/25/24	10/16/24
	QFD Calcs- NPV	Maciej	100%	9/25/24	10/16/24
Design Efforts	Make CAD ready for presentation	Aaron/Steven	100%	9/25/24	10/16/24
	Purchase refrigerator for chiller	Maciej	100%	9/25/24	10/16/24
	Wire vinyl tubes through chiller system	everyone	100%	9/25/24	10/16/24
	Add the pump to the chiller	everyone	100%	9/25/24	10/16/24
	Connect the walls to each other (test box)	everyone	100%	9/25/24	10/16/24
	Order Pico data logger	Maciej	100%	9/25/24	10/16/24
	Create new iteration of water bar	everyone	100%	9/25/24	10/16/24

	connect chiller to water bar	everyone	100%	9/25/24	10/16/24
	Connect chiller to the concrete box	everyone	100%	9/25/24	10/16/24
	Take pictures of design for presentation	everyone	100%	9/25/24	10/16/24
	Update calculations	Janelle/Steven	100%	9/25/24	10/16/24
Manufacturing Plan	Write what has already been manufactured	Courtney	100%	9/25/24	10/16/24
	Write what needs to still be manufactured	Courtney	100%	9/25/24	10/16/24
Demonstration	Bring hardware to class	Maciej	100%	9/25/24	10/16/24
	Prepare Old Man Jokes	Maciej, Janelle, Courtney, Aaron	100%	9/25/24	10/16/24
	PowerPoint Presentation	Janelle	100%	9/25/24	10/16/24
Gantt Chart Update	Update Gantt Chart	Courtney	100%	10/12/24	10/16/24
	Efest Registration				10/24/24
Registration	Registration	Janelle	100%	10/16/24	10/24/24
	Abstract	Janelle	100%	10/16/24	10/24/24
	Paragraph	Janelle	100%	10/16/24	10/24/24
	Draft of Poster				10/31/24
Poster Contents	Abstract	Janelle	100%	10/1/24	10/31/24
	Engineering and Customer Requirements	Janelle	100%	10/1/24	10/31/24
	Methods	Aaron/Maciej	100%	10/1/24	10/31/24
	Results and Conclusions	Aaron/Maciej	100%	10/1/24	10/31/24

	Pictures	Aaron/Maciej	100%	10/16/24	10/31/24
Submit	Submit	Aaron/Maciej	100%	10/29/24	10/31/24
	Finalized Testing Plan				11/1/24
Design Requirements Summary	Engineering and Customer Requirements (talk to Dr. Acker about what he wants for this)	Janelle	100%	10/20/24	11/1/24
Top Level Testing Summary	List tests you will be performing in a table	Courtney	100%	10/20/24	11/1/24
Detailed Testing Plans	Test/Experiments summary	Steven	100%	10/20/24	11/1/24
	Add steps to Gantt Chart	Courtney	100%	10/25/24	11/1/24
	Procedure	Courtney	100%	10/20/24	11/1/24
	Results	Janelle	100%	10/20/24	11/1/24
	Conclusion	Steven	100%	10/20/24	11/1/24
Specification Sheet Preparation	Customer Requirement Table Met/not met	Janelle	100%	10/20/24	11/1/24
	Engineering Requirements table met/not met	Janelle	100%	10/20/24	11/1/24
QFD	QFD Calcs- COST	Maciej	100%	10/20/24	11/1/24
	QFD Calcs - NPV	Maciej	100%	10/20/24	11/1/24
	QFD Calcs- MAINTENANCE	Steven	100%	10/20/24	11/1/24
	QFD Calcs-SAFETY	Steven	100%	10/20/24	11/1/24
	QFD Calcs- THERMAL EFFICIENCY	Steven	100%	10/20/24	11/1/24
	Hardware Status Update 100% build			11/7/24	

Design Efforts	CAD	Aaron	100%	10/16/24	11/7/24
	Update engineering calculations	everyone	100%	10/16/24	11/7/24
Purchasing Plan	Bill of Materials	Maciej	100%	10/16/24	11/7/24
	Submit purchasing request to get ready for 100% build	Maciej	100%	10/16/24	11/7/24
	Top level Budget	Maciej	100%	10/16/24	11/7/24
	QFD Calcs- NPV	Maciej	100%	10/16/24	11/7/24
Manufacturing Plan	Take images of design	Courtney/Steven	100%	10/16/24	11/7/24
	Finalize manufacturing plan	Courtney	100%	10/16/24	11/7/24
Demonstration	PowerPoint Presentation	Janelle	100%	10/16/24	11/7/24
	Bring final demonstration system to class	Maciej/Aaron	100%	10/16/24	11/7/24
Gantt Chart	Gantt Chart Update	Courtney	100%	10/16/24	11/7/24
	Final Poster and PowerPoint				11/14/24
Poster	Update Abstract	Maciej	100%	11/1/24	11/14/24
	Update pictures	Maciej	100%	11/1/24	11/14/24
	Update engineering and customer requirements	Maciej	100%	11/1/24	11/14/24
	Update methods	Courtney	100%	11/1/24	11/14/24
	Update results and conclusion	Courtney	100%	11/1/24	11/14/24
PowerPoint	Background	Steven	100%	11/1/24	11/14/24
	Customer and engineering requirements/QFD	Janelle	100%	11/1/24	11/14/24

	Benchmarking	Janelle	100%	11/1/24	11/14/24
	Literature review	everyone	100%	11/1/24	11/14/24
	Mathematical modeling	everyone	100%	11/1/24	11/14/24
	Functional Decomposition chart	Courtney	100%	11/1/24	11/14/24
	Insert concept generation	Courtney/Steven	100%	11/1/24	11/14/24
	Selection criteria	Janelle	100%	11/1/24	11/14/24
	Concept selection	Janelle	100%	11/1/24	11/14/24
	Factor of Safety	Steven	100%	11/1/24	11/14/24
	Schedule/Gantt Chart	Courtney	100%	11/1/24	11/14/24
	Budget	Maciej	100%	11/1/24	11/14/24
	Bill of Materials	Maciej	100%	11/1/24	11/14/24
	FMEA	Steven	100%	11/1/24	11/14/24
	Final hardware	Steven	100%	11/1/24	11/14/24
	Future Work	Courtney	100%	11/1/24	11/14/24
	Initial Testing Results				11/21/24
Design Requirement Summary	Summarize design requirements	Janelle	100%	11/1/24	11/21/24
	Engineering and customer requirements update	Janelle	100%	11/1/24	11/21/24
Top level testing summary	Make table of tests being performed	Courtney	100%	11/1/24	11/21/24
	Test/experiment summary	Steven	100%	11/1/24	11/21/24

Detailed Testing Plans	Procedure	Courtney	100%	11/1/24	11/21/24
	Results	Janelle	100%	11/1/24	11/21/24
Specification Sheet Preparation	Summarize results table	Steven	100%	11/1/24	11/21/24
	Make table if requirements were met or not	Janelle	100%	11/1/24	11/21/24
QFD	QFD	Janelle	100%	11/1/24	11/21/24
	Final CAD packet				11/22/24
CAD Requirements	Create PDF of final CAD packet	Aaron	100%	11/1/24	11/22/24
	Bill of Materials	Maciej	100%	11/1/24	11/22/24
	Check that drawings adhere to ASME GD&T standards	Aaron	100%	11/1/24	11/22/24
	Compile info needed to manufacture and build design	Steven	100%	11/1/24	11/22/24
	Create zip file	Aaron	100%	11/1/24	11/22/24
	Final Testing Results				11/27/24
Design Requirement Summary	Copy & paste engineering and customer requirements from previous assignment	Janelle	100%	11/1/24	11/27/24
Top Level Testing Summary	Update table of experiments/tests and results	Courtney	100%	11/1/24	11/27/24
Detailed Testing Plans	Update test/experiment summary	Steven	100%	11/1/24	11/27/24
	Procedure	Courtney	100%	11/1/24	11/27/24
	Results	Janelle	100%	11/1/24	11/27/24
Specification Sheet	Finalize tables for customer and engineering requirements	Janelle	100%	11/1/24	11/27/24

QFD	QFD	Janelle	100%	11/1/24	11/27/24
	Final Report				12/3/24
Report Sections	Background	Janelle	100%	11/1/24	12/3/24
	Requirements	Janelle	100%	11/1/24	12/3/24
	Design Space Research	everyone	100%	11/1/24	12/3/24
	Concept Generation and Design Selected	Janelle	100%	11/1/24	12/3/24
	Project Management	Janelle	100%	11/1/24	12/3/24
	Final Hardware	Steven	100%	11/1/24	12/3/24
	Testing	Courtney/Steven/Janelle	100%	11/1/24	12/3/24
	Risk Analysis and Mitigation	Steven	100%	11/1/24	12/3/24
	Looking Forward	Janelle	100%	11/1/24	12/3/24
	Conclusion	Janelle	100%	11/1/24	12/3/24
Final Formatting	Check Formatting	Janelle	100%	11/1/24	12/3/24
	Final Website Check				12/4/24
Website Requirements	Team short intro video	Courtney	100%	11/24/24	12/4/24
	Include pictures/action shots	Courtney	100%	11/24/24	12/4/24
	Email Brian Hanabury for advertising	Courtney	100%	11/24/24	12/4/24
	Make LinkedIn post	Courtney	100%	11/24/24	12/4/24
	Website is live	Courtney	100%	11/24/24	12/4/24
	Final Project Demo				12/5/24

Product Demonstration	Plan demonstration for class	everyone	100%	11/25/24	12/5/24
	Operation/Assembly Manual				12/5/24
Manual Requirements	Assembly	Aaron	100%	11/5/24	12/5/24
	Disassembly	Steven	100%	11/5/24	12/5/24
	Operation	Courtney	100%	11/5/24	12/5/24
	Maintenance Instructions	Janelle	100%	11/5/24	12/5/24
	A troubleshooting section for potential failures	Steven	100%	11/5/24	12/5/24
	Expo PPT and Poster Presentation Delivery Results		12/6/24		

5.2 Budget

Our group started this semester with a $5,000 initial budget that comes from Salt River Project (SRP). We were able to effectively fundraise an extra $500 thanks to our combined efforts, which strengthened our financial position. Thanks to this financial boost, we have been able to move closer to our objectives. We set aside some money from our budget for the creation of Prototypes 1 and 2 during this semester. Prototype 1 and Prototype 2 incurred $605.29 in total in these undertakings. These financial contributions have been essential to the advancement of our initiative and our progress toward achieving our goals. Our group closes out the first semester with $4,900 left over when we assess our financial situation at the conclusion.

Second semester brought some more expenses. $1,476.34 was spent towards the completion of the project which included 100% build of the project as well as covering the testing materials and preparing the testing environment. The final remaining balance including the fundraised money stays at $3,418.37.

5.3 Bill of Materials (BoM)

This section lists the necessary parts needed to assemble one unit of our final design concept. Each component is essential to accomplishing our project's goals and guaranteeing the thermal energy storage system's dependability, safety, and effectiveness.

- Phase Change Material

A Thermal energy storage system's core, the PCM compound, facilitates the effective storage and release of thermal energy. The system's overall performance and ability to save peak-load air conditioning costs for SRP customers are greatly dependent on the choice made.

- Insulation Material

To reduce heat transmission and preserve thermal integrity inside the storage unit, insulating foam is crucial. It improves system efficiency and guarantees peak performance throughout storage and release cycles by lowering heat input or loss.

- Heat Exchanger

The heat exchanger makes it easier for thermal energy to move from the PCM to its surroundings. In order to maximize the system's cooling capacity and reactivity, and efficient heat exchange is critical in its design and efficiency.

- Enclosure system

The enclosure offers the system's internal components protection and structural support. It guarantees the thermal energy storage unit's lifetime, robustness, and safe operation while protecting them from the elements.

- Control and Monitoring System

Temperature, timing, and energy flow are just a few of the characteristics that the control unit regulates and operates. It makes it possible to precisely regulate and optimize the system's performance to satisfy the unique needs of SRP clients. Sensors are essential in this case as they guarantee the thermal energy storage system's dependability and safety while facilitating proactive maintenance and early anomaly detection.

- Hardware

Numerous fasteners, connections, bolts, and nuts are necessary for the thermal energy storage system's entire construction and operation. They make it easier to install, maintain, and repair the system, which guarantees its lifetime and seamless operation.

For detailed prototyping BoMs, please refer to the appendix section of this report (figure 18).

Chapter 6: Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

According to the literature on CTES, a few apparent characteristics are likely to fail. Because the thermal mass is the only object we would have to model and create experiments on, the FEMA could only consist of one subsystem, the thermal mass. Because the thermal mass is supported by a vapor compression system and a heat exchanger with an HTF for the thermal mass, FEMA was created for them as well and is placed in appendix D. The thermal mass will have the most focus of the four subsystems, but the failure effects of the other subsystems are considered as they apply to the thermal mass. The SRP thermal mass team does not intend to create or prototype any other subsystems unless a vapor-to-liquid heat exchanger is designed at a later stage. Currently, vapor-to-liquid heat exchangers for glycol (glycol loops) can be purchased in a secondary custom manufacturing market.

Most thermal masses do not have moving parts or only a heat transfer fluid that moves through them; failures are due to improper installation. This may be part of every product; they can be particularly aggressive in this case. Improper installation and usage of the components will lead to cracks and bends in the required thin-walled piping. The HTF must maintain working pressures and mass flow rates. A crack will lead to a simple failure that could cause a poisonous substance to enter an environment. Worse would be a bend that prevents flow, resulting in a buildup that will destroy pumps and compressors or explode from the device. These failure modes will contaminate the environment and pose severe risks to human life. Many mitigation methods would overcome this issue but would come with a considerable trade-off. A thicker copper tube would prevent most of the errors involved with construction and installation. This would increase the cost, lower the manufacturability, lower heat transfer efficiency, and decrease ease of maintenance. Instead, a comprehensive plan for manufacturing and installation will be created to prevent these errors. This will slightly reduce the ease of maintenance and make manufacturability a little more complex, and the team considers this the best method.

Much of the literature references leakage or damage due to phase change materials causing stress and fatigue. The literature discusses cracks and corrosion of the containers and pipes as common failure modes. These values are discussed, but values are not readily apparent from reading. It is still considered unlikely in our small-scale prototypes, but the actual values of these failure modes have a calculation model. Using a standard formula and method for solving stresses in pressurized cylinders and press and shrink fits, the stresses can be known as a variable of the uniform density of the PCM against the walls of the pipe. The stresses calculated by the linear elastic fracture mechanics combined with thermal loading create a better picture of the life span of the copper pipe in the thermal mass.

Ice does not form in a manner that is predictable or consistent. Hence, the literature and research are pursuing physically stabilizing PCMs. The current method to mitigate this issue is to create a process to place the PCM in an orientation that is relatively safe. For example, suspending the copper tube through the PEX-A and installing the thermal mass horizontally will help produce consistent loading and a more predictable failure. In the concrete model, vertical installation and reducing condensation on the surface can mitigate the likelihood of concrete degradation and cracking.

