Thermal Energy Storage (TES) for Home Cooling in Salt River Project District

- *Aaron Espinoza (Manufacturing Engineer and CAD Specialist)*
- *Maciej Ziomber (Test Engineer and Financial Manager)*
- *Steven Galloway (Manufacturing Engineer and CAD Specialist)*
- *Janelle Peña (Co-Project Manager and Logistics Manager)*
- *Courtney Hiatt (Co-Project Manager and Website Developer)*

Finalized Specification Sheet

Engineering Requirement		Target	Tolerance	Measured/ Calculated Value	ER met? (yes or no)	Client Acceptable (yes or no)
Provide energy during the 4-8pm peak hours	ER1	11kW	+/- 9 kW	Calculated	Yes	
Charge thermal mass during non-peak hours	ER2	265257 kJ	+/- 238148 kJ	Calculated	Yes	
Reduce costs	ER3	Less than 25.85 ₵/kWh	+/- 5 ₵	Calculated	Yes	
Initial Costs	ER4	Less than $5000	+ $0	Measured	Yes	

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Finalized Specification Sheet

Customer Requirement		CR met? (yes or no)	Client Acceptable (yes or no)
User Friendly (ease of access & easy to assemble and integrate) (min, %)	CR1	Yes	
Reliability (be able to cool down the house)	CR2	Yes	
Safety (safe to keep it in the house)	CR3	No	
Affordability (Return on investment no longer than five years)	CR4	Yes	
Help reach SRP goal to decrease carbon emissions from 2005 levels by 65% by 2035	CR5	Yes	
Provide air conditioning through the thermal mass between 4-8 pm	CR6	Yes	
Charge the thermal mass during non-peak hours	CR7	Yes	
Provide state of the art research/literature review	CR8	Yes	
Determine typical SRP electricity use during peak months	CR9	Yes	
Provide savings	CR10	Yes	
Consider SRP customer rate programs with and without customer-site solar PV generation	CR11	Yes	
Provide economic analysis of designs	CR12	Yes	
Choose one thermal energy storage solution to build and test	CR13	Yes	
Propose a full-scale design	CR14	Yes	
Stay within $5000 budget	CR15	Yes	

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Safety Minute

PPE
- Safety Goggles
- Gloves
- Closed Toed Shoes
- Cover Visible Skin

Background

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Project Description

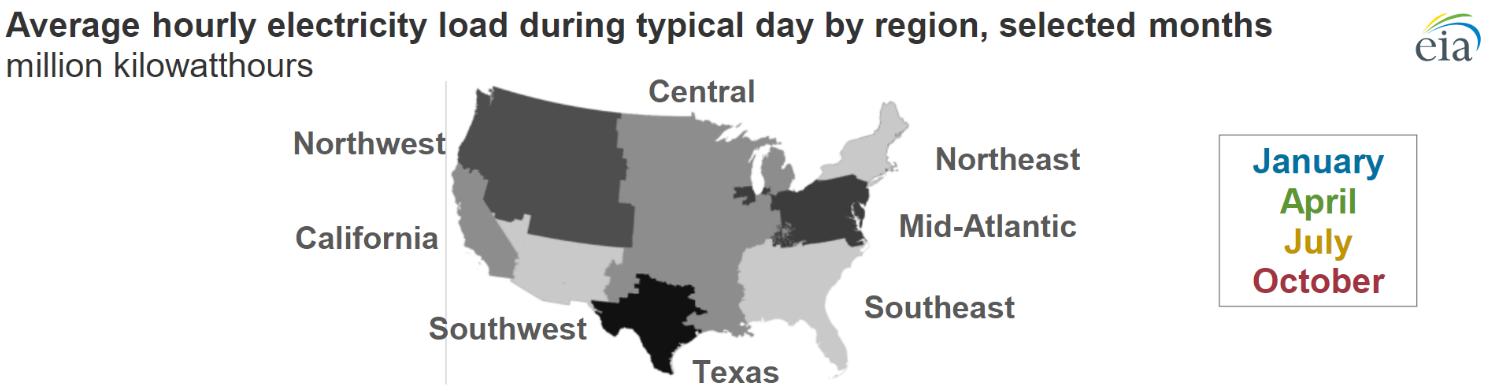
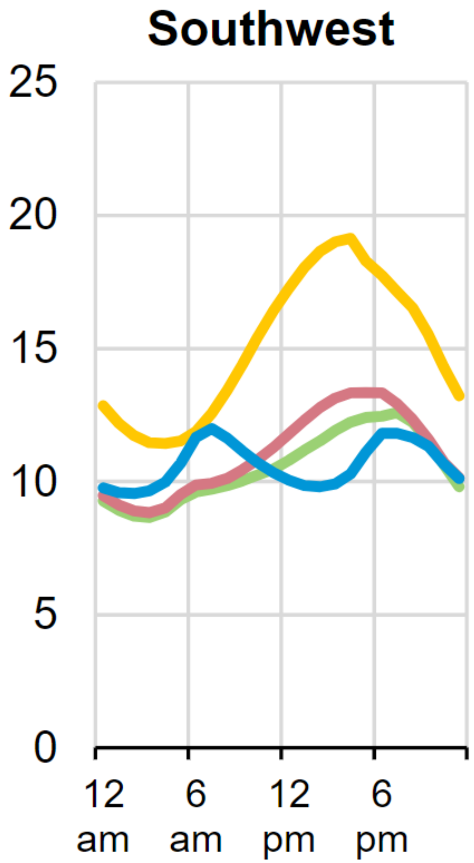


Fig. 1 Average hourly electricity load by region [20]



- The peak of the demand has the highest cost
- The peak demand is also the most difficult and expensive to produce
- Using more energy storage in the minimum demand times and releasing that energy during the peak demand is our goal
- Sponsored by SRP
- Budget of $5,000

[20] Hourly electricity consumption varies throughout the day and across seasons - U.S. Energy Information Administration (EIA), https://www.eia.gov/todayinenergy/detail.php?id=42915 (accessed Feb. 5, 2024).

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Deliverables

- A comprehensive study 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 test at least one thermal energy storage solution.
- A full-scale design proposal is based on test results, including an initial techno-economic analysis.

Success Metrics

Technical Performance: Testing the heat transfer through the design will allow us to verify the system scalability, capacity, and efficiency

Economic Viability: Analyzing financial feasibility using NPV to confirm financial sustainability

Reliability: consistent cooling performance during operating hours

Cost Saving: Comparing pre and post implementation electricity bills

Safety: Compliance with building codes and safety standards

Maintenance:

Requirements

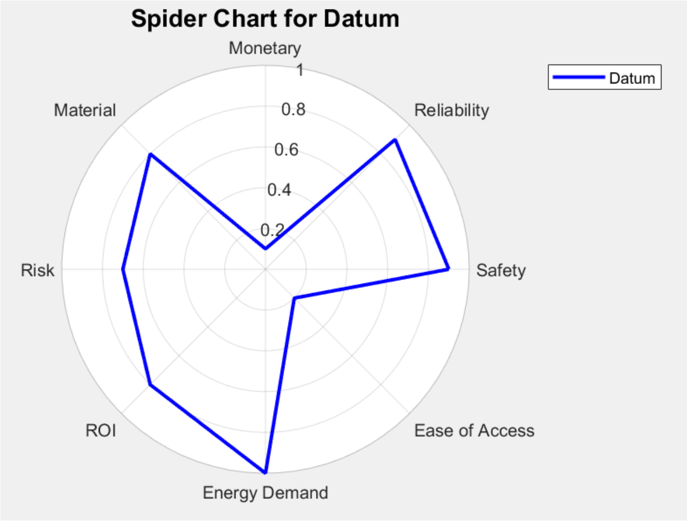
Customer Requirements

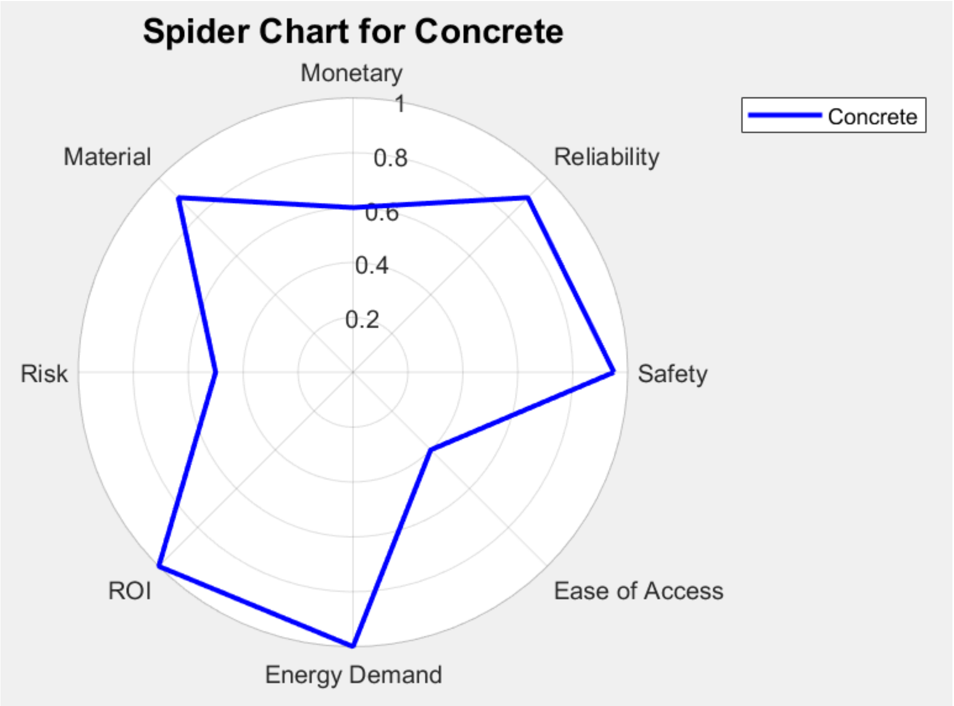
- System must provide a clear return on investment by reducing electricity costs during peak hours
- Easy for customers to use with minimal involvement in daily operations
- Support for SRP’s peak electricity load reduction, aligning with carbon reduction goals.
- Components meeting industry safety standards and requiring minimal repairs
- Compatibility with Existing AC Systems

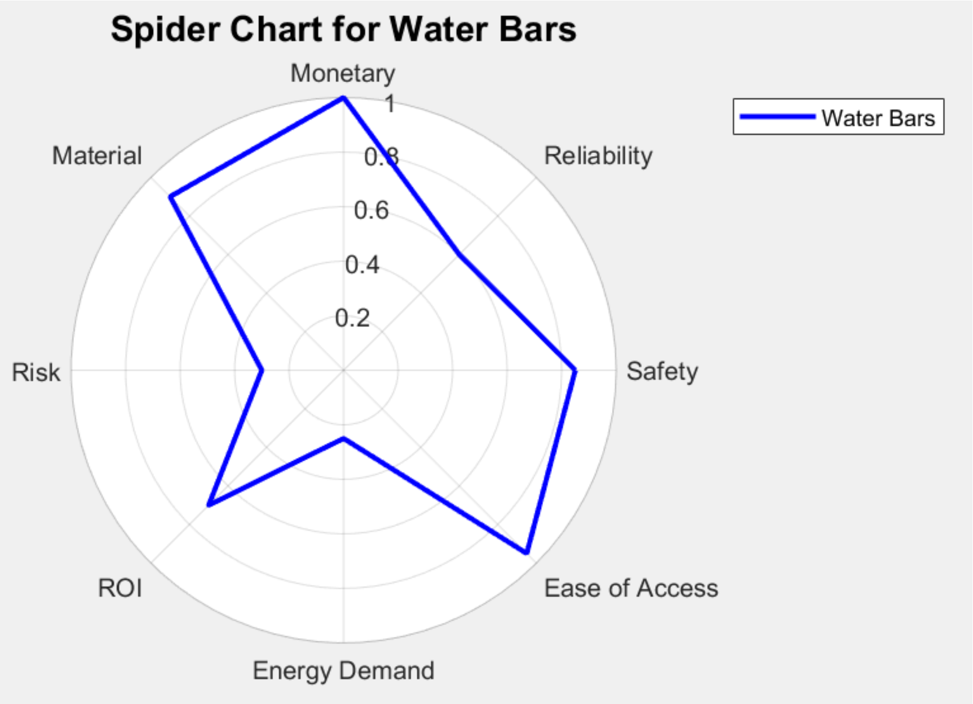
Engineering Requirements

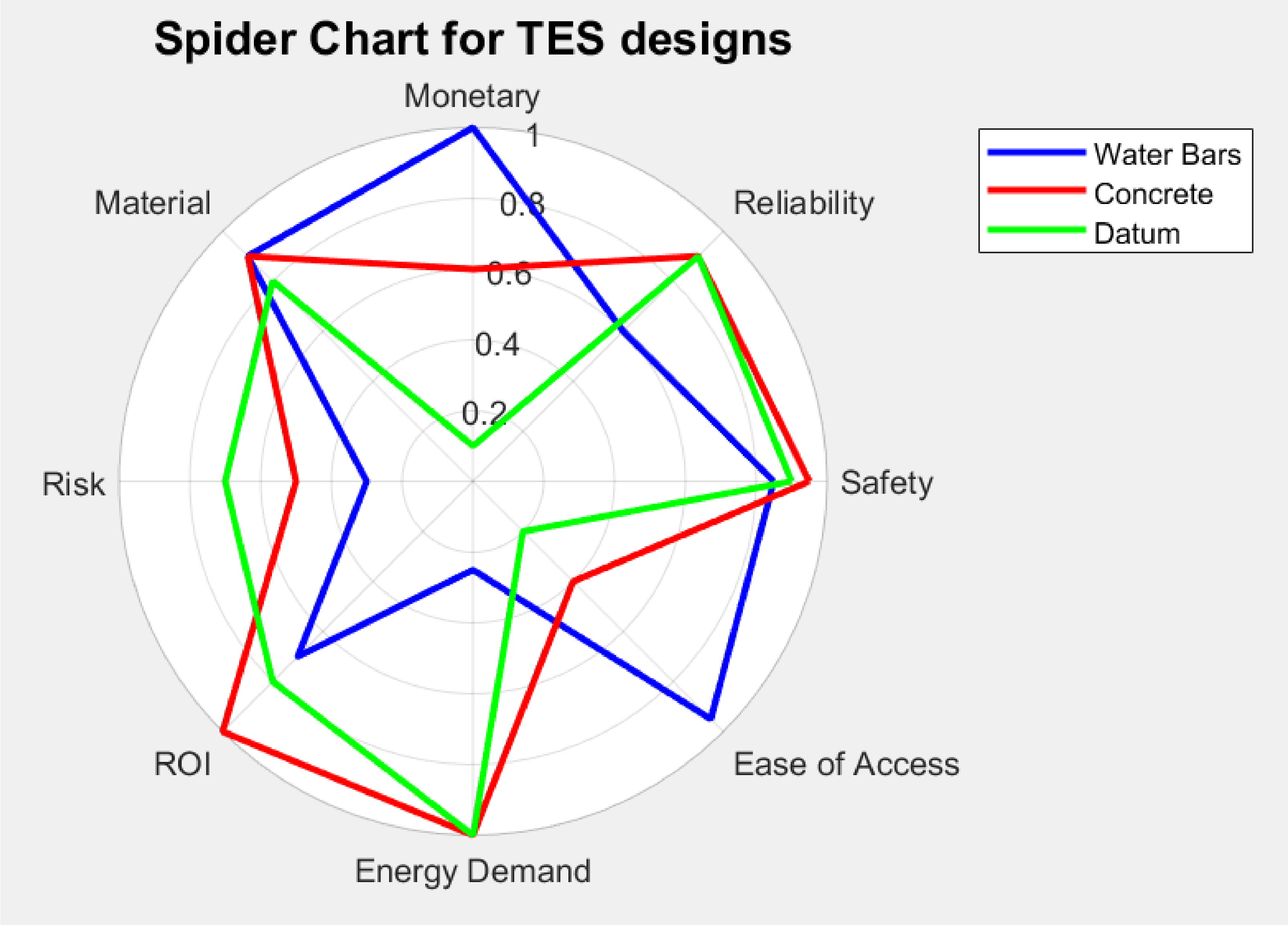
- TES must store enough thermal energy to cover at least 4 hours of AC load reduction during peak hours
- System must deliver a cooling effect equivalent to a standard residential AC unit
- Components must comply with residential safety standards and building codes
- System components and materials must withstand the minimal and maximal operating temperatures