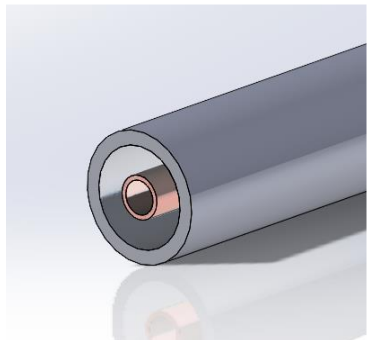


Figure 27

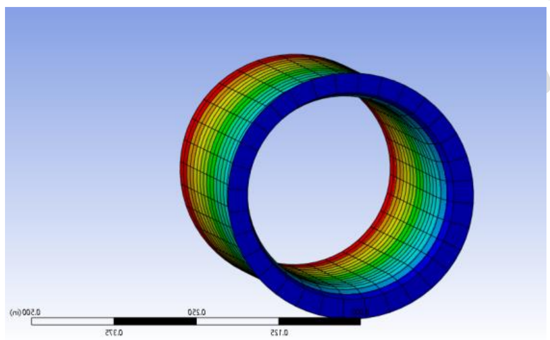


Figure 28

The use of Ethylene Glycol as a heat transfer fluid in these proof-of-concept devices was performed in a controlled environment with personal protective equipment because of the danger of working with the HTF. The Material Safety and Data Specification Sheet for ethylene glycol is provided in appendix C shows that it is extremely toxic. Proposing a safer HTF with the use propylene glycol, MSDS available in appendix C,

6.2 Initial Prototyping

6.2.1 The virtual concrete prototype

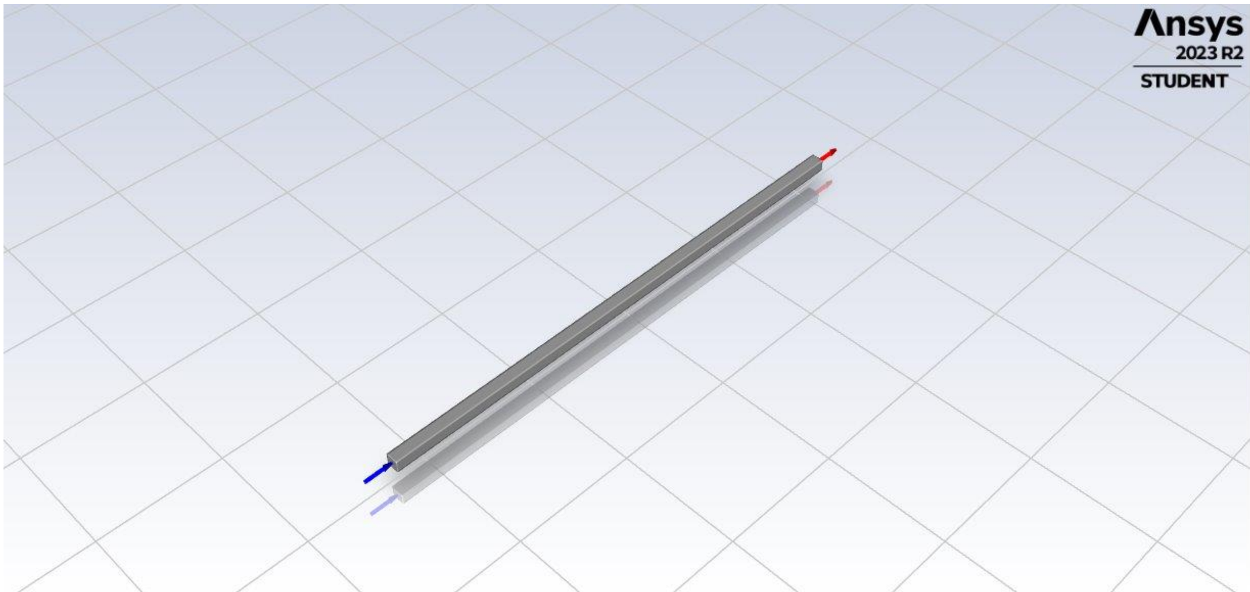


Figure 29

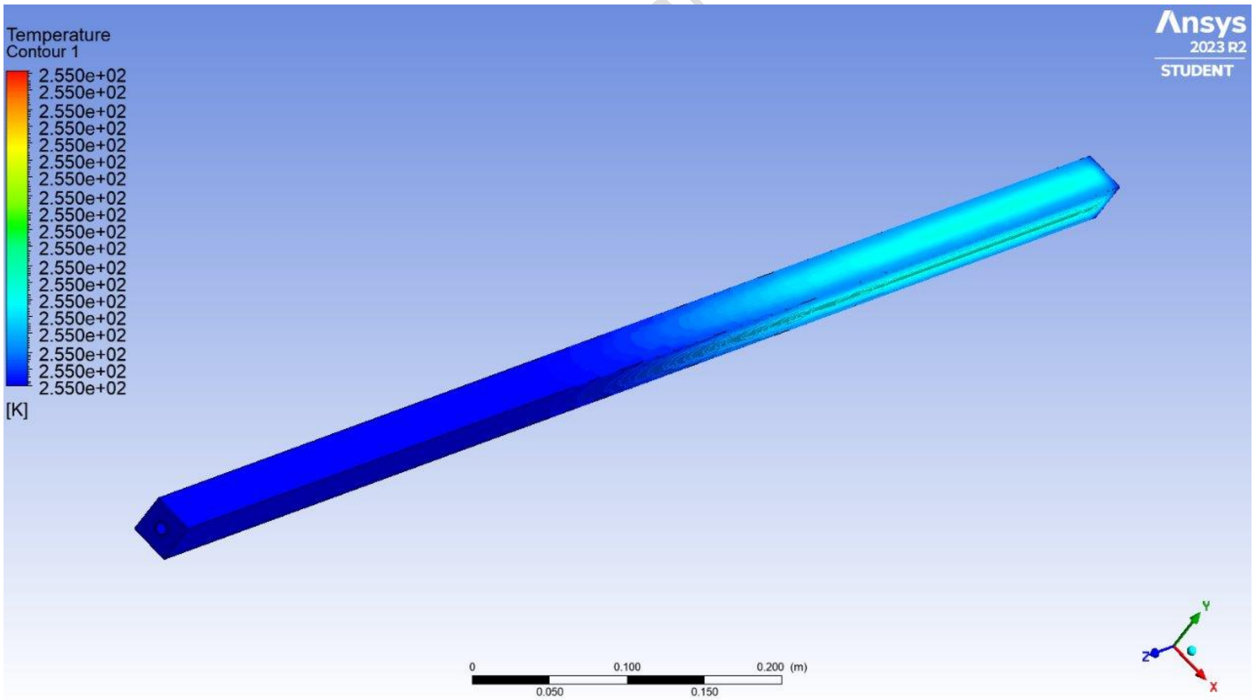


Figure 30

The virtual concrete model showed how the ice is going to freeze as time goes on. The amount of time that it takes to chill to the desired temperature for the heat transfer fluid on the inside of the pipe that is within the concrete. This model was created by ANSYS. This virtual prototype answered the question of how long it is going to take to freeze internally. ANSYS said that it would take about 30 mins. Then with the physical prototype we made with PEX pipe we were able to test the accuracy of the model. We determined that the model was accurate to the point of when it starts to melt. The virtual model was useful in answering this question.

6.2.2 The ice in Pex-A

The teams initial physical prototype consisted of a straight copper tube running through the center of a Pex-A tube where the copper is intended to carry the cooling fluid which it did not have but was expected to be a ethylene glycol water mixture. Surrounding the copper and encased in the Pex-A tube is water being used as the PCM. This is encased by using hot glue at each end for flexibility. The prototype was used to test the durability of the Pex-A since the water expansion could cause the tube or pipe to leak and after testing the team found that with materials used, there was no leaking and significantly less chance of failure since Pex-A tubing can expand at the same rate as the water. This prototype is considered due to the thermal properties of water and with less chance of failure due to the piping. With the information from this prototype the team concluded that Pex-A would be suitable for the application where water needs to be frozen and melted constantly.

6.2.3 Hexahydrates Phase Change Heat Exchanger

The team created an apparatus that encased a mix of 66% CaCl2+6H20 and 33% MgCl2+6H20 in 3 copper tubes. These 3 tubes are all inside of an ABS pipe with an inlet and outlet used for pumping water through. The goal of the prototype was to test the material for the heat capacity by using water that sits above the mixture's melting point. The temperature was taken over time until reaching steady state. Thermocouples are fitted on each end to measure the change in temperature of the by recording temperature over time as the water flows and meets the copper tubes. The team found that the temperature difference of the water was about 3degreesd Celsius colder at the outlet when running the water at 0.000014 m^3/s. By running this experiment with the prototype, the teams aim is to create a very similar experiment but to use a controlled blower or AC that can be used in place of a water pump since air would translate better to the scope of the project. Although the process of mixing and encasing the PCM helps in the development of manufacturing knowledge needed for the final design. The water also allowed for better heat transfer and facilitated recording data and ease of measuring flowrate opposed to air.

6.2.4 Failure analysis of thermal mass tubing

According to the FMEA and the literature cracking and loss of thermal mass is a significant issue in most of the products available. The current iteration of our device includes a copper pipe in compression and fully reversed fatigue. If that copper pipe fails, the thermal mass fails. A structural model of the copper pipe in the ice has been created to analyze the forces developed on the walls of the pipe in the thermal mass. Theoretical pressures and point loads are currently in the model and the strains can be numerically approximated. A deeper understanding of the modes of water phase change and the predicted values for the point loads is now a new research opportunity to explore for the future of our team.

The G. Lamé equation for thick-walled cylinders can determine the stress radial and tangential as well as the displacement.

$$\sigma_r = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} - \frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r^2} \tag{13}$$

$$\sigma_\theta = \frac{a^2 p_i - b^2 p_o}{b^2 - a^2} + \frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r^2} \tag{14}$$

$$u = \frac{1-\nu}{E} * \frac{(a^2 p_i - b^2 p_o)r}{b^2 - a^2} + \frac{1+\nu}{E} * \frac{(p_i - p_o)a^2 b^2}{(b^2 - a^2)r^2} \tag{15}$$

These equations will allow the team to calculate the analytical maximum and fully reversed stresses and displacements. To predict individual point loads and uneven stress concentrations an Ansys simulation is used. The analytical solution has been modeled in Matlab to compare it to the Ansys model. Greater refinement of the model in Ansys will have to be understood.

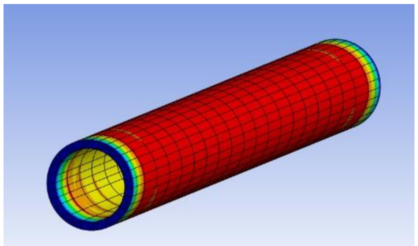


Figure 31: Ansys

6.3 Other Engineering Calculations

The SRP Thermal Mass team began with the need to understand latent and sensible heat. This is the only method to store heat. The calculations for these methods have been discussed, but where they have been applied has not. In understanding and applying different materials, we often needed to make a side calculation, a "sanity check," for the materials we used. The materials informed our decisions, as did the application of the cost-benefit analysis. The value of latent heat in paraffin was our initial focus, and the calculations were promising but proved not to be cost-effective as a device and more effective in a passive cooling apparatus. This was apparent in our decision matrix as well.

The phase change materials being tested for the final prototype are becoming a hybrid method incorporating latent heat and the chiller the team had represented in the concept generation phase. The chiller is some form of vapor compression cycle that uses energy to expel heat from the thermal mass. The amount of energy used by the chiller and its efficiency are included in our calculations. They were also verified experimentally.

Every method and apparatus discussed needs a few heat transfer calculations, such as heat transfer through PEX-A or free convection calculations against concrete. Many of these heat transfer calculations are not documented because many were performed now to validate assumptions. Geometry and morphology are other calculations that go unnoticed because of how often they are employed; using density and latent heat are now part of the simple processes.

The factor of safety calculations is still cropping up as we understand the failure modes. Understanding that we will still need to calculate FoS for many objects we did not build to move forward. The internal pressures on the coolant lines of the vapor compression chiller will be applied to the FoS of the lines that run directly through the concrete. Along with the calculations for thermal cycling, we will determine the likely failure of a concrete thermal mass system. This is the same method we employed to determine the failure of the copper pipe in the water thermal mass model.

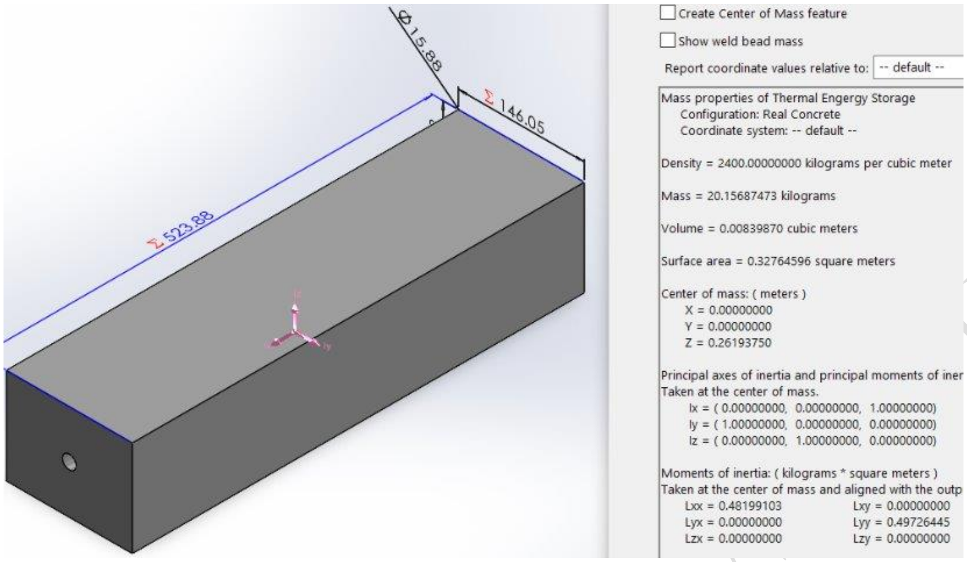


Figure 32

Using the measured mass of the concrete thermal mass and knowing the specific heat of concrete being 880 J/kg*C, the calculation was made to determine that for this mass of concrete to get the mass from 20° to 0° C the system will use 355 kJ. This means that it would take 3.29 hours to decrease the temperature of the concrete thermal mass from 20° to 0° C. Using these calculations and the client requirement that the thermal mass must charge in the span of 10 hours while the grid is being supplemented by solar energy, we are able to scale mass. By increasing the size of the thermal mass, we can maximize the thermal energy storage capacity as long as the mass can be charged in the given time.

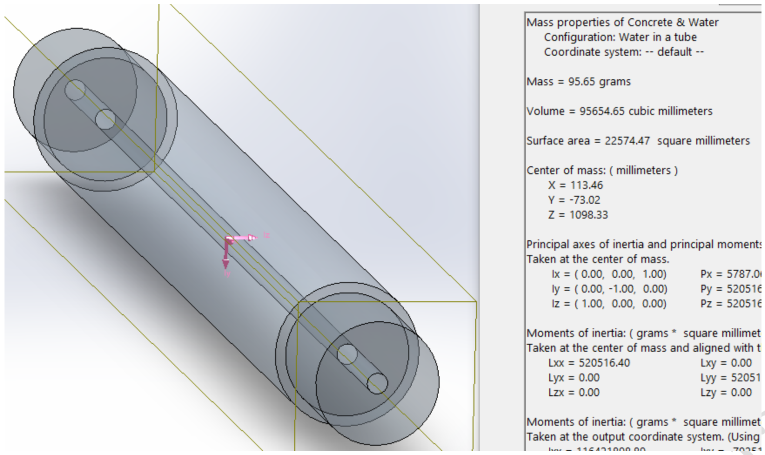


Figure 33

Using the measured mass of the water thermal mass and knowing the specific heat of water being 4184 J/kg*C, and the heat of fusion being 334 kJ/kg, the calculation was made to determine that for this mass of water to get the water from 20° to 0° C the system will use 400 J per bar and this temperature change will freeze the Waterbar. There are 5 bars in the Waterbar storage so therefore it would take 2000 J to get all 5 bars to 0. To get the water to phase change and therefor use the possible latent heat of fusion afterward the Waterbars require 32 kJ. Water proves to store thermal energy much more efficiently when compared to concrete because of its higher specific heat and its availability of latent heat.

6.4 Testing Results

The tests that were completed were calculating the appropriate flow rate needed to achieve the highest heat transfer for both the concrete and the water bars. Another test that was also implemented on both different apparatuses was measuring the flow gradient of both of them. The results can be seen below in the appropriate tables and figures below.