Spider Charts for our two final designs and Datum








Spider Chart for TES designs
Monetary
Reliability
Safety
Ease of Access
Energy Demand
ROI
Risk
Material
1
0.8
0.6
0.4
0.2
Water Bars
Concrete
Datum

SRP Clientel Satisfaction	+	++	++		++
User Friendly	(- +)	-	-		--
Reliability	++	(- +)	+		--
Safety	++	+	+		-
Affordability	(- +)	+	+		+

	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
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

Design Requirements and Engineering Requirements Relation

Experiment/Test/Model	Relevant DR's
Concrete TM heat evacuation (actual) $Q_{Conctrete}$	ER1 (2,3,4), ER2 (2,3), ER4 (1,4); CR4,CR2
Water-bar TM heat evacuation (actual) $Q_{waterbar}$	ER1 (2,3,4), ER2 (2,3), ER4 (1,4); CR4,CR2
Concrete TM forced convective heat (actual) $q_s''{}_{Concrete}$	ER1 (2,3,4), ER2; CR2, CR1, CR3
Water-bar TM forced convective heat (actual) $q_s''{}_{Water-bar}$	ER1 (1,2,3,4), ER2; CR2, CR1, CR3
Total simulation (Actual, Theoretical, Error calculations)	ER1(1), ER2 (2,3,4), ER3 (1,2,3), ER4 (2,3) ; CR2, CR3, CR4

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Design Space Research

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Benchmarking

BAC TSU-M ICE CHILLER

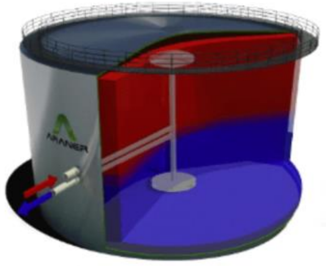
- Unit consists of glycol thermal storage tank with a chiller and heat exchanger to create ice in galvanized steel coils [1].
- Ice is made in off peak hours and melted when needed to be used to cool in HVAC system [7]

Paraffin TES

- Paraffins shown to freeze without supercooling. Chemically stable material good for many cycles of freezing and heating. [2]
- The wax can absorb heat when heated and melts and when cooled in off peak hours it will slowly release the heat.

Chilled Water TES

- Tank of water is chilled and insulated to hold at desired temperature, cold water can be separated from hot due to stratification of layers from temperature/ density difference [3].
- Avoiding phase change in the water allows for simplicity and cost reduction over ice storage



"Paraffin: Thermal Energy Storage Applications" *(book)* [7]

Pros and Cons of storage systems: sensible storage is best if the operating temperature is higher, latent is best at narrow operating ranges

Useful for research and concept generation (**Janelle/everyone**)

"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

Useful for financial analysis (**Maciej**)

"Advances in Thermal Energy Storage Systems" *(Book)* [9]

Comprehensive analysis of thermal energy storage systems using water, molten salts, concrete, aquifers, boreholes, and phase-change materials

Useful for prototyping/manufacturing (**Steven/Aaron**)

"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

Useful for research/data collection (**Janelle**)

"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 (**Maciej and Courtney**)

"Thermal Energy Storage" *(Government Website)* [12]

Provides website links to specific thermal energy storage projects

Useful during concept generation production (**everyone**)

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

Provides useful graphs showing average daily load using solar panels used to heating and cooling

Provides overview of methods to storing thermal masses in buildings

Fluid Mechanics: Fundamentals and Applications (Textbook) [14]

- Provides information on how Fluid Mechanics works
  - Transition of fluids for Transient Heat Specifically
- Provides useful equations on Fluid Mechanics

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Energy Storage (Book) [18]

- Chapter 4 Heat Storage
- Explains the importance of heat storage and heat exchange devices.
- Explains the different ways to analyze heat storage and heat exchange devices.
- Useful Graphs and Figures as well

Air Conditioning with Thermal Energy Storage (Journal Article) [19]

- Talks about almost exactly to what this project is about.
- Materials-PCM's, construction materials, concepts
- ASHRAE Figures
- Similar Prototypes

Hybrid HVAC with Thermal Energy Storage Research and Demonstration (Website) [20]

- Another College team set out to create a Thermal Energy Storage Device to support the grid.
- Compares chemical analysis with a thermal analysis.
- Has a comparable functionality report
- Black Box model that is useful and comparable

Storing Thermal Heat in Materials (Website) [21]

- Has a table with the important Thermal Heat Storage values for different materials that we plan on testing

Fundamentals of Heat and Mass Transfer (Textbook) [15]

- Provides information on Heat Transfer
  - Transient Heat Specifically
- Provides useful equations on Heat Transfer

***Fundamentals of Engineering Thermodynamics* (Textbook) [16]**

- **Provides information on Thermodynamics**
- **Provides useful equations on Thermodynamics**

Storing energy : with special reference to renewable energy sources (Book) [17]

- Chapter 13 specifically provides details about Phase Change Materials
- Chapter 13 for Phase Change Material Equation

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Patent-based trend analysis for advanced thermal energy storage technologies and their applications (Journal Article) [22]

Organized and separated the patent search into items for cold storage alone.

Pointed to the Emerging Topics in Energy Storage.

Emerging topics in energy storage based on a large-scale analysis of academic articles and patents (Journal Article) [23]

Creates a map to the finding CTES patents and orders them using google patents.

References Phase Change Materials Based Cold Thermal chapter 4 and Overview of current development.

Phase change material based cold thermal energy storage: Materials, techniques and applications – A review (Journal Article) [24]

A study in many types of phase change materials

giving visual representation for thermal conductivity and a 6-factor analysis including cost of multiple materials

Hydrates for cold energy storage and transport: A review (Journal Article) [25]

A proposed portable cold energy storage

Heat and cold storage containers, systems and processes (Patent) [26]

CTES devices that are buried underground.

Eutectic salt cold-storage material (Patent) [27]

Explains the application of a organic-inorganic cold storage device

Armstrong World Industries BUILDING PANEL SYSTEM Patent Application (Patent Application) [28]

The patent for Armstrong's PCM CTES panels

Advanced Strength and Applied Elasticity (textbook) [29]

2-dimensional analysis of thick-walled tube under compression and buckling

A First Course in Finite Elements (textbook) [30]

Finite element methods for numerical heat transfer approximations and failure mode analysis

Ansys Learning Resources (website) [31]

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

Air Source Heat Pumps Tax Credit | ENERGY STAR (government website) [29]

Lays out the requirements for a company to apply for ENERGY STAR

How to create a device that is ENERRGY STAR compliant

2018 International Fire Code (IFC) (government website) [30]

The requirements for wiring and spacing.

Also discusses the safety requirements for some products like air conditioners.

2018 International Building Code (IBC) (government website) [31]

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

2018 International Mechanical Code (IMC) (government website) [32]

All the rules for ducting and air handling for a structure

Hints at digging holes and how and why regulations apply to burning things.

2018 International Plumbing Code (IPC) | ICC Digital Codes (government website) [33]

The rules and regulations for geothermal devices

Hints back to the IMC and digging holes and points to the swimming pool and Spa Code

2018 International Swimming Pool and Spa Code (ISPSC) (government website) [34]

The rules about digging shallow holes.

Give the ways to classify the use of a hole.

The Consumer Product Safety Improvement Act (CPSIA) (government website) [35]

A list by category about every type of product

Every category has rules about how to safely create and injury proof a device.

Led to the discussion about what does this device do in an earthquake or tornado.

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

A building material that uses PCM to regulate temperature in a passive method.

Their products can be purchased on a website.

Phase Change Materials | PCMs | Ceiling Systems (website) [36]

Ceiling tiles using the passive method and a different PCM.

They advertise a PCM that is a cable to distribute in a building.

Hybrid HVAC with Thermal Energy Storage Research and Demonstration (government website) [20]

Government research into a working model of CTES for a small commercial or residential structures

Includes investment and material costs.

PCM Products (website) [37]

Products with PCMs into the range of refrigeration or freezer usage

A very wide range of items for heating and cooling applications

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

A PCM built simply for refrigerators and freezers.

The simple design lowers cost and maintenance

Paratherm- Low Temperature Heat Transfer Fluids (website) [38]

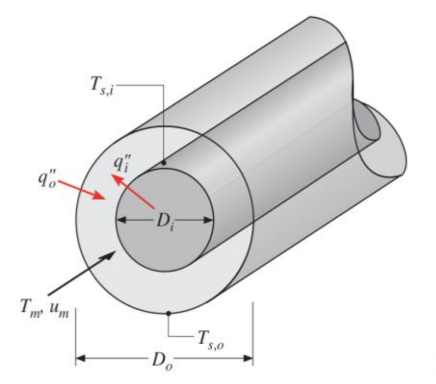
Specialized heat transfer fluids purchasable on the website

These are incredibly low temperature fluids.

SRP Time-of-Use (TOU) Price Plan | SRP (website) [39]

The chart that started the discovery of number of hours of cooling

Lead to the discovery of the cooling value and the baselines of the project



Mathematical Modeling

MATLab Thermal Resistivity and Theoretical Heat Transfer

Re_eg = 3665.2 %Reynolds # for Ethylene Glycol Pr_eg = 18.837 %Prandtl # for Etyhylene Glycol

→ h_F1 = 142.99 %Convective heat transfer coefficient for ethylene glycol

→ Re_water = 29718 %Reynolds # for water

→ Pr_water = 6.9667 %Prandtl # for water

→ h_F2 = 3823.7 %Convective heat transfer coefficient for water

→ RConv1 = 1.1059 % Convective resistance for ethylene glycol (inside copper)

→ RCond1 = 0.0029983 % Conductive resistance through copper

→ RConv2 = 0.0041356 % Convective resistance for water (the region between copper and PEX)

→ R_Cond2 = 0.040997 % Conductive resistance through PEX

→ **Total Thermal Resistance: 1.1541 K/W**
Heat Transfer Rate: 69.3194 W

Mathematical Modeling - NPV

$$NPV = \sum_{i=1}^{n} \frac{Cash\ Flow_i}{(1+r)^i} - Initial\ Investment$$

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		

Initial investment and **Cash Flow** Calculations were precisely performed in Excel to obtain those results

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

ROI Calaculations	
H2O Bars	Concrete
13%	24%

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

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Mathematical Modeling- ASHRAE Cooling Load [44]

Max Q Values (Btu)	Max Q Values (kJ)	Max Q Values (kWh)
477,000	503,000	140
Min Q Values (Btu)	Min Q Values (kJ)	Min Q Values (kWh)
54,100	57,100	16
Max Qdot Values (Btu/h)	Max Qdot Values (kJ/h)	Max Qdot Values (kW)
68,200	72,000	20
Min Qdot Values (Btu/h)	Min Q Values (kJ/h)	Min Qdot Values (kW)
7,730	8,160	2

Equation 1

$Q_{windows}=U_{windows}*A_{windows}*CLTD_{corrected}$

Equation 2

$Q_{walls}=U_{walls}*A_{walls}*CLTD_{corrected}$

Equation 3

$Q_{total}=Q_{roof}+Q_{windows}+Q_{walls}$

Mathematical Modeling - Materials

```
function MaterialProperties(HeatofFusion, SpecificHeat, DensityMatrix, MinEnergyRequirement, MaxEnergyRequirement, LowestTemp)
```