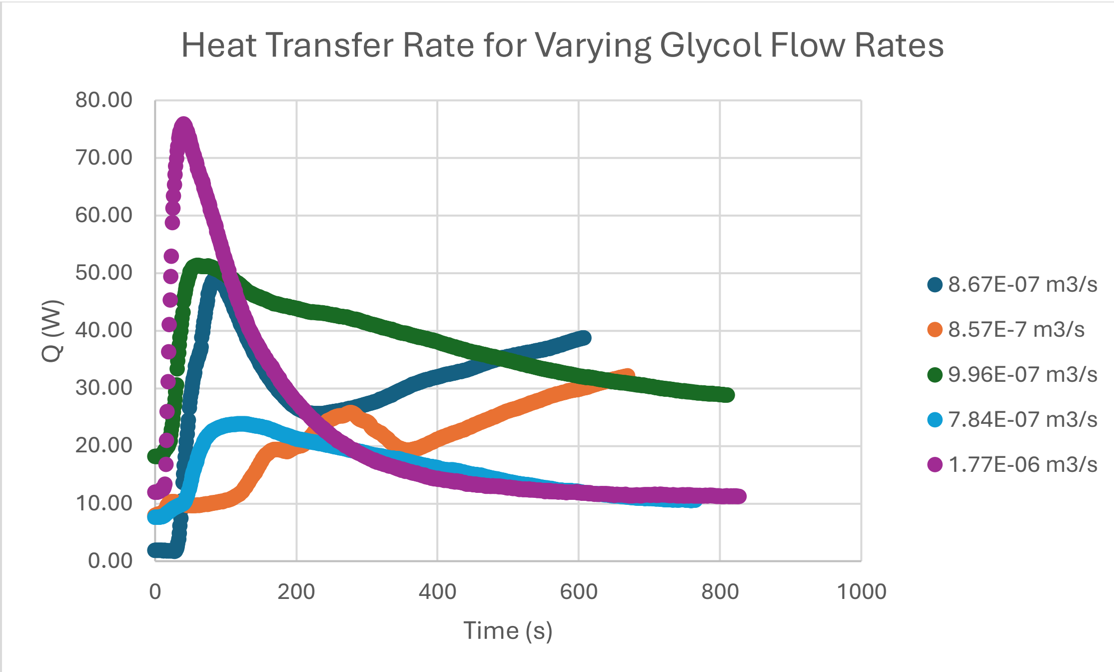


Figure 34

Figure 34 above shows the plot of data recorded for heat transfer over time when pumping the chilled ethylene glycol into the Waterbars. As expected, when the pump is initiated there is a visible peak where heat transfer is at its highest suspecting it is because that is when temperature difference is at its highest. After that the heat transfer drops for flow rates except for one outlier. Here it was determined that the optimal flowrate would be 9.96E-07 m3/s seen in figure 34 in the green color.

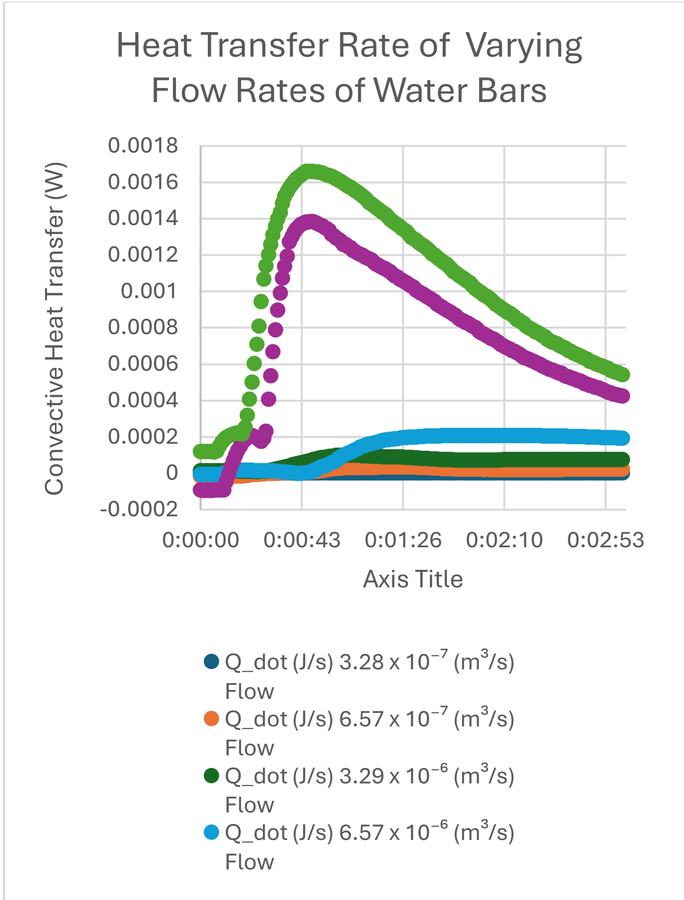


Figure 35

Figure 35 above is the plot of the data collected and shows the heat transfer over time in the Waterbars. Figure 35 only covers nearly the first 3 minutes. The 2 highest flow rates can be seen creating a peak near the 45 second mark. That shows that for the system the most efficient way to remove thermal energy from the Waterbars is to run the pump at higher flow rates. This peak is also seen in the tests ran for the concrete thermal mass.

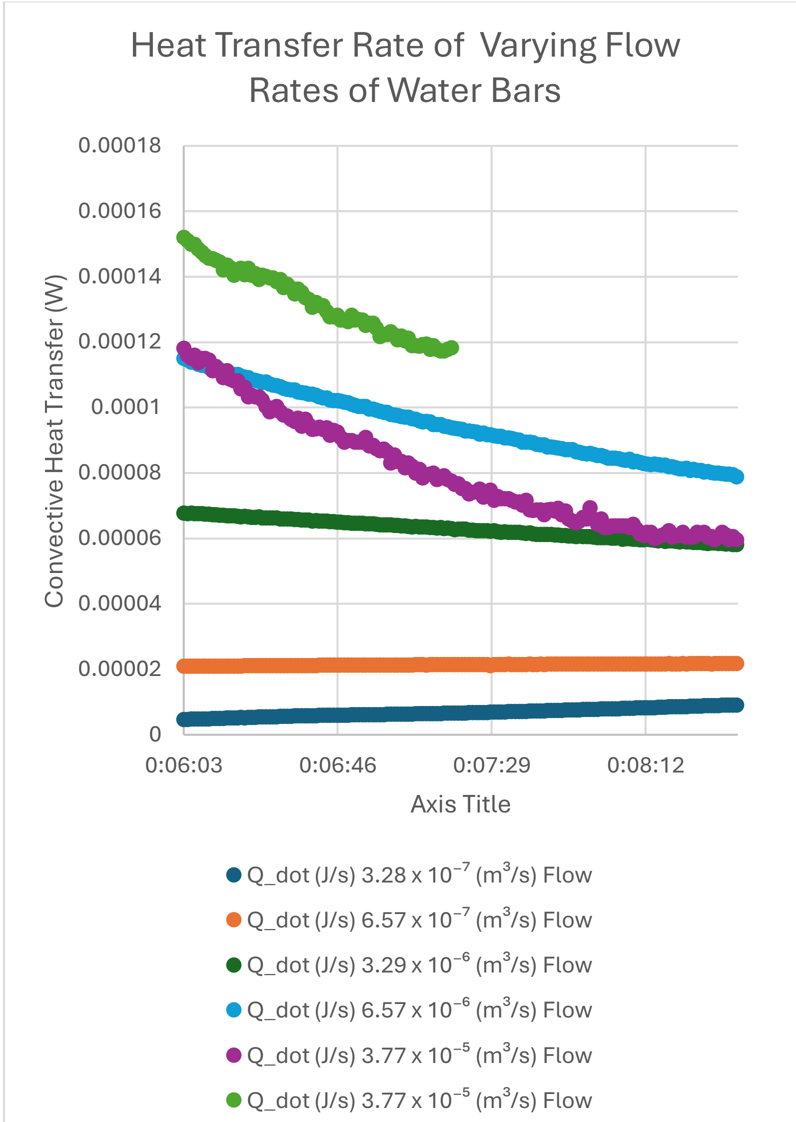
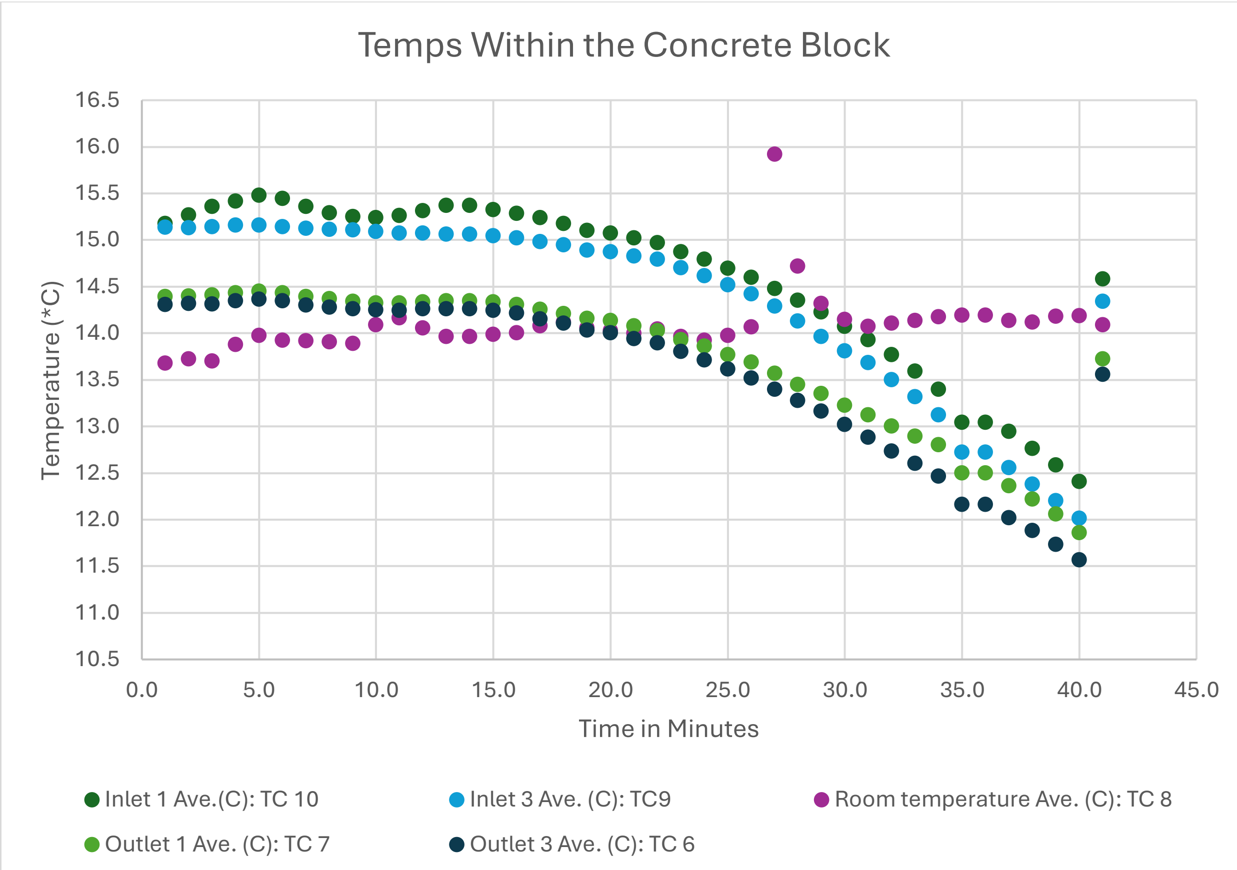


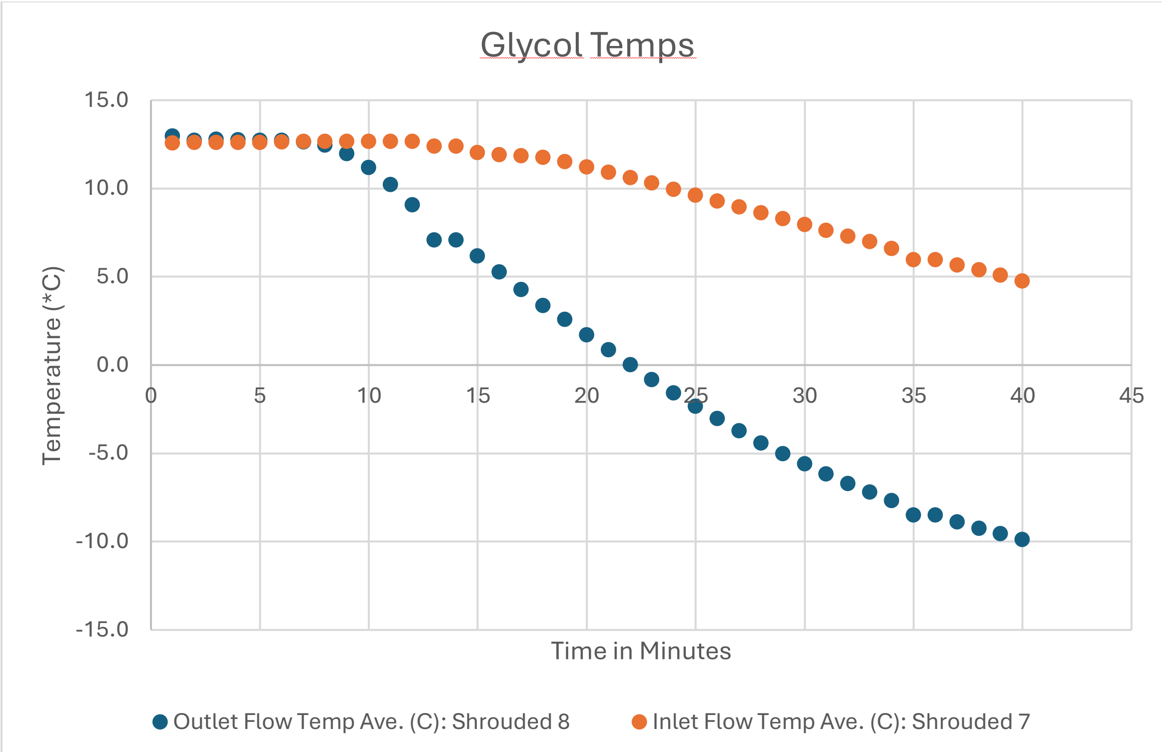
Figure 36:

Figure 36 above is a continuation of the plot in figure 35 and shows data from 6 minutes and runs for over 2 minutes and shows that after a while of the pump running the flow in the tubing is laminar and once the temperature difference decreases it cause the heat transfer rate decreases between the ethylene and the water I the tube. This is a clear design flaw, and our system is not able to cool the Waterbars in the required time. The results show that to increase the heat transfer from the ethylene to the glycol there would have to be turbulent flow forced into the copper tubes.

Experiment/Test	Relevant DRs	Testing Equipment Needed	Other Resources
EXP1 – Glycol CV Heat Transfer	ER2 - Charge thermal mass during non-peak hours CR2 - Reliability CR 10- Reduce costs ER1- Heat Transfer Rate	• Thermocouples • Graduated Cylinder • Stopwatch • Pico Data Logger	Safety equipment working with glycol Solar Shack Dr. Wade's Lab
EXP2 – Thermal Mass Temperature Profile/Heat Transfer	ER 2 - Charge thermal mass during non-peak hours CR 2 - Reliability CR 10 - Reduce costs ER1- Heat Transfer Rate	• Thermocouples • Graduated Cylinder • Stopwatch • Pico Data Logger • Drill	Safety equipment working with glycol Solar Shack Dr. Wade's Lab



Temps Within the Concrete Block
Temperature (*C)
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Time in Minutes
Inlet 1 Ave.(C): TC 10
Inlet 3 Ave. (C): TC9
Room temperature Ave. (C): TC 8
Outlet 1 Ave. (C): TC 7
Outlet 3 Ave. (C): TC 6



6.5 Future Testing Potential

After the model has been united and tested for bugs, the process of creating methods to guarantee our calculations will begin. We will need a test for every aspect of the model in one smaller prototype. Where possible, the engineering requirements will be combined, and a prototype will test as many variables as possible at once. A test situation room will likely need to be constructed, and a scaled prototype representation must be put through the same rigors expected. These experiments will yield values that can be compared to the calculations of our representative models. After these tests and the validation of our models, we can then construct the complex multifactor analysis of the entire project to optimize the prototype and report the true viability of our project.

Chapter 7: Conclusion

The Salt River Project's Thermal Mass project is making major advances in providing a product that can be prototyped and iterated into a marketable design. Using the engineering method processes and working together, we worked through creating the project demands. The project required 12 kilowatt hours of cold storage or 43.2 megajoules per hour. This cold storage must be delivered over 3 hours to an average-sized home in Phoenix, Arizona. The effect will be to reduce the customers' need to turn on the air conditioning in the afternoon. The client input and research done created the customer requirements of user-friendliness, reliability, safety, affordability, and ease of maintenance. The team created the engineering requirements of efficiency, cost, safety, comfort level, and system analysis. The QFD is made from the requirements, and the concept generation has started. Concept generation exposes the sub-functions, which are combined and compared to the available engineering models. Each concept is represented morphologically and economically in a functional decomposition. The selections are made for the final design that can be fully justified by the values generated. The final design is determined to be most cost-effective and built into an existing air conditioning unit.

This project effectively addressed the requirement for meeting a demand of thermal energy storage technologies designed for central Arizona residential customers with the goal of lowering peak electricity consumption and related expenses. The Water Bars and Concrete Wall systems were two designs that we developed and evaluated against a thorough set of engineering and customer requirements in order to determine their distinct advantages and disadvantages. Technical feasibility, economic viability, and user-friendliness were all balanced in a thorough evaluation process that was made possible by the inclusion of a datum for comparison.

The Concrete Wall design provided strong performance in new projects with notable contributions to lowering energy consumption, while the Water Bars design showed promise as an affordable and easily accessible option. These results open the door for further advancements and improvements in thermal energy storage devices, despite obstacles like turbulent flow optimization and material constraints.

Through prototyping, testing, and data analysis, the project aligns with the Salt River Project goals to promote sustainable energy practices and improve SRP's customers electricity bills. The insights and lessons learnt provide a strong foundation for research and development of new advanced thermal energy storage systems and their integration with residential housing units.

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Appendix A: Figures

Table 11.3 Heat exchanger effectiveness relations [5]

Flow Arrangement	Relation		
Parallel flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 + C_r)]}{1 + C_r}$		(11.28a)
Counterflow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 - C_r)]}{1 - C_r \exp[-\mathrm{NTU}(1 - C_r)]}$	$(C_r < 1)$	
	$\varepsilon = \dfrac{\mathrm{NTU}}{1 + \mathrm{NTU}}$	$(C_r = 1)$	(11.29a)
Shell-and-tube			
One shell pass (2, 4, . . . tube passes)	$\varepsilon_1 = 2\left\{1 + C_r + (1 + C_r^2)^{1/2} \times \dfrac{1 + \exp[-(\mathrm{NTU})_1(1 + C_r^2)^{1/2}]}{1 - \exp[-(\mathrm{NTU})_1(1 + C_r^2)^{1/2}]}\right\}^{-1}$		(11.30a)
n shell passes ($2n$, $4n$, . . . tube passes)	$\varepsilon = \left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - 1\right]\left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - C_r\right]^{-1}$		(11.31a)
Cross-flow (single pass)			
Both fluids unmixed	$\varepsilon = 1 - \exp\left[\left(\dfrac{1}{C_r}\right)(\mathrm{NTU})^{0.22}\{\exp[-C_r(\mathrm{NTU})^{0.78}] - 1\}\right]$		(11.32)
C_{max} (mixed), C_{min} (unmixed)	$\varepsilon = \left(\dfrac{1}{C_r}\right)(1 - \exp\{-C_r[1 - \exp(-\mathrm{NTU})]\})$		(11.33a)
C_{min} (mixed), C_{max} (unmixed)	$\varepsilon = 1 - \exp(-C_r^{-1}\{1 - \exp[-C_r(\mathrm{NTU})]\})$		(11.34a)
All exchangers ($C_r = 0$)	$\varepsilon = 1 - \exp(-\mathrm{NTU})$		(11.35a)

Figure 1: Table 11.3 [15]

TABLE 11.4 Heat exchanger NTU relations

Flow Arrangement	Relation		
Parallel flow	$\mathrm{NTU} = -\dfrac{\ln[1-\varepsilon(1+C_r)]}{1+C_r}$		(11.28b)
Counterflow	$\mathrm{NTU} = \dfrac{1}{C_r-1}\ln\left(\dfrac{\varepsilon-1}{\varepsilon C_r-1}\right)$	$(C_r < 1)$	
	$\mathrm{NTU} = \dfrac{\varepsilon}{1-\varepsilon}$	$(C_r = 1)$	(11.29b)
Shell-and-tube			
One shell pass (2, 4, . . . tube passes)	$(\mathrm{NTU})_1 = -(1+C_r^2)^{-1/2}\ln\left(\dfrac{E-1}{E+1}\right)$		(11.30b)
	$E = \dfrac{2/\varepsilon_1-(1+C_r)}{(1+C_r^2)^{1/2}}$		(11.30c)
n shell passes ($2n$, $4n$, . . . tube passes)	Use Equations 11.30b and 11.30c with		
	$\varepsilon_1 = \dfrac{F-1}{F-C_r} \quad F = \left(\dfrac{\varepsilon C_r-1}{\varepsilon-1}\right)^{1/n} \quad \mathrm{NTU} = n(\mathrm{NTU})_1$		(11.31b, c, d)
Cross-flow (single pass)			
C_{max} (mixed), C_{min} (unmixed)	$\mathrm{NTU} = -\ln\left[1+\left(\dfrac{1}{C_r}\right)\ln(1-\varepsilon C_r)\right]$		(11.33b)
C_{min} (mixed), C_{max} (unmixed)	$\mathrm{NTU} = -\left(\dfrac{1}{C_r}\right)\ln[C_r\ln(1-\varepsilon)+1]$		(11.34b)
All exchangers ($C_r = 0$)	$\mathrm{NTU} = -\ln(1-\varepsilon)$		(11.35b)

Figure 2: Table 11.4 [15]

$$\frac{T_{s,1}-T_{s,2}}{T_{s,2}-T_\infty} = \frac{(L/kA)}{(1/hA)} = \frac{R_{t,\mathrm{cond}}}{R_{t,\mathrm{conv}}} = \frac{hL}{k} \equiv Bi$$

Figure 3: Equation 5.9 Biot number [15]

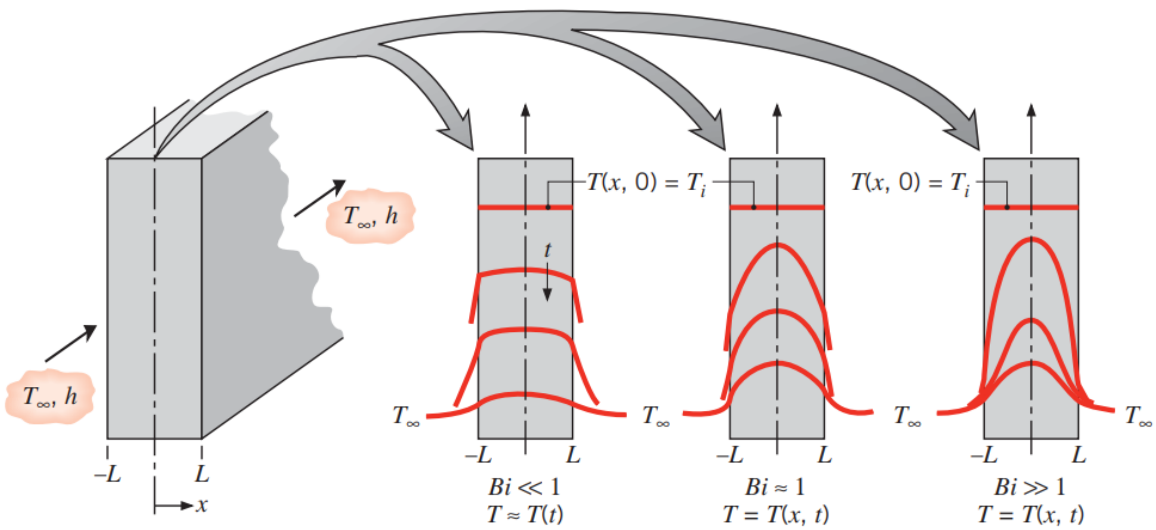


FIGURE 5.4 Transient temperature distributions for different Biot numbers in a plane wall symmetrically cooled by convection.

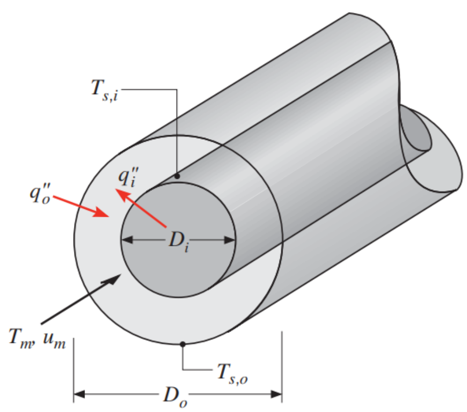


FIGURE 8.11 The concentric tube annulus.

Figure 4: Figure 5.4 and Figure 8.11 from the Textbook [18]

$$\frac{hA_st}{\rho Vc} = \frac{ht}{\rho cL_c} = \frac{hL_c}{k}\frac{k}{\rho c}\frac{t}{L_c^2} = \frac{hL_c}{k}\frac{\alpha t}{L_c^2}$$

$$\frac{hA_st}{\rho Vc} = Bi \cdot Fo$$

Figure 5: Equation 5.11 Exponent value for the Transient Conduction Equation [15]

$$Fo \equiv \frac{\alpha t}{L_c^2}$$

Figure 6: Equation 5.12 Fourier Number [15]

$$\frac{\theta}{\theta_i} = \frac{T - T_\infty}{T_i - T_\infty} = \exp(-Bi \cdot Fo)$$

Figure 7: Equation 5.13 Transient Conduction Equation [15]

$$\boldsymbol{Temp\ (C) = (V - 0.5) * 100}$$

Figure 8: Equation used for Arduino

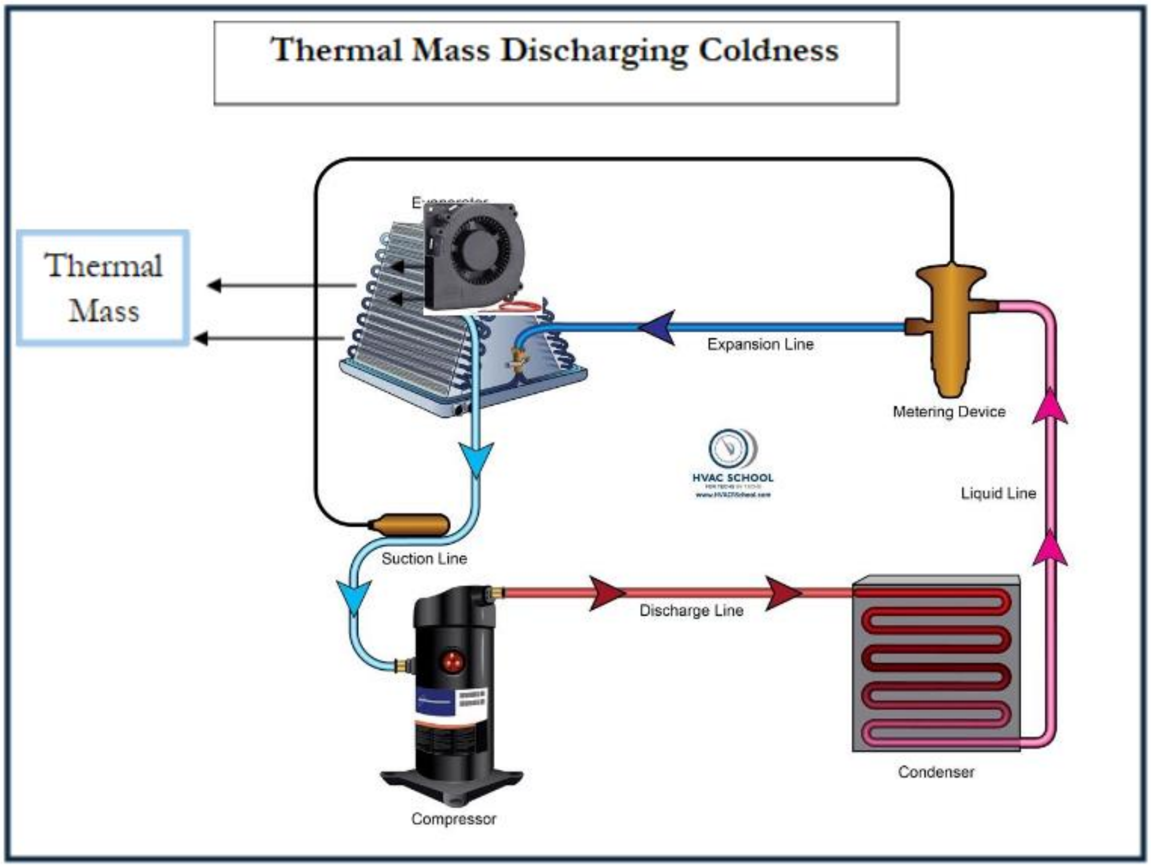


Figure 9: AC System Cycle Dischargin Thermal Mass

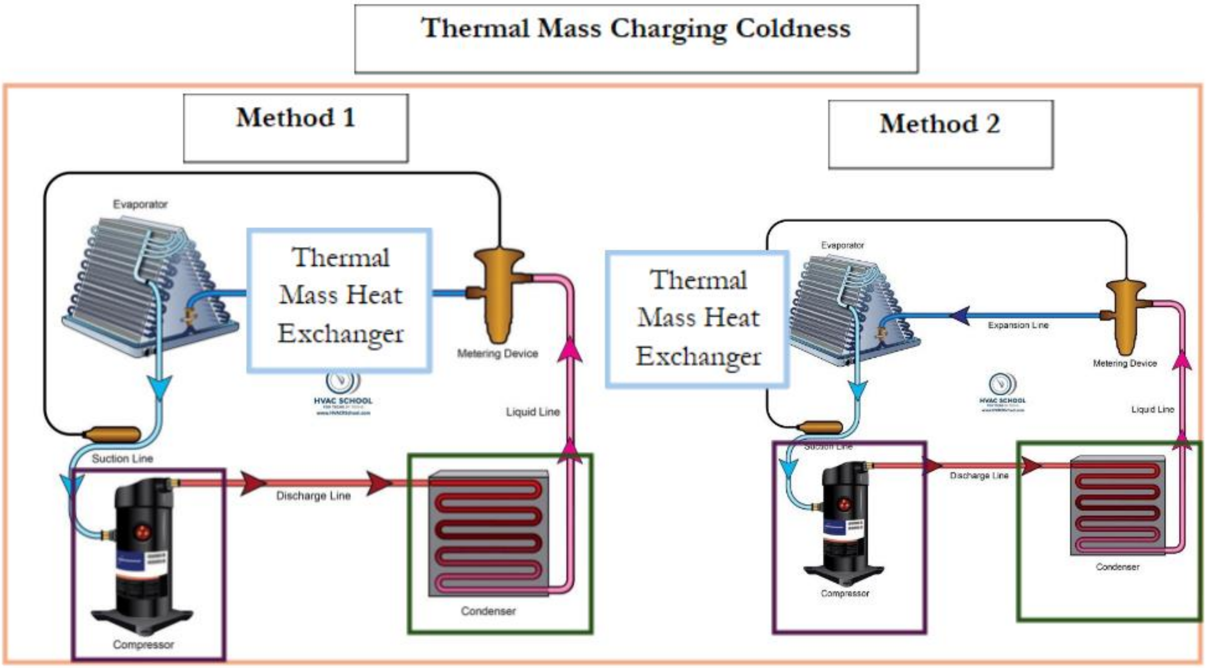


Figure 10: AC System Cycle Charging With Thermal Mass

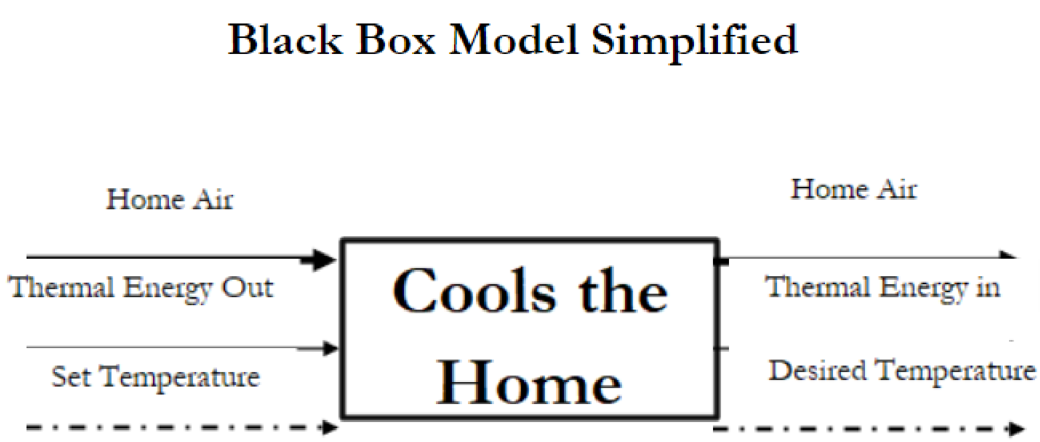


Figure 11: Simplified Black Box Model

SRP Customers approximate savings			
	May/June/Sept./Oct.	July/August	Total

Daily	$	2.72	$	3.10		
Weekly (5 day week)	$	13.62	$	15.51		
Whole Term	$	236.99	$	137.37	$	374.36