Formula for Sensible and Latent Heat

$$Q = mCp\Delta T + mF$$

Rearranged to Solve for Mass

$$m=Q/(Cp\Delta T+F)$$

Convert Mass to Volume

$$V = m/d$$

Q = Thermal Energy Stored

m = Mass

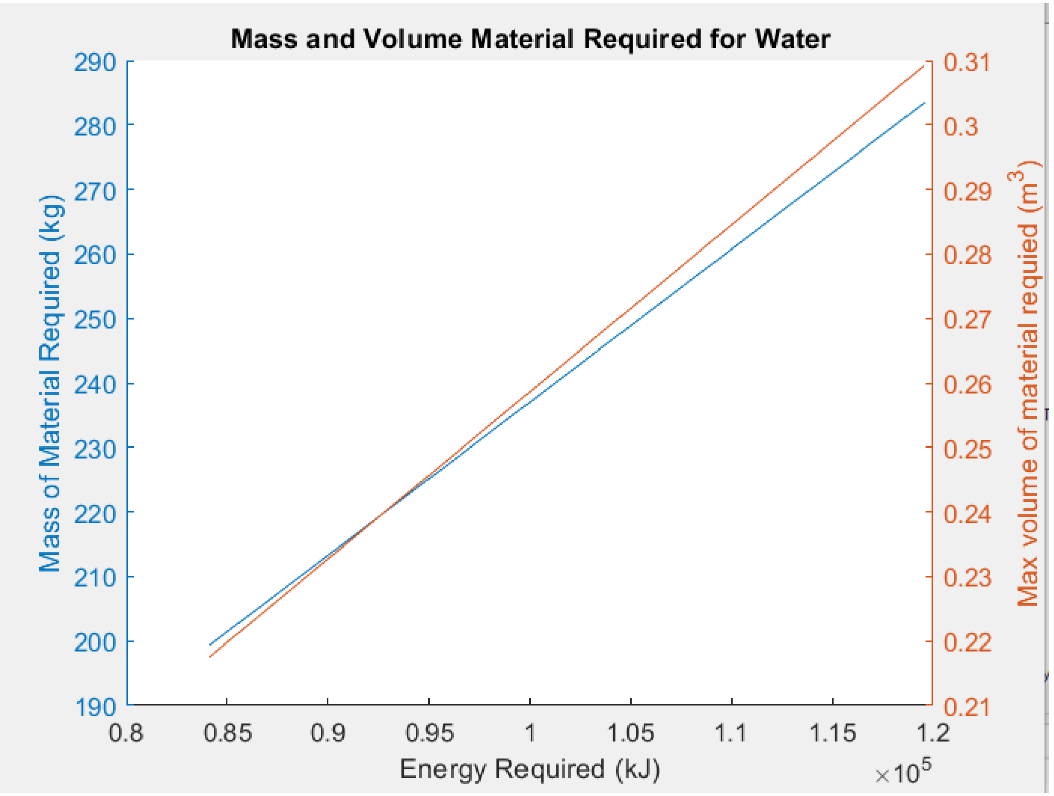
Cp = Specific Heat

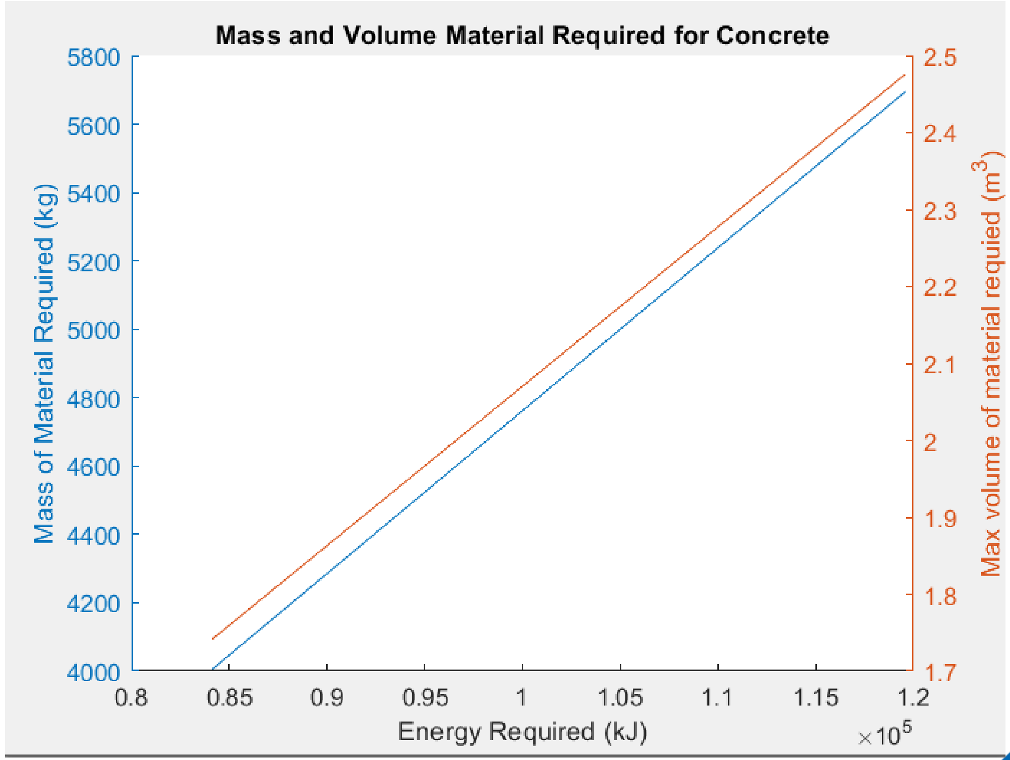
T = Temperature

F = Heat of Fusion (constant)

D = Density

MATLAB Material Analysis





External Flow Convective Heat Transfer - MATLAB

Code was developed to analyze the air flow around the concrete device using MATLAB

$$\overline{Nu_D} \equiv C\, Re_D^m\, Pr^n \left(\frac{Pr}{Pr_s}\right)^{\frac{1}{4}}$$

$$\bar{h} = \frac{q}{A(T_s - T_\infty)} = \overline{Nu_D}\,\frac{k}{D}$$

The shape of the device varies, and the method of analytical solution varies in the code.

Geometry	Re_D	C	m
Square			
(diamond, V →, D)	6000-60000	0.304	0.59
(square, V →, D)	5000-60000	0.158	0.66
Hexagon			
(V →, D)	5200-20400	0.164	0.638
	20400-10500	0.039	0.78
(V →, D)	4500-90700	0.150	0.638
Thin plate perpendicular to flow			
(V →, D) Front	10000-50000	0.667	0.500
Back	7000-80000	0.191	0.667

Bank of Tubes Convective Heat Transfer - MATLAB

Code was developed to analyze the air flow through the water bars device using MATLAB

$$\overline{Nu_D} \equiv C_1 C_2 \, Re_{D,max}^{m} \, Pr^{0.36} \left(\frac{Pr}{Pr_s}\right)^{\frac{1}{4}}$$

$$\begin{bmatrix} N_L \geq 20 \\ 0.7 \leq Pr \leq 500 \\ 10 \leq Re_{D,max} \leq 2 * 10^6 \end{bmatrix}$$

$$V_{max} = \frac{S_T}{S_T - D} V$$

$$q' = N(\bar{h} \pi D \Delta T_{lm})$$

$$\Delta p = N_L \chi \left(\frac{\rho V_{max}^2}{2}\right) f$$

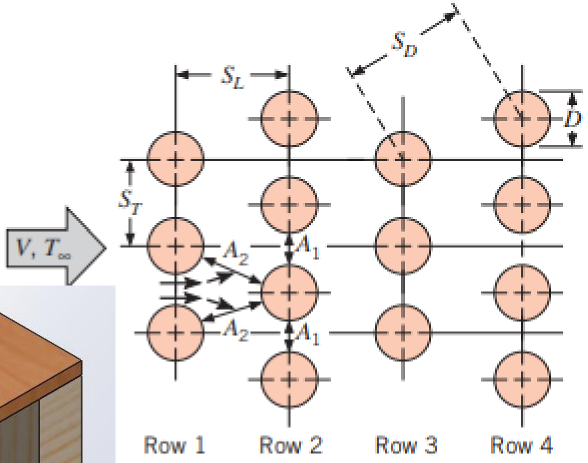
TABLE 7.5 Constants of Equation 7.58 for the tube bank in cross flow [17]

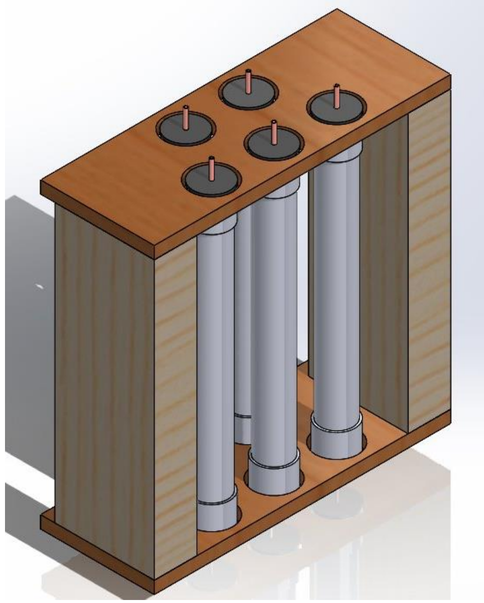
Configuration	$Re_{D,max}$	C_1	m
Aligned	10–10^2	0.80	0.40
Staggered	10–10^2	0.90	0.40
Aligned	10^2–10^3	Approximate as a single (isolated) cylinder	
Staggered	10^2–10^3		
Aligned ($S_T/S_L > 0.7$)[a]	10^3–2×10^5	0.27	0.63
Staggered ($S_T/S_L < 2$)	10^3–2×10^5	$0.35(S_T/S_L)^{1/5}$	0.60
Staggered ($S_T/S_L > 2$)	10^3–2×10^5	0.40	0.60
Aligned	2×10^5–2×10^6	0.021	0.84
Staggered	2×10^5–2×10^6	0.022	0.84

[a]For $S_T/S_L < 0.7$, heat transfer is inefficient and aligned tubes should not be used.