Figure 12: SRP customers electricity spendings

Initial Investment Water w/ chiller			
Chiller	$	3,000.00	unit
Water	$	11.86	40 gal
Copper	$	800.00	1200ft
PEX-A	$	739.00	1200ft
Glycol	$	56.04	4.16gal
Total	$	4,606.90	

Figure 13: Initial investment option 1

Initial Investment Concrete w/ chiller			
Chiller	$	3,000.00	unit
Concrete	$	317.82	2 cubic yards
Water	$	50.00	
Glycol	$	83.33	6.18gal
Copper	$	923.00	
Total	$	4,374.15	

Figure 14: Initial investment option 1

Initial Investment Water			
Pump	$	169.89	unit
Water	$	11.86	40 gal
Copper	$	800.00	1200ft
PEX-A	$	739.00	1200ft
Heat Exchanger	$	60.00	unit
Glycol	$	56.04	4.16gal

Total	$	1,836.79

Figure 15: Initial investment option 1

Initial Investment Concrete			
Pump	$	169.89	unit
Concrete	$	317.82	2 cubic yards
Water	$	50.00	
Glycol	$	83.33	6.18gal
Heat Exchanger	$	60.00	unit
Copper	$	923.00	
Total	$	1,604.04	

Figure 16: Initial investment option 1

Initial Investment Water with pump replacement			
Pump	$	339.78	unit
Water	$	11.86	40 gal
Copper	$	800.00	1200ft
PEX-A	$	739.00	1200ft
Heat Exchanger	$	60.00	unit
Glycol	$	56.04	4.16gal
Total	$	2,006.68	

Figure 17: Initial investment option 1

Assembly Name	Thermal Energy Storage	Total Parts	155	Bill of Materials
Assembly Number	1	Parts Acquired	160	
Date of Approval	N/A	Parts Donated	15	
		Parts Purchased	136	
Total Cost	$ 1,830.63	Part Status (Purchase	88%	
		Parts Status (On-Hand	103%	

Item no.	Catalog #	Vendor Name	Description	Size	Qty	Price	Total Cost	#On-Hand?	#Purchased?	Link
1	M2670	Sigma-Aldrich	Magnesium Chloride Hexahydrate	500g	1	$ 104.64	$ 104.64	1	1	https://www.sigmaaldrich.com
2	442909	Sigma-Aldrich	Calcium Chloride Hexahydrate	1kg	1	$ 58.36	$ 58.36	1	1	https://www.sigmaaldrich.com
3	324257997	Home Depot	latium Univ Antifreeze Plus Coolar	1gal	2	$ 61.10	$ 122.20	1	1	https://www.homedepot.com/
4	321314142	Home Depot	QuQuyi Copper Tube	1/8"	1	$ 15.05	$ 15.05	1	1	https://www.amazon.com/Qu(
5	G5147807	Zoro	NOM C Copper Cap	1/8"	16	$ 2.82	$ 45.12	16	16	https://www.zoro.com/nibco-1
6	313834600	Zoro	Charlotte Pipe ABS DWC Cap	4"	2	$ 20.90	$ 41.80	2	2	https://www.homedepot.com/
7	38753391007	Home Depot	DMV Knock Out Test Cap	1-1/2"	4	$ 0.63	$ 2.52	4	4	https://www.homedepot.com/
8	38753391007	Home Depot	ABS CAP HUB	1-1/2"	2	$ 6.68	$ 13.36	2	2	https://www.homedepot.com/
9	670750951794	Home Depot	PEX Plastic TEE (5pack)	1/2"	1	$ 8.38	$ 8.38	1	1	https://www.homedepot.com/
10	811000011152	Home Depot	ABS Pipe	1/2 x 2ft	1	$ 6.51	$ 6.51	1	1	https://www.homedepot.com/
11	309282462	Home Depot	ABS Cell Core Pipe	4" x 10'	1	$ 45.77	$ 45.77	1	1	https://www.homedepot.com/
12	685768276371	Home Depot	Type M Copper Tube	1/2" x 2'	1	$ 7.23	$ 7.23	1	1	https://www.homedepot.com/
13	850003465029	Home Depot	White PEX-A Pipe	1" x 10'	1	$ 15.45	$ 15.45	1	1	https://www.homedepot.com/
14	883652807254	Home Depot	Heavy Duty Fitting Brush	1"	1	$ 4.27	$ 4.27	1	1	https://www.homedepot.com/
15	43425501127	Home Depot	Clearweld Epoxy Syringe	25ml	1	$ 7.78	$ 7.78	1	1	https://www.homedepot.com/
16	670750292736	Home Depot	Push PEX Pipe Cutter	1/2" - 1"	1	$ 9.98	$ 9.98	1	1	https://www.homedepot.com/
17	38753391014	Home Depot	DWV Knock Out Test Cap	2"	4	$ 0.59	$ 2.36	4	4	https://www.homedepot.com/
18	887480001891	Home Depot	Barb MTP Adapter Brass	1/2' x 1/2'	1	$ 6.57	$ 6.57	1	1	https://www.homedepot.com/
19	887480022896	Home Depot	MIP x FIP Pipe Bushing Brass	1/2' x 3/8'	1	$ 5.57	$ 5.57	1	1	https://www.homedepot.com/
20	C24216489	Amazon	CGELE K-Type Thermocouple NPT	-	2	$ 13.09	$ 26.18	2	2	https://www.amazon.com/s?k
21	887480026399	Home Depot	MIP x FIP Pipe Bushing Brass	1/2' x 1/4'	1	$ 5.57	$ 5.57	1	1	https://www.homedepot.com/
22	887480019599	Home Depot	FIP Red Brass Tee	1/2' x 1/2' x 1/2'	2	$ 9.57	$ 19.14	2	2	https://www.homedepot.com/
23	78864178500	Home Depot	Pipe Tape	1/2' x 260'	1	$ 0.98	$ 0.98	1	1	https://www.homedepot.com/
24	18578000490	Home Depot	Cap for CI, ST, PL CU	2'	1	$ 4.36	$ 4.36	1	1	https://www.homedepot.com/
25	39923359667	Home Depot	Cop Cap C	1/2"	6	$ 1.05	$ 6.30	6	6	https://www.homedepot.com/
26	685768275602	Home Depot	Type L Copper	1/2" x 2'	3	$ 9.76	$ 29.28	3	3	https://www.homedepot.com/
27	811000011022	Home Depot	ABS Pipe	2' x 2'	1	$ 8.97	$ 8.97	1	1	https://www.homedepot.com/
28	611942027989	Home Depot	ABS Cap Hub	2'	1	$ 10.84	$ 10.84	1	1	https://www.homedepot.com/
29	30699207862	Home Depot	LD Single Robe Hook MB 5pk	-	1	$ 9.47	$ 9.47	1	1	https://www.homedepot.com/
30	76308410834	Home Depot	Black Drywall Hook	15lbs/3.3ft	1	$ 11.98	$ 11.98	1	1	https://www.homedepot.com/
31	887480031812	Home Depot	Mach Screw Zinc Comb Rnd	1/2"	1	$ 1.68	$ 1.68	1	1	https://www.homedepot.com/
32	887480023190	Home Depot	MIP x FIP Bushing Brass	3/8" x 1/4"	2	$ 5.48	$ 10.96	2	2	https://www.homedepot.com/
33	887480022896	Home Depot	MIP x FIP Bushing Brass	1/2" x 3/8"	2	$ 5.57	$ 11.14	2	2	https://www.homedepot.com/
34	43425051332	Home Depot	J-B Weld PlasticBonder	-	2	$ 8.68	$ 17.36	2	2	https://www.homedepot.com/
35	202106230	Home Depot	OSB Sheathing Panel	4' x 8' thickness = 7/16"	3	$ 19.33	$ 57.99	3	3	https://www.homedepot.com/
36	312528776	Home Depot	2 in. x 4 in. x 8 ft. Prime Stud	2" x 4" x 8'	10	$ 3.99	$ 39.90	10	10	https://www.homedepot.com/
37	304185143	Home Depot	Clear Vinyl Tubing	1/2"ID x 3/4" OD x 10'	1	$ 11.97	$ 11.97	1	1	https://www.homedepot.com/
38	B0BRJD1HJL	Amazon	EVIL ENERGY 3/4" Heater Hose	3/4" ID 10' long	2	$ 40.37	$ 80.74	2	2	https://www.amazon.com/dp/E
39	B0BRJFG4B8	Amazon	EVIL ENERGY 5/8" Heater Hose	5/8" 10' long	2	$ 35.79	$ 71.58	2	2	https://www.amazon.com/dp/E
40	399098	AutoZone	Duralast HVAC Heater Core	-	1	$ 43.74	$ 43.74	1	1	https://www.autozone.com/cc
41	764661004073	Home Depot	Sakrete Floor Mud Mortar	50 lbs	1	$ 8.59	$ 8.59	1	1	https://www.homedepot.com/
42	810016113133	Home Depot	Everbilt Staple Tab Insulation	16"x25'	2	$ 19.97	$ 39.94	2	2	https://www.homedepot.com/
43	887480008708	Home Depot	HEX Bolt Zinc	3/8 x 3-1/2 (25pc)	1	$ 21.44	$ 21.44	1	1	https://www.homedepot.com/
44	887480259711	Home Depot	JAM Nut Zinc	3/8"-16	3	$ 1.68	$ 5.04	3	3	https://www.homedepot.com/
45	887480077124	Home Depot	Flat Washer SAE Zinc	3/8" (50pc)	1	$ 6.87	$ 6.87	1	1	https://www.homedepot.com/
38	B0BRJD1HJL	Amazon	EVIL ENERGY 3/4" Heater Hose	3/4" ID 10' long	2	$ 40.37	$ 80.74	2	2	https://www.amazon.com/dp/E
39	B0BRJFG4B8	Amazon	EVIL ENERGY 5/8" Heater Hose	5/8" 10' long	2	$ 35.79	$ 71.58	2	2	https://www.amazon.com/dp/E
40	399098	AutoZone	Duralast HVAC Heater Core	-	1	$ 43.74	$ 43.74	1	1	https://www.autozone.com/cc
41	764661004073	Home Depot	Sakrete Floor Mud Mortar	50 lbs	1	$ 8.59	$ 8.59	1	1	https://www.homedepot.com/
42	810016113133	Home Depot	Everbilt Staple Tab Insulation	16"x25'	2	$ 19.97	$ 39.94	2	2	https://www.homedepot.com/
43	887480008708	Home Depot	HEX Bolt Zinc	3/8 x 3-1/2 (25pc)	1	$ 21.44	$ 21.44	1	1	https://www.homedepot.com/
44	887480259711	Home Depot	JAM Nut Zinc	3/8"-16	3	$ 1.68	$ 5.04	3	3	https://www.homedepot.com/
45	887480077124	Home Depot	Flat Washer SAE Zinc	3/8" (50pc)	1	$ 6.87	$ 6.87	1	1	https://www.homedepot.com/
46	D1	Donated	Igloo Cooler	26L	1	-	-	1	1	
47	670750842832	Home Depot	PEX A expansion barb plug	1" (10-pack)	1	$ 27.00	$ 27.00	1	1	https://www.homedepot.com/
48	D2	Donated	Copper Elbows	2"	6	-	-	6	6	
49	204811799	Home Depot	Philips Flat-Head Deck Screws	2" (5lb pack)	1	$ 31.47	$ 31.47	1	1	https://www.homedepot.com/
50	670750842191	Home Depot	PEX A expansion sleeve/ring	1" (25-pack)	1	$ 17.20	$ 17.20	1	1	https://www.homedepot.com/
51	670750841545	Home Depot	PEX A expansio sleeve/ring	3/4 " (25-pack)	1	$ 8.98	$ 8.98	1	1	https://www.homedepot.com/
52	D3	Donated	Thermocouple K-type	Donated	6	-	-	6	6	
53	B01C3A2A6Q	Amazon	Pico TC-08	-	1	$ 479.00	479.00	1	1	https://www.amazon.com/dp/E
54	203423635	Home Depot	Floor Mud Mortar	50lbs	1	$ 8.59	$ 8.59	1	1	https://www.homedepot.com/
56	D4	Donated	Fan	-	1	-	-	1	1	
59	B0CKMS75Z4	Amazon	Compact Chest Freezer, Deep	3.5 cubic feet	1	$ 214.49	$ 214.49	1	1	https://www.amazon.com/Fcic
60	FR-PPU12-188	Amazon	Pump	5W (350L/h)	1	$ 8.99	$ 8.99	1	1	https://www.amazon.com/DOI
62	810016113133	Home Depot	ouble Reflective Insulation Staple T	16 in. x 25 ft	2	$ 19.97	$ 39.94	2	2	https://www.homedepot.com/
63	887480008708	Home Depot	Zinc Plated Hex Bolt (25-Pack)	3/8 in.-16 x 3-1/2 in	1	$ 21.44	$ 21.44	1	1	https://www.homedepot.com/
64	887480259711	Home Depot	Zinc Plated Jam Nut (6-Pack)	3/8 in.-16	3	$ 1.68	$ 5.04	3	3	https://www.homedepot.com/
65	887480077124	Home Depot	Zinc Flat Washer (50-Pack)	3/8 in.	1	$ 6.87	$ 6.87	1	1	https://www.homedepot.com/
66	8925154006	Home Depot	J-Shank Jig Saw Blade Set (12-Piece	-	1	$ 14.47	$ 14.47	1	1	https://www.homedepot.com/
67	38902035370	Home Depot	PG10 EXT SCREW 5 LB	#8 X 2"	1	$ 31.47	$ 31.47	1	1	
68	670750842832	Home Depot	EX-A Expansion Barb Plug (10-Pac	1"	1	$ 27.00	$ 27.00	1	1	https://www.homedepot.com/
69	670750842191	Home Depot	X-A Expansion Sleeve/Ring (25-Pa	1"	1	$ 17.20	$ 17.20	1	1	https://www.homedepot.com/
70	670750841545	Home Depot	X-A Expansion Sleeve/Ring (25-Pa	3/4"	1	$ 8.98	$ 8.98	1	1	https://www.homedepot.com/
71	202528473	Home Depot	JB Water Weld	-	3	$ 7.48	$ 22.44	1	1	https://www.homedepot.com/
72	B0C2TY8VYP	Amazon	Anemometer Handheld Wind	-	1	$ 147.15	$ 147.15	1	1	https://www.amazon.com/Vor
73	B0865P1SQJ	Amazon	Thermocouple K-type Connector	(10-pack)	1	$ 34.99	$ 34.99	1	1	https://www.amazon.com/20p
74	B0CZ3YHS5X	Amazon	Voltage Transformer	-	1	$ 51.99	$ 51.99	1	1	https://www.amazon.com/VE\
75	203531910	Home Depot	Zip Ties	(100-pack)	1	$ 10.98	$ 10.98	1	1	https://www.homedepot.com/
76		Donated	Pump (P.Dou)	-	1	$ -	$ -	1	1	
77		Home Depot	IPEX Rigid PVC Schedule 40 Pipe	1 in. x 24 in.	1	$ 4.24	$ 4.24	1	1	https://www.homedepot.com/
78		Amazon	Spa Manifold Vita Spas VIT231457	1 in. Spig 5 Port 3/8 Barb	2	$ 14.23	$ 28.46	2	2	https://www.amazon.com/Hot
79		Home Depot	PVC Schedule 40 Reducer	1 in. x 3/4 in.	2	$ 2.81	$ 5.62	2	2	https://www.homedepot.com/
80		Home Depot	PVC Schedule 40 Reducer Bushing	3/4 in. x 1/2 in.	2	$ 1.87	$ 3.74	2	2	https://www.homedepot.com/
81		Home Depot	Brass Adapter Fitting	5/8 in. Barb x 1/2 in. MIP	2	$ 5.27	$ 10.54	2	2	https://www.homedepot.com/
82		Home Depot	Foam Semi-Slit Pipe Insulation	1 in. x 6 ft.	5	$ 2.98	$ 14.90	5	5	https://www.homedepot.com/
83		Home Depot	Vinyl Micro Fuel Line	1/4 in. O.D. x 1/8 in. I.D.	1	$ 6.33	$ 6.33	5	5	https://www.homedepot.com/
84		Home Depot	Vinyl Micro Fuel Line	1/4 in. O.D. x 7/64 in. I.D.	1	$ 6.33	$ 6.33	5	5	https://www.homedepot.com/

Figure 37: Bill of Materials

Appendix B: Code

Material Properties MATLAB code

```
function MaterialProperties(Material,HeatofFusion, TempofFusion, SpecificHeat,
DensityMatrix, MinEnergyRequirement, MaxEnergyRequirement, LowestTemp, Costperkg)
% AUTHOR: Courtney Hiatt
% DATE: 3/26/2024
% INPUTS: Material Properties and Energy Requirements
% OUTPUTS: Graphs and Tables regarding mass and volume requirements

% This MATLAB code inputs the material properties and minimum to maximum
% energy requirements and outputs data and graphs on the required mass,
% volume, and price required to run the AC through the night.


%Initializing values
RoomTemp = 20; %C
dT = RoomTemp-LowestTemp; %C
T = linspace(LowestTemp,RoomTemp,20)'; %C
density = interp1(DensityMatrix(1,:),DensityMatrix(2,:),T); %kg/m^3
MinDensity = min(density); %kg/m^3
EnergyValues = linspace(MinEnergyRequirement, MaxEnergyRequirement, 20)'; %kJ
Mass = EnergyValues./(SpecificHeat*dT+HeatofFusion); %kg
Volume = Mass/MinDensity;
Latent = Mass*HeatofFusion;
Sensible = EnergyValues-Latent;
Cost = Mass*Costperkg;

% If the material does not go through phase change, the latent heat is 0,
% and this can be accounted for by changing the heat of fusion to 0.
if (LowestTemp > TempofFusion) || (TempofFusion > RoomTemp)
    HeatofFusion = 0;
end

%Plotting and creating a table of the mass and volume required for the
%minimum to maximum energy requirements
A = [EnergyValues, Mass, Volume, Latent, Sensible];
Table1 = array2table(A, 'VariableNames', {'Energy Requirmenets (kJ)', 'Mass Required
(kg)', 'Volume Required (m^3)', 'Latent Heat Storage (kJ)', 'Sensible Heat Storage
(kJ)'});
text = 'Mass and Volume Requirements for Energy Requirements ';
```

```
txt = append(text,Material);
Table1 = table(Table1, 'VariableNames', {txt})

figure
hold on
text = 'Mass and Volume Material Required for ';
txt = append(text,Material);
title(txt)
xlabel('Energy Required (kJ)')
yyaxis left
plot(EnergyValues,Mass)
ylabel('Mass of Material Required (kg)')
yyaxis right
plot(EnergyValues,Volume)
ylabel('Max volume of material requied (m^3)')
hold off

figure
hold on
text = 'Price and Mass Material Required for ';
txt = append(text,Material);
title(txt)
xlabel('Energy Required (kJ)')
yyaxis left
plot(EnergyValues,Mass)
ylabel('Mass of Material Required (kg)')
yyaxis right
plot(EnergyValues,Cost)
ylabel('Cost ($)')
hold off

%This creates a table and plot of the changes in volume for the max and min energy
%requirement
MaxMass = MaxEnergyRequirement./(SpecificHeat*dT+HeatofFusion); %kg
MaxVolumes = MaxMass./density; %m^3
MinMass = MinEnergyRequirement./(SpecificHeat*dT+HeatofFusion); %kg
MinVolumes = MinMass./density; %m^3

B = [T, MaxVolumes];
Table2 = array2table(B, 'VariableNames', {'Temperature (C)', 'Volume'});
text = 'Volume Requirements for Maximum Energy Requirements ';
txt = append(text,Material);
Table2 = table(Table2, 'VariableNames', {txt})
C = [T, MinVolumes];
Table3 = array2table(C, 'VariableNames', {'Temperature (C)', 'Volume (m^3)'});
text = 'Volume Requirements for Minimum Energy Requirements ';
txt = append(text,Material);
Table3 = table(Table3, 'VariableNames', {txt})

figure
hold on
plot(T,MaxVolumes)
```

```
plot(T,MinVolumes)
xlabel('Temperature (C)')
ylabel('Volume (m^3)')
text = 'Volume Requirements at Varying Temperatures for ';
txt = append(text,Material);
title(txt)
legend('Max Energy Requirements', 'Min Energy Requirements')
hold off

end
```

Material Properties Driver MATLAB code

```
% AUTHOR: Courtney Hiatt
% DATE: 3/26/24
% This code is the driver for the material properties function and outputs
% mass, volume, and cost requirements for different materials.


clc
clear all

LowestTemp = -1; %deg C
MinEnergyRequirement = 43200; %kJ
MaxEnergyRequirement = 50400; %kJ

%Properties of water
Water = 'Water';
WaterHeatofFusion = 334; %kJ/kg
WaterSpecificHeat = 4.187; %kJ/kgC
TempofFusion = 0; %deg C
WaterDensityMatrix = [-50 -40 -35 -30 -25 -20 -15 -10 -5 0 1 4 10 15 20 25 30 35 40
45 50 55 60 65 70; 921.6 920.8 920.4 920 919.6 919.4 919.4 918.9 917.5 916.2 999.90
999.97 999.70 999.10 998.21 997.05 995.65 994.03 992.22 990.21 998.04 985.69 983.21
980.55 977.76]; %kg/m3
WaterCost = 0.0002189;
MaterialProperties(Water, WaterHeatofFusion, TempofFusion, WaterSpecificHeat,
WaterDensityMatrix, MinEnergyRequirement, MaxEnergyRequirement, LowestTemp,
WaterCost)


%Properties of concrete
Concrete = 'Concrete';
ConcreteHeatofFusion = 0; %kJ/kg
ConcreteSpecificHeat = 1; %kJ/kgC
ConcreteDensityMatrix = [-100,0, 80, 95, 180; 2300, 2300, 2300, 2300, 2254];
ConcreteTempofFusion = 1200; %deg C
ConcreteCost = 0.10;
```

```
MaterialProperties(Concrete, ConcreteHeatofFusion, ConcreteTempofFusion,
ConcreteSpecificHeat, ConcreteDensityMatrix, MinEnergyRequirement,
MaxEnergyRequirement, LowestTemp, ConcreteCost)
```

Arduino Temperature Sensor Code

```
int sensor1 = 0;

void setup()
{
  Serial.begin(9600);
}

void loop()
{
  int reading = analogRead(sensor1);
  float voltage = reading * 5.0198;
  voltage /= 1024.0;

  float temperatureC = (voltage - 0.5)*100;
  Serial.print(temperatureC);
  Serial.println(" degrees C");

  delay(1000);
}
```

MATLab Code for Resistive Thermal Network of Water Bars

```
% Inputs
% Convert inches to meters
r1_inch = 0.13 * (254 / 10000);
r2_inch = 1.30 * (254 / 10000);
L_inch = 12 * (254 / 10000);

% Define material properties (thermal conductivity in W/mK)
material.k_1 = 401; % Copper thermal conductivity (W/mK)
material.k_2 = 0.38; % PEX thermal conductivity (W/mK)

% Define fluid properties for ethylene glycol (inside copper pipe)
fluid1.mu = 0.002; % Dynamic viscosity of ethylene glycol (Pa·s)
fluid1.k = 0.258; % Thermal conductivity of ethylene glycol (W/m·K)
fluid1.Cp = 2430; % Specific heat capacity of ethylene glycol (J/kg·K)
fluid1.rho = 1110; % Density of ethylene glycol (kg/m³)
fluid1.T_inlet = 120; % Inlet temperature of ethylene glycol (°C)
fluid1.v = 1; % Flow velocity (m/s) - assumed for now

% Define fluid properties for water (in the annular region)
fluid2.mu = 0.001; % Dynamic viscosity of water (Pa·s)
fluid2.k = 0.6; % Thermal conductivity of water (W/m·K)
fluid2.Cp = 4180; % Specific heat capacity of water (J/kg·K)
fluid2.rho = 1000; % Density of water (kg/m³)
fluid2.T_inlet = 40; % Inlet temperature of water (°C)

% Define geometry (pipe dimensions in meters)
geometry.r1_inner = r1_inch; % Inner radius of copper pipe (m)
geometry.r2_outer = r2_inch; % Outer radius of copper pipe/inner radius of PEX (m)
geometry.L = L_inch; % Length of the pipe (m)

heat_transfer_rate = concentric_pipes_heat_transfer(material, fluid1, fluid2, geometry);
```

```
function heat_transfer_rate = concentric_pipes_heat_transfer(material, fluid1, fluid2,
geometry)
% Inputs:
% material: structure containing material properties (e.g., 'k_copper', 'k_PEX')
```

```
% fluid1: structure with properties of the fluid inside the copper tube (ethylene glycol)
% fluid2: structure with properties of the fluid in the annular space (water)
% geometry: structure with pipe dimensions (r1_inner, r2_outer, L) [m]

% Extracting geometry parameters (in meters)
r1_inner = geometry.r1_inner; % Inner radius of the copper pipe (m)
r2_outer = geometry.r2_outer; % Outer radius of the PEX pipe (m)
L = geometry.L; % Length of the pipe (m)

% Thermal conductivities (W/m·K)
k_1 = material.k_1; % Copper thermal conductivity
k_2 = material.k_2; % PEX thermal conductivity

% Calculating convective heat transfer coefficients using empirical formulas
% Ethylene Glycol (inside copper pipe):
Re_eg = (fluid1.rho * fluid1.v * 2 * r1_inner) / fluid1.mu % Reynolds number
Pr_eg = (fluid1.mu * fluid1.Cp) / fluid1.k % Prandtl number

if Re_eg > 4000
% Turbulent flow: Use Dittus-Boelter correlation for Nusselt number
Nu_eg = 0.023 * Re_eg^0.8 * Pr_eg^0.4;
else
% Laminar flow: Simplified Nusselt number for fully developed flow
Nu_eg = 3.66;
end

h_F1 = (Nu_eg * fluid1.k) / (2 * r1_inner) % Convective heat transfer coefficient for ethylene
glycol

% Water (in annular region between copper and PEX):
Re_water = (fluid2.rho * fluid1.v * (r2_outer - r1_inner)) / fluid2.mu % Reynolds number for
water
Pr_water = (fluid2.mu * fluid2.Cp) / fluid2.k % Prandtl number for water

if Re_water > 4000
% Turbulent flow
Nu_water = 0.023 * Re_water^0.8 * Pr_water^0.4;
else
```

```
% Laminar flow
Nu_water = 3.66;
end

h_F2 = (Nu_water * fluid2.k) / (r2_outer - r1_inner) % Convective heat transfer coefficient for water

% Temperatures (Celsius)
Tinlet_F1 = fluid1.T_inlet; % Inlet temperature of ethylene glycol (°C)
Tinlet_F2 = fluid2.T_inlet; % Inlet temperature of water (°C)

% Calculate surface areas (m²)
A1 = 2 * pi * r1_inner * L; % Surface area for convective heat transfer with glycol (inner copper pipe)
A2 = 2 * pi * r2_outer * L; % Surface area for convective heat transfer with water (outer PEX pipe)

% Convective resistance for ethylene glycol (inside copper tube)
RConv1 = 1 / (h_F1 * A1)

% Conductive resistance through copper (between r1_inner and r2_outer)
RCond1 = log(r2_outer / r1_inner) / (2 * pi * k_1 * L)

% Convective resistance for water (in the annular region between copper and PEX)
RConv2 = 1 / (h_F2 * A2)

% Conductive resistance through PEX
r_Outer2 = r2_outer + 0.001; % Add thickness of PEX pipe (assumed 1mm for this example)
R_Cond2 = log(r_Outer2 / r2_outer) / (2 * pi * k_2 * L)

% Total thermal resistance
R_total = RConv1 + RCond1 + RConv2 + R_Cond2;

% Temperature difference (between ethylene glycol and water)
delta_T = Tinlet_F1 - Tinlet_F2;

% Heat transfer rate
q = delta_T / R_total; % Heat transfer rate (W)
```

```
% Display results
fprintf('Total Thermal Resistance: %.4f K/W\n', R_total)
fprintf('Heat Transfer Rate: %.4f W\n', q)

% Output heat transfer rate
heat_transfer_rate = q;
end
```

```
%Lumped Capacitance ahe

Ti = -40;        % Initial temperature of the TES (°C)
T_inf = 36;      % Ambient temperature (°C)
h = ;            % Convective heat transfer coefficient (W/m^2.K)
A = 0.00262903663;      % Wetted surface area of the TES (m^2)
rho = 1000;      % Density of the material (kg/m^3)
V = 0.0056613;   % Volume of the TES (m^3)
cp = 4182;       % Specific heat capacity of the material (J/kg.K)
k = 0.6;         % Thermal conductivity of the material (W/m.K)
tmax = 14400;    % Time in seconds (1hr=3600s, 4 hr=14400s)

% Calculate the characteristic length
L_c = V / A;

% Calculate the Biot number
Bi = h * L_c / k;
```

```
% Check if lumped capacitance method is valid
if Bi >= 0.1
    error('Biot Number is too large (Bi = %.3f). Lumped Capacitance method is not valid.', Bi);
else
    disp(['Biot Number: ', num2str(Bi)])
    disp('Lumped capacitance method is valid. Proceeding with the solution...')
end
% Time vector (seconds)
t = linspace(0,tmax, 100);  % Time from 0 to tmax

% Lumped capacitance solution
T_t = T_inf + (Ti - T_inf) * exp(-h * A * t / (rho * V * cp));

% Plot the results
figure;
plot(t, T_t, 'LineWidth', 2);
xlabel('Time (s)');
ylabel('Temperature (°C)');
title('Temperature vs. Time using Lumped Capacitance Method');
grid on;
```

Spider Chart MATLAB Code

```
% Data values (normalized 0 to 1)
close all
```

```
% Water Bars
values = [0.85, 0.6, 1, 0.9, 0.3, 0.7, 0.25, 0.95];
% Concrete
values2 = [0.95, 0.9, 0.6, 0.9, 0.5, 1, 1, 0.4];
% Baltimore Air Coil
values3 = [0.9, 0.9, 0.1, 0.8, 0.7, 0.8, 1, 0.2];
% Labels for each axis
labels = {'Safety', 'Reliability', 'Monetary', 'Material', ...
    'Risk', 'ROI', 'Energy Demand', 'Ease of Access'};
% Close the values to make a complete loop
values = [values, values(1)];
values2 = [values2, values2(1)];
values3 = [values3, values3(1)];
% Number of variables
num_vars = length(labels);
% Angles for the radar chart
angles = linspace(0, 2*pi, num_vars+1);
% Create the figure
figure;
polarplot(angles, values, 'b-', 'LineWidth', 2);
hold on;
polarplot(angles, values2, 'r-', 'LineWidth', 2);
polarplot(angles, values3, 'g-', 'LineWidth', 2);
% Set the axes labels
ax = gca;
ax.ThetaTick = rad2deg(angles(1:end-1));
ax.ThetaTickLabel = labels;
% Set radial limits and labels
rlim([0 1]);
```

```
rticks([0.2 0.4 0.6 0.8 1]);
title('Spider Chart for TES designs', 'FontSize', 14);
legend('Water Bars','Concrete','Datum', 'Location', 'northeastoutside');
hold off;
```

Appendix C:

Thermo Fisher SCIENTIFIC

SAFETY DATA SHEET

Creation Date 02-Feb-2010 **Revision Date** 24-Dec-2021 **Revision Number** 5

1. Identification

Product Name **Ethylene glycol**

Cat No. : **E177-4; E177-20**

CAS No 107-21-1
Synonyms Monoethylene glycol; 1,2-Ethanediol

Recommended Use Laboratory chemicals.
Uses advised against Food, drug, pesticide or biocidal product use.