TABLE 7.6 Correction factor C_2 of Equation 7.59 for $N_L < 20$ ($Re_{D,max} \gtrsim 10^3$) [17]

N_L	1	2	3	4	5	7	10	13	16
Aligned	0.70	0.80	0.86	0.90	0.92	0.95	0.97	0.98	0.99
Staggered	0.64	0.76	0.84	0.89	0.92	0.95	0.97	0.98	0.99





Concept Generation and Selection

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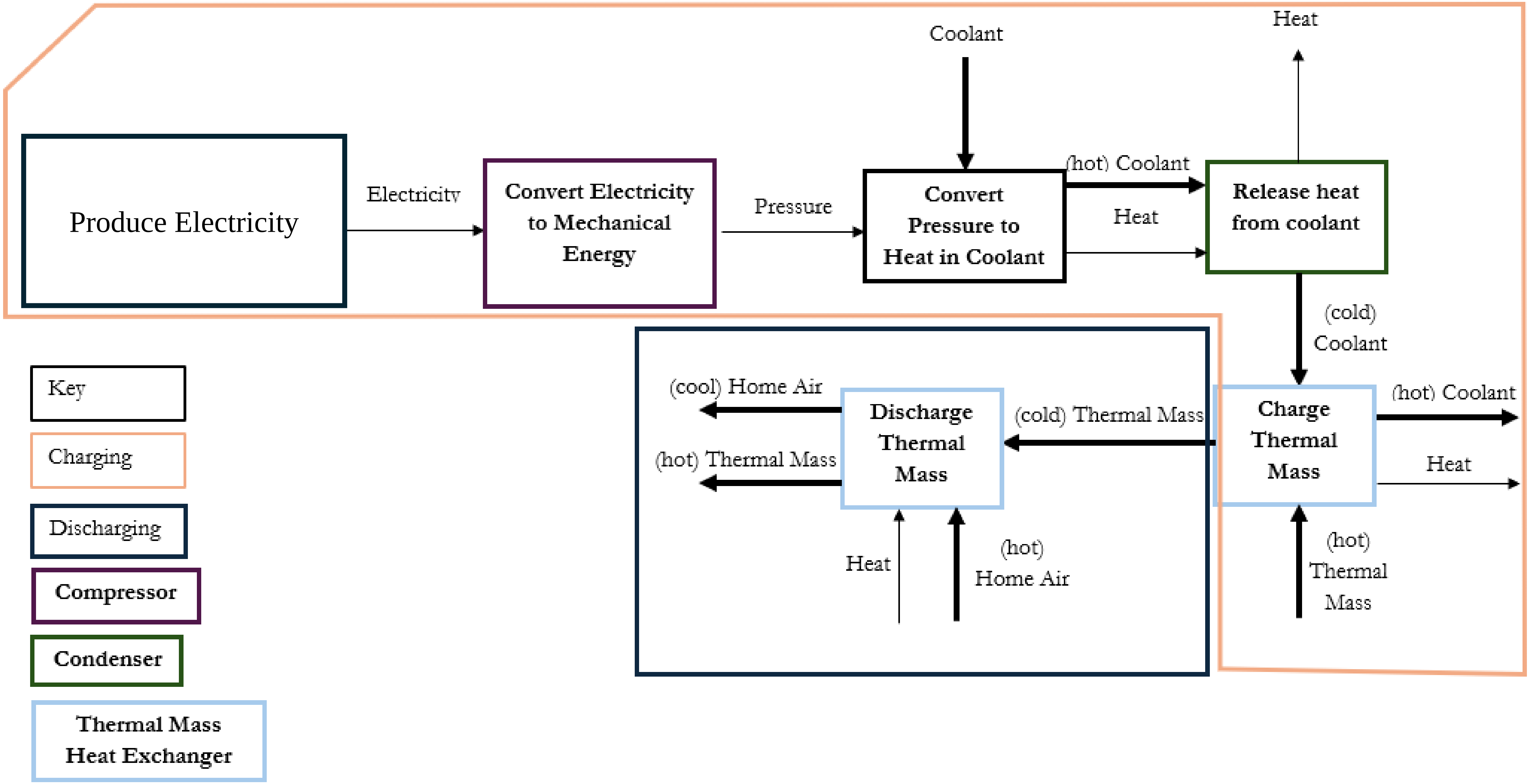
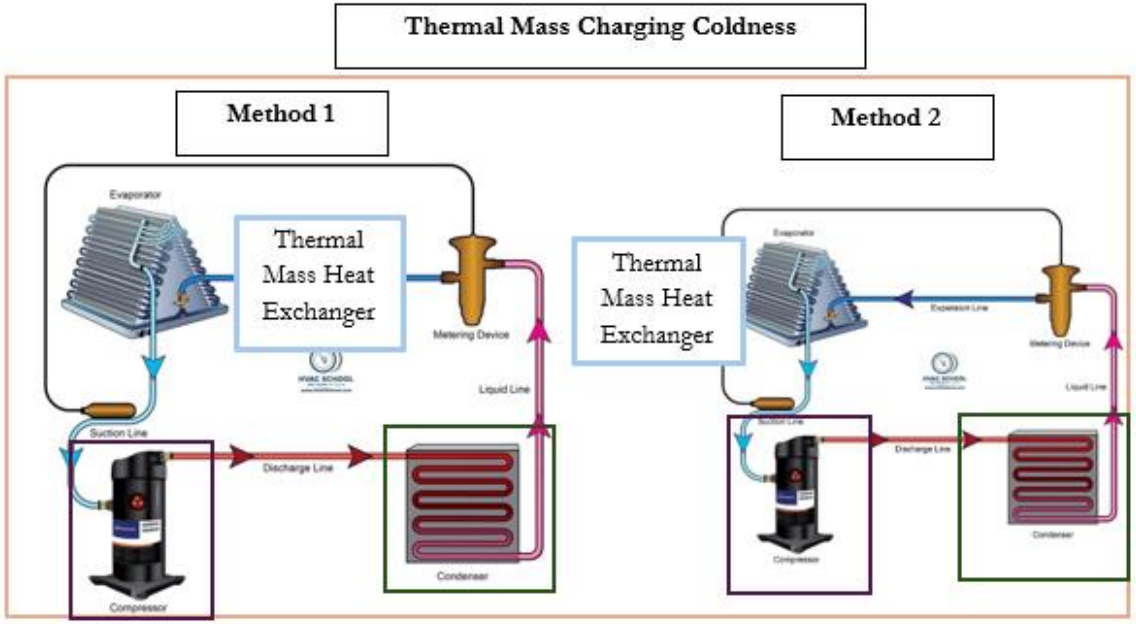
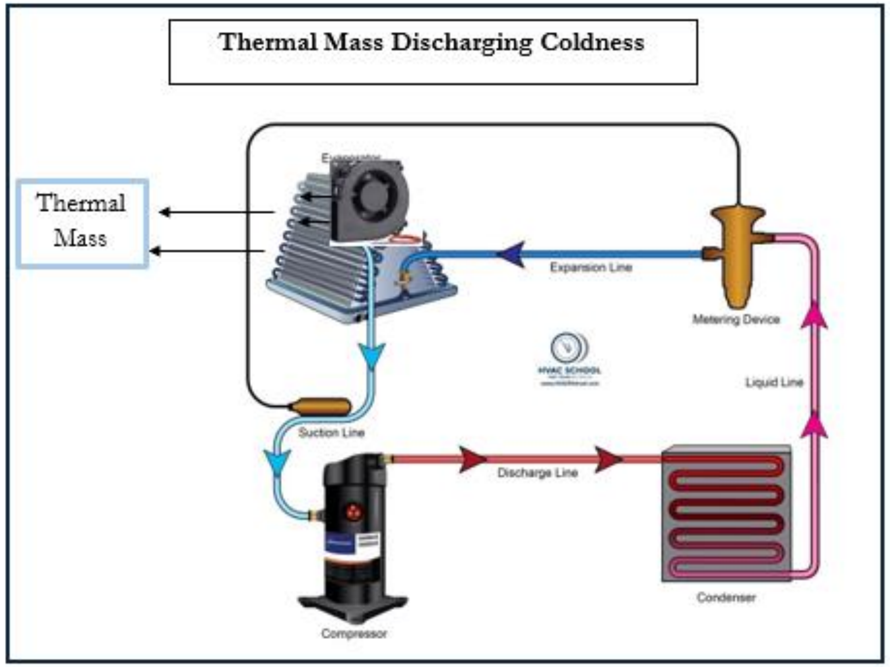
Black Box Model Diagram