Details of the supplier of the safety data sheet

Company
Fisher Scientific Company
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

Classification
This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Acute oral toxicity	Category 4
Specific target organ toxicity (single exposure)	Category 3
Target Organs - Central nervous system (CNS).	
Specific target organ toxicity - (repeated exposure)	Category 2
Target Organs - Kidney, Liver.	

Label Elements

Signal Word
Warning

Hazard Statements
Harmful if swallowed
May cause drowsiness or dizziness

May cause damage to organs through prolonged or repeated exposure

Precautionary Statements
Prevention
Wash face, hands and any exposed skin thoroughly after handling
Do not eat, drink or smoke when using this product
Do not breathe dust/fume/gas/mist/vapors/spray
Use only outdoors or in a well-ventilated area
Response
Get medical attention/advice if you feel unwell
Inhalation
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
Call a POISON CENTER or doctor/physician if you feel unwell
Ingestion
IF SWALLOWED: Call a POISON CENTER or doctor/physician if you feel unwell
Rinse mouth
Storage
Store in a well-ventilated place. Keep container tightly closed
Store locked up
Disposal
Dispose of contents/container to an approved waste disposal plant
Hazards not otherwise classified (HNOC)

WARNING. Reproductive Harm - https://www.p65warnings.ca.gov/.

3. Composition/Information on Ingredients

Component	CAS No	Weight %
Ethylene glycol	107-21-1	>95

4. First-aid measures

Eye Contact Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

Skin Contact Wash off immediately with plenty of water for at least 15 minutes. Get medical attention immediately if symptoms occur.

Inhalation Remove to fresh air. Do not use mouth-to-mouth method if victim ingested or inhaled the substance; give artificial respiration with the aid of a pocket mask equipped with a one-way valve or other proper respiratory medical device. Get medical attention immediately if symptoms occur. If not breathing, give artificial respiration.

Ingestion Do NOT induce vomiting. Call a physician or poison control center immediately.

Most important symptoms and effects Difficulty in breathing.

Notes to Physician Treat symptomatically

5. Fire-fighting measures

Suitable Extinguishing Media Water spray, carbon dioxide (CO_2), dry chemical, alcohol-resistant foam.

Unsuitable Extinguishing Media No information available

Flash Point 111 °C / 231.8 °F

Method - DIN 51758

Autoignition Temperature 413 °C / 775.4 °F

Explosion Limits
Upper 15.30 vol %
Lower 3.20 vol %
Sensitivity to Mechanical Impact No information available
Sensitivity to Static Discharge No information available

Specific Hazards Arising from the Chemical
Thermal decomposition can lead to release of irritating gases and vapors. Keep product and empty container away from heat and sources of ignition.

Hazardous Combustion Products
Carbon monoxide (CO). Carbon dioxide (CO_2).
Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPA

Health	Flammability	Instability	Physical hazards
2	1	1	N/A

6. Accidental release measures

Personal Precautions Ensure adequate ventilation. Use personal protective equipment as required.
Environmental Precautions Should not be released into the environment. See Section 12 for additional Ecological Information.

Methods for Containment and Clean Up Soak up with inert absorbent material. Keep in suitable, closed containers for disposal.

7. Handling and storage

Handling Wear personal protective equipment/face protection. Ensure adequate ventilation. Do not breathe mist/vapors/spray. Avoid contact with skin, eyes or clothing.

Storage. Keep containers tightly closed in a dry, cool and well-ventilated place. Keep away from heat, sparks and flame. Incompatible Materials. Strong oxidizing agents. Strong acids. Strong bases. Aldehydes.

8. Exposure controls / personal protection

Exposure Guidelines

Component	ACGIH TLV	OSHA PEL	NIOSH IDLH	Mexico OEL (TWA)
Ethylene glycol	TWA: 25 ppm STEL: 50 ppm STEL: 10 mg/m³	(Vacated) Ceiling: 50 ppm (Vacated) Ceiling: 125 mg/m³		Ceiling: 100 mg/m³

Legend

ACGIH - American Conference of Governmental Industrial Hygienists

OSHA - Occupational Safety and Health Administration

Engineering Measures	Ensure adequate ventilation, especially in confined areas. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection	Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.
Skin and body protection	Wear appropriate protective gloves and clothing to prevent skin exposure.
Respiratory Protection	Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.
Hygiene Measures	Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

Physical State	Viscous liquid Liquid
Appearance	Colorless
Odor	Odorless
Odor Threshold	No information available
pH	5.5-7.5 50% aq. sol
Melting Point/Range	-13 °C / 8.6 °F
Boiling Point/Range	196 - 198 °C / 384.8 - 388.4 °F @ 760 mmHg
Flash Point	111 °C / 231.8 °F
Method -	DIN 51758
Evaporation Rate	No information available
Flammability (solid,gas)	Not applicable
Flammability or explosive limits	
Upper	15.30 vol %
Lower	3.20 vol %
Vapor Pressure	0.12 mmHg @ 20 °C
Vapor Density	2.14 (Air = 1.0)
Specific Gravity	1.113
Solubility	miscible
Partition coefficient; n-octanol/water	No data available
Autoignition Temperature	413 °C / 775.4 °F
Decomposition Temperature	> 500°C
Viscosity	21 cP (20°C)
Molecular Formula	C2 H6 O2
Molecular Weight	62.06

10. Stability and reactivity

Reactive Hazard	None known, based on information available
Stability	Hygroscopic.
Conditions to Avoid	Incompatible products. Excess heat. Exposure to moist air or water.
Incompatible Materials	Strong oxidizing agents, Strong acids, Strong bases, Aldehydes
Hazardous Decomposition Products	Carbon monoxide (CO), Carbon dioxide (CO_2)
Hazardous Polymerization	Hazardous polymerization does not occur.

Hazardous Reactions None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information
Component Information

Component	LD50 Oral	LD50 Dermal	LC50 Inhalation
Ethylene glycol	7712 mg/kg (Rat)	LD50 = 9530 µL/kg (Rabbit) LD50 = 10600 mg/kg (Rat) LD50 > 3500 mg/kg (mice)	LC50 > 2.5 mg/L (Rat) 6 h

Toxicologically Synergistic Products No information available

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation May cause skin, eye, and respiratory tract irritation

Sensitization No information available

Carcinogenicity The table below indicates whether each agency has listed any ingredient as a carcinogen.

Component	CAS No	IARC	NTP	ACGIH	OSHA	Mexico
Ethylene glycol	107-21-1	Not listed	Not listed	Not listed	Not listed	Not listed

Mutagenic Effects No information available

Reproductive Effects No information available.

Developmental Effects No information available.

Teratogenicity No information available.

STOT - single exposure Central nervous system (CNS)
STOT - repeated exposure Kidney Liver

Aspiration hazard No information available

Symptoms / effects,both acute and delayed No information available

Endocrine Disruptor Information No information available

Other Adverse Effects The toxicological properties have not been fully investigated.

12. Ecological information

Ecotoxicity
Do not empty into drains. .

Component	Freshwater Algae	Freshwater Fish	Microtox	Water Flea
Ethylene glycol	EC50: 6500 - 13000 mg/L, 96h (Pseudokirchneriella subcapitata)	LC50: 14 - 18 mL/L, 96h static (Oncorhynchus mykiss) LC50: = 27540 mg/L, 96h static (Lepomis macrochirus) LC50: = 40761 mg/L, 96h static (Oncorhynchus mykiss) LC50: 40000 - 60000 mg/L, 96h static (Pimephales promelas) LC50: = 16000 mg/L, 96h static (Poecilia reticulata)	Not listed	EC50: = 46300 mg/L, 48h (Daphnia magna)

		LC50: = 41000 mg/L, 96h (Oncorhynchus mykiss)		

Persistence and Degradability Persistence is unlikely

Bioaccumulation/ Accumulation No information available.

Mobility Will likely be mobile in the environment due to its water solubility.

Component	log Pow
Ethylene glycol	-1.93

13. Disposal considerations

Waste Disposal Methods Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

14. Transport information

DOT Not regulated
TDG Not regulated
IATA Not regulated
IMDG/IMO Not regulated

15. Regulatory information

United States of America Inventory

Component	CAS No	TSCA	TSCA Inventory notification - Active-Inactive	TSCA - EPA Regulatory Flags
Ethylene glycol	107-21-1	X	ACTIVE	-

Legend:
TSCA US EPA (TSCA) - Toxic Substances Control Act, (40 CFR Part 710)
X - Listed
'-' - Not Listed

TSCA 12(b) - Notices of Export Not applicable

International Inventories
Canada (DSL/NDSL), Europe (EINECS/ELINCS/NLP), Philippines (PICCS), Japan (ENCS), Japan (ISHL), Australia (AICS), China (IECSC), Korea (KECL).

Component	CAS No	DSL	NDSL	EINECS	PICCS	ENCS	ISHL	AICS	IECSC	KECL
Ethylene glycol	107-21-1	X	-	203-473-3	X	X	X	X	X	KE-13169

KECL - NIER number or KE number (http://ncis.nier.go.kr/en/main.do)

U.S. Federal Regulations

SARA 313

Component	CAS No	Weight %	SARA 313 - Threshold Values %
Ethylene glycol	107-21-1	>95	1.0

SARA 311/312 Hazard Categories See section 2 for more information

CWA (Clean Water Act) Not applicable

Clean Air Act

Component	HAPS Data	Class 1 Ozone Depletors	Class 2 Ozone Depletors
Ethylene glycol	X		-

OSHA - Occupational Safety and Health Administration: Not applicable

CERCLA: This material, as supplied, contains one or more substances regulated as a hazardous substance under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302)

Component	Hazardous Substances RQs	CERCLA EHS RQs
Ethylene glycol	5000 lb	-

California Proposition 65: This product contains the following Proposition 65 chemicals.

Component	CAS No	California Prop. 65	Prop 65 NSRL	Category
Ethylene glycol	107-21-1	Developmental	-	Developmental

U.S. State Right-to-Know Regulations

Component	Massachusetts	New Jersey	Pennsylvania	Illinois	Rhode Island
Ethylene glycol	X	X	X	X	-

U.S. Department of Transportation
Reportable Quantity (RQ): Y
DOT Marine Pollutant N
DOT Severe Marine Pollutant N

U.S. Department of Homeland Security: This product does not contain any DHS chemicals.

Other International Regulations

Mexico - Grade: Slight risk, Grade 1

Authorisation/Restrictions according to EU REACH

Safety, health and environmental regulations/legislation specific for the substance or mixture

Component	CAS No	OECD HPV	Persistent Organic Pollutant	Ozone Depletion Potential	Restriction of Hazardous Substances (RoHS)
Ethylene glycol	107-21-1	Listed	Not applicable	Not applicable	Not applicable

Component	CAS No	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Major Accident Notification	Seveso III Directive (2012/18/EC) - Qualifying Quantities for Safety Report Requirements	Rotterdam Convention (PIC)	Basel Convention (Hazardous Waste)
Ethylene glycol	107-21-1	Not applicable	Not applicable	Not applicable	Not applicable

16. Other information

Prepared By: Regulatory Affairs
Thermo Fisher Scientific
Email: EMSDS.RA@thermofisher.com

Creation Date: 02-Feb-2010

Revision Date	24-Dec-2021
Print Date	24-Dec-2021
Revision Summary	This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text

End of SDS

SAFETY DATA SHEET
Propylene Glycol

1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

SDS Name:	Propylene Glycol
Product ID:	PG4, PG10
Synonyms:	1, 2,-propanediol, 1,2-dihydroxypropane
Chemical Formula:	$CH_3CHOHCH_2OH$
Distributed by:	Solvet 7226- 107th Avenue South East Calgary, Alberta Canada T2C5N6
For information, call:	(403) 456-2245
Emergency number:	(613) 996-6666 (CANUTEC) 1-800 463-5060 OR (418) 656-8090 (Control Poison Center)

2. HAZARDS IDENTIFICATION

OSHA Hazard Communication Standard
This product is not a "Hazardous Chemical" as defined by the OSHA Hazard Communication Standard, 29 CFR 1910.1200

Potential Health Effects:

Eye Contact:	May cause slight temporary eye irritation. Corneal injury is unlikely. Mist may cause eye irritation.
Skin Contact:	Prolonged contact is essentially not irritating to skin. Repeated contact may cause flaking and softening of skin.
Skin Absorption:	Prolonged skin contact is unlikely to result in absorption of harmful amounts.
Inhalation:	At room temperature, exposure to vapor is minimal due to low volatility. Mist may cause irritation of upper respiratory tract (nose and throat).
Ingestion:	Very low toxicity if swallowed. Harmful effects not anticipated from swallowing small amounts.
Aspiration Hazard:	Based on physical properties, not likely to be an aspiration hazard.
Effects of Repeated Exposure:	In rare cases, repeated excessive exposure to propylene glycol may cause central nervous system effects.

Label Elements:

Signal Word:
Warning
Hazard Statements

May cause drowsiness or dizziness
May cause damage to organs through prolonged or repeated exposure

3. COMPOSITION / INFORMATION ON INGREDIENTS

Name	Amount	CAS #
Propylene Glycol	> 99.5%	57-55-6

Toxicological Data on Ingredients: Propylene glycol: ORAL (LD50): Acute: 20000 mg/kg (Rat). 22,000 mg/kg (Mouse). DERMAL (LD50): Acute: 208000 mg/kg (Rabbit).

4. FIRST AID MEASURES

Eye Contact: Flush eyes thoroughly with water for several minutes. Remove contact lenses after the initial 1-2 minutes and continue flushing for several additional minutes. If effects occur, consult a physician, preferably an ophthalmologist.

Skin Contact: Wash skin with soap and plenty of water.

Inhalation: Move person to fresh air; if effects occur, consult a physician.

Ingestion: No emergency medical treatment necessary. Rinse mouth with water.

Most Important symptoms and effects, both acute and delayed
Aside from the information found under Description of first aid measures (above) and Indication of immediate medical attention and special treatment needed (below), no additional symptoms and effects are anticipated.

Indication of immediate medical attention and special treatment needed
No specific antidote. Treatment of exposure should be directed at the control of symptoms and the clinical condition of the patient.

5. FIRE FIGHTING MEASURES

Suitable extinguishing media: Water fog or fine spray. Dry chemical fire extinguishers. Carbon dioxide fire extinguishers. Foam. Alcohol resistant foams (ATC type) are preferred. General purpose synthetic foams (including AFFF) or protein foams may function, but will be less effective.

Extinguishing Media to Avoid: Do not use direct water stream. May spread fire.

Special hazards arising from the substance or mixture

Hazardous Combustion Products: During a fire, smoke may contain the original material in addition to combustion products of varying composition which may be toxic and / or irritating. Combustion products may include and are not limited to: Carbon monoxide. Carbon dioxide.

Unusual Fire and Explosion Hazards: Container may rupture from gas generation in a fire situation. Violent steam generation or eruption may occur upon application of direct water stream to hot liquids.