Functional Decomposition





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Concept Generation

Thermal Materials

	Density kg/m³	Specific Heat J/g°C	Thermal Conductivity W/m K	Melting Point °C	Cost $/kg
Concrete	2000	1000	1.95		0.13
Paraffin (C_{16})	773	?	?	20	155,200
Tetradecane ($C_{14}H_{30}$)	763	?	0.14	6	380
Ethylene Glycol	1110	2.43	0.256	-13	2.99
Exotic (Eutectic)	1000-1280	4.19-3.15	0.2-0.6	0-(-74)	17.92
Water	1000	4200	0.598	0	0.01
Concrete water mix	?	?	?	?	?
Terracotta	780	1800	0.8		1.98
Air Crete	800		1.3 -0.17		1.19
Brick	1920	835	0.72		0.45
Stone	2300	1000	1.8		1.1
Timber	510	1380	0.12		0.98
Plywood	545	1215	0.12		1.01

Application		
Mode	Cost	Saving
New Built Structure	low	high
Pre-existing Structure	high	high
Off-the-shelf	high	low
Pre-existing product modification	low	low

Concept Generation Ideas

Datum

TSU-M ICE CHILLER® Thermal Storage Unit

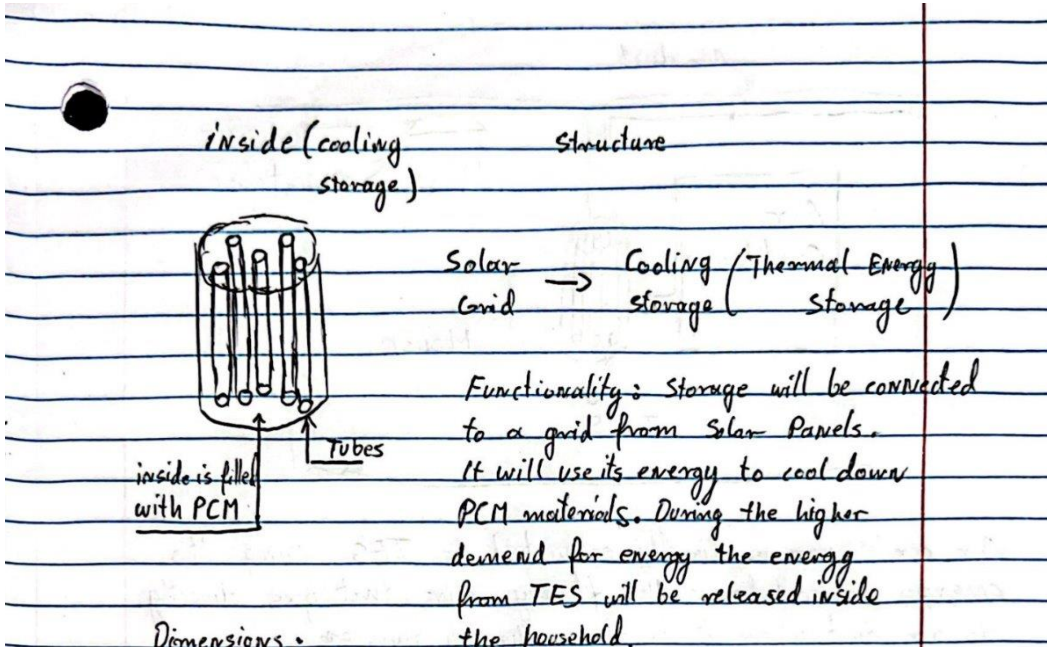
The TSU-M ICE CHILLER® Thermal Storage Unit reduces energy costs by storing cooling while shifting energy usage to off-peak hours. The internal melt process has an easy-to-design closed loop making it ideal for a variety of HVAC applications. Some examples include office buildings, district cooling for urban settings, schools, hospitals, sports arenas, convention centers, and more.