Advice for firefighters

Fire Fighting Procedures: Keep people away. Isolate fire and deny unnecessary entry. Use water spray to cool fire exposed containers and fire affected zone until fire is out and danger of reignition has passed. Fight fire from protected location or safe distance. Consider the use of unmanned hose holders or monitor nozzles. Immediately withdraw all personnel from the area in case of rising sound from venting safety device or discoloration of the container. Burning liquids may be extinguished by dilution with water. Do not use direct water stream. May spread fire. Move container from fire area if this is possible without hazard. Burning liquids may be moved by flushing with water to protect personnel and minimize property damage.

Special Protective Equipment for Firefighters: Wear positive-pressure self-contained breathing apparatus (SCBA) and protective firefighting clothing (includes firefighting helmet, coat, trousers, boots and gloves). If protective equipment is not available or not used, fight fire from a protected location or safe distance.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions, protective equipment and emergency procedures:
Spilled material may cause a slipping hazard. Keep unnecessary and unprotected personnel from entering the area. Use appropriate safety equipment. For additional information, refer to Section 8, Exposure Controls and Personal Protection.

Environmental precautions: Prevent from entering into soil, ditches, sewers, waterways and/ or ground water. See Section 12, Ecological Information.

Method and materials for containment and cleaning up:
Contain spilled material if possible. Small spills: Any absorbent material. Collect in suitable and properly labeled open containers. Wash the spill site with large quantities of water. Large spills: Dike area to contain spill. Pump into suitable and properly labeled containers. See Section 13, Disposal Considerations, for additional information.

7. HANDLING AND STORAGE

Handling:

General Handling: Spills of these organic materials on hot fibrous insulations may lead to lowering of the auto ignition temperature possibly resulting in spontaneous combustion. See Section 8, Exposure Controls and Personal Protection.

Storage: Store away from direct sunlight or ultraviolet light. Keep container tightly closed when not in use. Store in a dry place. Protect from atmospheric moisture. Store in the following material(s). Stainless steel. Aluminum. Plasite 3066 lined container. 316 stainless steel. Opaque HDPE plastic container.

Shelf life: Use within 12 Months

Maximum Storage Temperature: 40°C

8. EXPOSURE CONTROLS/ PERSONAL PROTECTION

Exposure Limits

Component	List	Type	Value
Propylene Glycol	WEEL	TWA Aerosol	10 mg/m^3

Engineering Controls:

Ventilation: Use local exhaust ventilation, or other engineering controls to maintain airborne levels below exposure limit requirements or guidelines. If there are no applicable exposure limit requirements or guidelines, general ventilation should be sufficient for most operations. Local exhaust ventilation may be necessary for some operations.

9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance	
Physical State:	Liquid
Color:	Colorless
Odor:	Odorless
Odor Threshold:	No test data available
pH:	Not applicable
Melting point/ Freezing Point:	-60 °C (-76 °F)
Boiling Point:	187°C (369°F)
Flash Point-Closed Cup:	103°C (217°F)
Flash Point-Open Cup:	No test data available
Evaporation Rate (Butyl Acetate=1):	0.01 Estimated
Flammability (solid, gas):	Not applicable to liquids
Flammable Limits In Air:	Lower: 2.6% (V) Estimated Upper: 12.5% (V) Estimated
Vapor Pressure	20 Pa @25°C EC Method A4
Vapor Density (air=1):	2.63
Specific Gravity (H_2O =1):	1.03 20°C / 20°C EU Method A.3 (Relative Density)
Solubility in water (by weight):	100% @ 20°C EU Method A.6 (Water Solubility)
Partition coefficient, n-octanol/water (log Pow):	-1.07 Measured
Autoignition Temperature:	100.01 kPa.400oC (>752oF) EC Method A15
Decomposition Temperature:	No test data available
Dynamic Viscosity:	43.4 mPa.s @ 25°C Literature
Kinematic Viscosity:	No test data available
Explosive properties:	Not explosive
Oxidizing properties:	No
Liquid Density:	1.03 g/cm³ @ 20°C Literature
Solubility in Solvents:	No test data available
Pour Point:	<-57°C (<-71°F) Literature
Henry's Law Constant (H):	1.2E-08 atm*m³/mole Measured

10. STABILITY AND REACTIVITY

Reactivity:	No dangerous reaction known under conditions of normal use.
Chemical Stability:	Stable under recommended storage conditions. See Storage, Section 7, Hygroscopic.
Possibility of hazardous reactions:	Polymerization will not occur.
Conditions to Avoid:	Exposure to elevated temperatures can be cause product to decompose. Generation of gas during decomposition can cause pressure in closed systems. Avoid direct sunlight or ultraviolet sources.

Incompatible Materials:	Avoid contact with: Strong acids. Strong bases. Strong oxidizers.
Hazardous decomposition products:	Decomposition products depend upon temperature, air supply and the presence of other materials. Decomposition Products can include and are not limited to: Aldehydes. Alcohols. Ethers. Organic acids.

11. TOXICOLOGICAL INFORMATION

Acute Toxicity	
Ingestion:	LD50, rat >20,000 mg/kg
Dermal	LD50, rabbit >2,000 mg/kg
Inhalation	No deaths occurred at this concentration. LC50, 2 h, Aerosol, rabbit 317.042 mg/l
Eye damage/eye irritation	May cause slight temporary eye irritation. Corneal injury is unlikely. Mist may cause eye irritation.
Skin corrosion/ irritation	Prolonged contact is essentially non-irritating to skin. Repeated contact may cause flaking and softening of skin.
Sensitization	
Skin	Did not cause allergic skin reactions when tested in humans.
Respiratory	No relevant data found
Repeated Dose Toxicity	In rare cases, repeated excessive exposure to propylene glycol may cause central nervous system effects.
Chronic Toxicity and Carcinogenicity	Did not cause cancer in Laboratory animals.
Developmental Toxicity	Did not cause birth defects or any other fetal effects in laboratory animals.
Reproductive Toxicity	In animal studies, did not interfere with reproduction. In animal studies, did not interfere with fertility.
Genetic Toxicology	In vitro genetic toxicity studies were negative. Animal genetic toxicity studies were negative.

12. ECOLOGICAL INFORMATION

Toxicity	Material is practically non-toxic to aquatic organisms on an acute basis (LC50/EC50/EL50/LL50>100 mg/L in the most sensitive species tested).
Fish Acute & Prolonged Toxicity	LC50, Oncorhynchus mykiss (rainbow trout), static test, 96 h: 40,613 mg/l
Aquatic Invertebrate Acute Toxicity	LC50, Ceriodaphnia Dubia (water flea) static test, 48h: 18,340 mg/l
Aquatic Plant Toxicity	Er50, Pseudokirchneriella subcapitata (green algae), Growth rate inhibition, 96h: 19,000 mg/l
Toxicity to Micro-organisms	NOEC, no data available; Pseudomonas putida, 18h: >20,000 mg/l
Aquatic Invertebrates Chronic Toxicity Value	Ceriodaphnia Dubia (water flea), semi-static test, 7 d, number of offspring, NOEC: 13020 mg/l

Persistence and Degradability Material is readily biodegradable. Passes OECD test(s) for ready biodegradable. Biodegradation may occur under anaerobic conditions (in the absence of oxygen).

OECD Biodegradation Tests:

Biodegradation	Exposure Time	Method	10 Day Window
81%	28 d	OECD 301F test	Pass
96%	64 d	OECD 306 Test	Not applicable

Indirect Photo degradation with OH Radicals

Rate Constant	Atmospheric Half-life	Method
1.28E-11 cm^3/s	10 h	Estimated

Biological oxygen demand (BOD):

BOD 5	BOD 10	BOD 20	BOD 28
69.00%	70.00%	86.00%	

Chemical Oxygen Demand: 1.53 mg/mg
Theoretical Oxygen Demand: 1.68 mg/mg

Bioaccumulative potential
Bioaccumulation: Bioconcentration potential is low (BCF<100 or Log Pow<3).
Partition coefficient, n-octanol/water (log Pow): -1.07 Measured
Bioconcentration Factor (BCF): 0.09; Estimated.

Mobility in Soil
Mobility in soil: Given its very low Henry's constant, volatilization from natural bodies of water or moist soil is not expected to be an important fate process, Potential for mobility in so is very high (Koc between 0 and 50).
Partition coefficient, soil organic carbon/water (Koc): < Estimated.
Henry's Law Constant (H): 1.2 E-08 atm*m3/mole Measured

13. DISPOSAL CONSIDERATIONS

DO NOT DUMP INTO ANY SEWERS, ON THE GROUND, OR INTO ANY BODY OF WATER. All disposal practices must be in compliance with all Federal, State/Provincial and local laws and regulations. Regulations may vary in different locations. Waste characterizations and compliance with applicable laws are the responsibility solely of the waste generator.

14. TRANSPORT INFORMATION

DOT Non –Bulk Not Regulated

DOT Bulk Not Regulated

IMDG Not Regulated

ICAO/IATA Not Regulated

This information is not intended to convey all specific regulatory or operational requirements/information relating to this product. Additional transportation system information can be obtained through an authorized sales or customer service representative. It is the responsibility of the transporting organization to follow all applicable laws, regulations and rules relating to the transportation of the material.

15. REGULATORY INFORMATION

OSHA Hazard Communication Standard
This product is not a "Hazardous Chemical" as defined by the OSHA Hazard Communication Standard, 29 CFR 1910.1200.

Superfund Amendments and Reauthorization Act of 1986 Title III (Emergency Planning and Community Right-to- Know Act of 1986) Sections 311 and 312

Immediate (Acute) Health Hazard	No
Delayed (Chronic) Health Hazard	No
Fire Hazard	No
Reactive Hazard	No
Sudden Release of Pressure Hazard	No

Superfund Amendments and Reauthorization Act of 1986 Title III (Emergency Planning and Community Right-to-Know Act of 1986) Section 313
To the best of our knowledge, this product does not contain chemicals at levels which require reporting under this statute.

Pennsylvania (Worker and Community Right-To-Know Act): Pennsylvania Hazardous Substances List and/ or Pennsylvania Environmental Hazardous Substance List:
The following product components are citied in the Pennsylvania Hazardous Substance List and / or the Pennsylvania Environmental Substance List, and are present at levels which require reporting.

Component	CAS #	Amount
Propylene Glycol	57-55-6	>=99.5%

Pennsylvania (Worker and Community Right-To-Know Act): Pennsylvania Special Hazardous Substances List:
To the best of our knowledge, this product does not contain chemicals at levels which require reporting under this statute.

Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Section 103
To the best of our knowledge, this product does not contain chemicals at levels which require reporting under this statute.

US. EPA Emergency Planning and Community Right-To-Know Act (EPCRA) SARA Title III Section 302 Extremely Hazardous Substance (40 CFR 355, Appendix A)
To the best of our knowledge, this product does not contain chemicals at levels which require reporting under this statute.

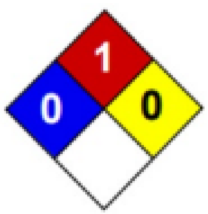
California Proposition 65 (Safe Drinking Water and Toxic Enforcement Act of 1986)
This product contains no listed substances known to the State of California to cause cancer, birth defects or other reproductive harm, at levels which would require a warning under the statute.

US. Toxic Substance Control Act
All components of this product are on the TSCA Inventory or are exempt from TSCA Inventory requirements under 40 CFR 720.30
CEPA – Domestic Substances List (DSL)
All substances contained in this product are listed on the Canadian Domestic Substances List (DSL) or are not required to be listed.
European Inventory of Existing Commercial Chemical Substances (EINECS)
The components of this product are on the EINECS inventory or are exempt from inventory requirements.

16. OTHER INFORMATION

Hazard Rating System

NFPA	Health	Fire	Reactivity
	0	1	0



The information above is believed to be accurate and represents the best information currently available to us. However, we make no warranty of merchantability or any other warranty, express or implied, with respect to such information, and we assume no liability resulting from its use. Users should make their own investigations to determine the suitability of the information for their particular purposes. In no event shall Alberta Veterinary Laboratory Ltd. be liable for any claims, losses, or damages of any third party or for lost profits or any special, indirect, incidental, consequential or exemplary damages, howsoever arising, even if Alberta Veterinary Laboratory Ltd. has been advised of the possibility of such damages.

This product has been classified in accordance with the hazard criteria of the CPR and the SDS contains all of the information required by the CPR

Revision Date: 2020-03-16

Product Name	SRP Thermal mass	SRP Thermal Mass Team	
System Name	Thermal masses		FMEA
Subsystem Name	Mass and supports		Date: 11/17/24
Component Name			

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurrence (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
copper pipe	kink	stop flow	9	Improper installation technique	2	visual inspection	1	18	Enclose the pipe to protect it and solve for fatigue failure to prevent thermal fatigue.
	crack	Leak	7	Thermal stress, Rapid changes in temperature	2	visual and dye test	3	42	Enclose the pipe to protect it and solve for fatigue failure to prevent thermal fatigue.
	burst	loss of fluid	10	Exposure to high pressure	1	design FOS	1	10	Find the FOS and engineer accordingly
	corrosion	Leakage, Pipe Rupture	10	Water with high acidity or alkalinity	2	minimal access to the system	2	40	Use best practices for installation
	melt	Leakage and contamination	10	Exposure to high temperature	1	connection to the expansion valve	3	30	Use best practices for installation
Water	evaporation	Slow decay of thermal efficiency	5	cracks, corrosion, damage	3	seal system	7	105	Use best practices for installation
	contamination	rapid decay of thermal efficiency	5	cracks, corrosion, damage	3	seal system	7	105	Use best practices for installation
Concrete	crack	Structural Integrity Compromised, Moisture Damage	8	Rapid Moisture Loss, Temperature Variations	5	visual inspection	4	160	develop best practices for installation
	erosion	Structural Integrity Compromised, Moisture Damage	7	exposure to high acidity or alkalinity	7	visual inspection	3	147	develop best practices for installation
	thermal fatigue	Cracking	7	Cyclic heating and cooling	8	visual inspection	3	168	develop best practices for installation
	loading fatigue	Cracking	7	Concrete Strengths, Occupant Loads	8	visual inspection	3	168	develop best practices for installation
Ethylene glycol	contamination	Health Risk, Environmental Degradation	9	Degradation of Seals, Leaks	4	contamination test	2	72	refill and test location
Pex -A	kink	change in the FOS of the copper pipe	7	Improper installation technique	1	visual inspection	1	7	Use best practices for installation
	crack	Water Damage	7	Thermal stress, Rapid changes in temperature	2	visual inspection	1	14	Use best practices for installation
	burst	Loss of thermal mass	9	Exposure to high pressure	1	visual inspection	1	9	Use best practices for installation
	melt	Poison gas	10	Exposure to high temperature	1	User caution	1	10	User warning
Electric Pump	broken impeller	Decreased Efficiency, Loss of coolant Circulation	8	Repeated Stress	5	FOS Calculation	6	240	Engineer FOS
	clogged filter	Reduced Water Flow	8	Cavitation, Accumulation of Debris	4	accessible filter	3	96	Reduce possible contamination locations
	loss of power	Interrupted Services	3	Electrical supply interruption	5	visual inspection	1	15	Use best practices for installation
fan	broken impeller	Loss of air circulation	5	Excessive Farique, Number of Cycles	4	visual inspection	1	20	Engineer FOS
	motor failure	Loss of air circulation	8	Electric Overload	3	Inspection	1	24	develop best practices for installation
	loss of power	Loss of air circulation	5	Electrical supply interruption	5	Inspection	1	25	Use best practices for installation
Insulator	crack	heat leak	8	Heat Shock or impact	3	visual inspection	5	120	Use best practices for installation
	leak	indirect contact	8	Dirt and improper install	4	IR camera	10	320	Use best practices for installation
	burn	Health Risk, Environmental Degradation	8	Exposure to high temperature	2	User caution	2	32	User warning
	moisture	Corrosion, Equipment Damage	8	Moisture absorption, pollution decomposition	4	visual inspection	3	96	Use best practices for installation
Propylene glycol	contamination	Reduced Heat Transfer	3	Degradation of Seals, Leaks	4	contamination test	2	24	refill and test location