- **Thermal Capacity**: 90 - 125,000 ton hours
- HVAC Applications

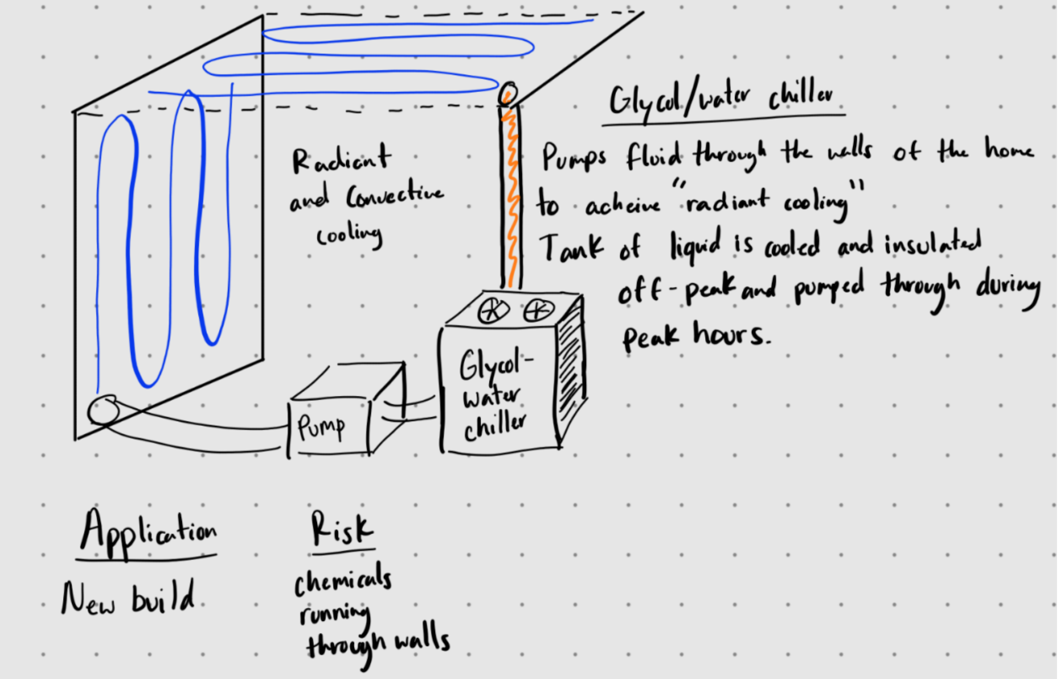
Scaling Down

Concept Generation Ideas

Tubes running through TES

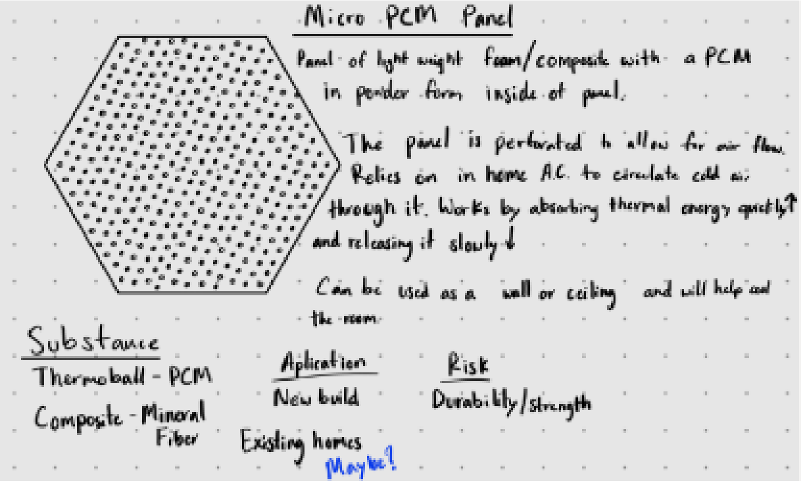


Radiant Cooling

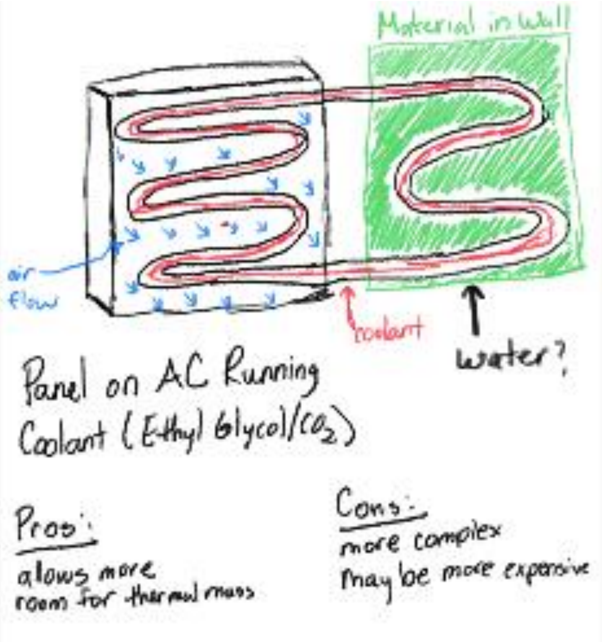


Concept Generation Ideas

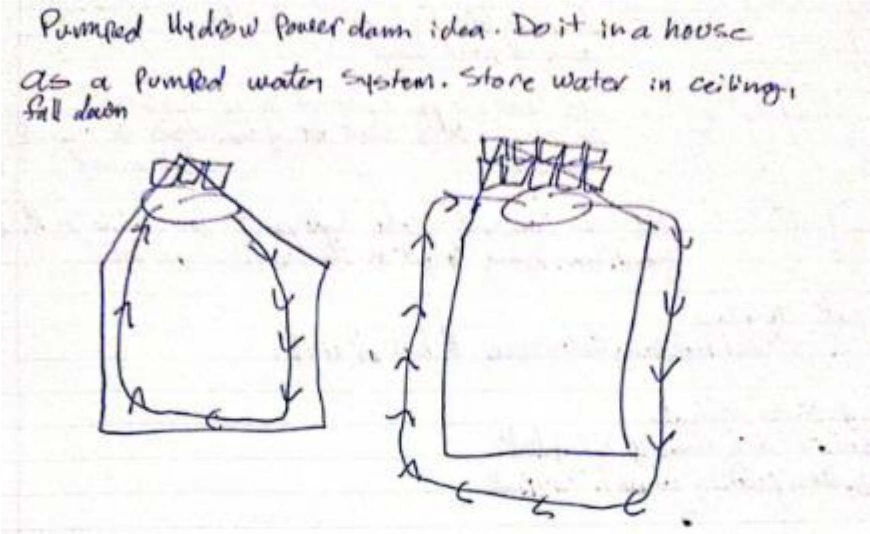
PCM Panel



Coolant Pipes

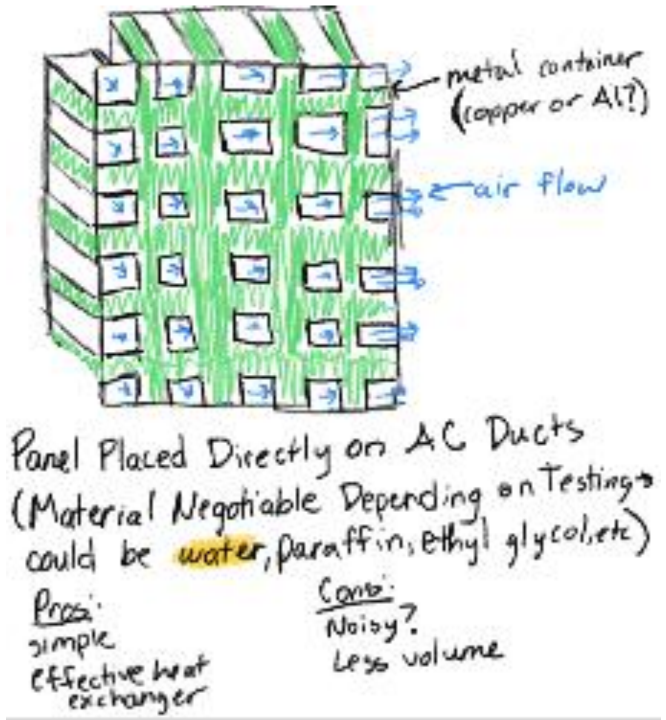


Pumping Fluid

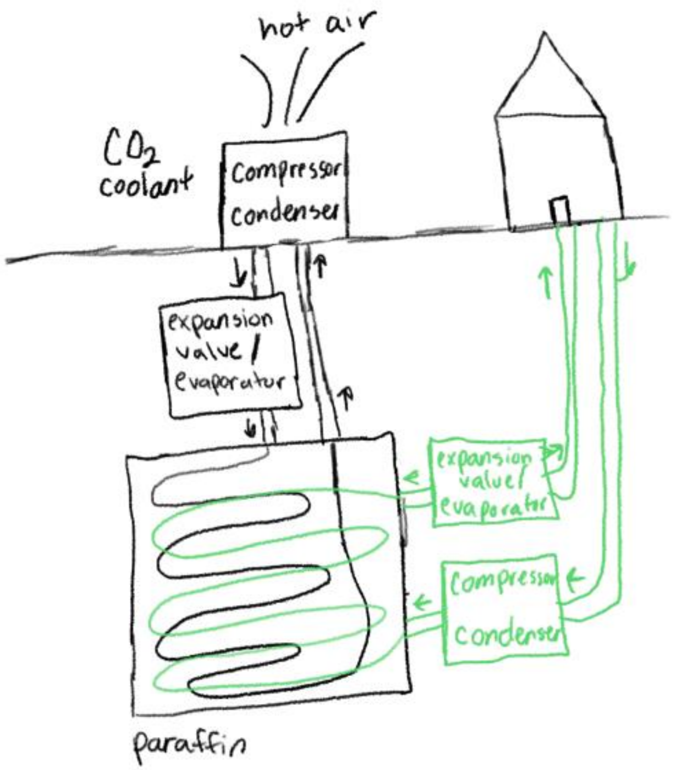


Concept Generation Ideas

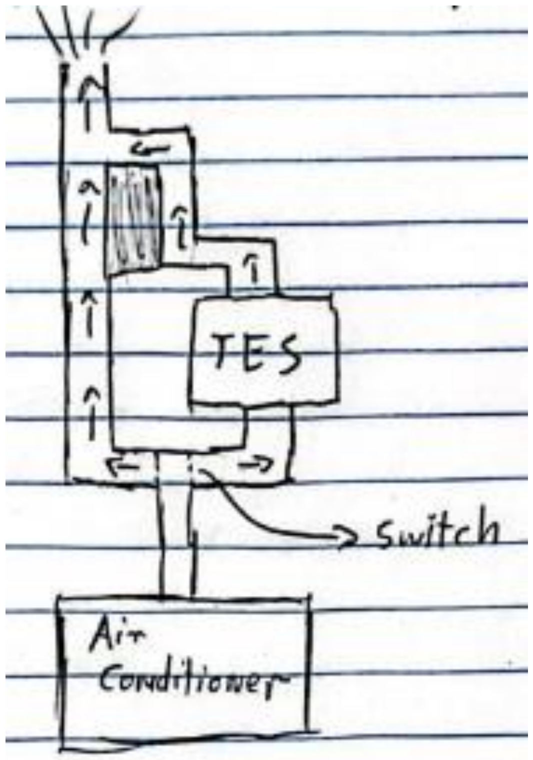
AC ducts



Underground



Switch



Selection Criteria

- Cost: Pre-build
- Comfort level
- Efficiency
- Internal rate of return (IRR)
- Net present value (NVP)
- Ease of maintenance
- Power saving/grid assistance
- Cost: pre-exsisting structure
- Safety

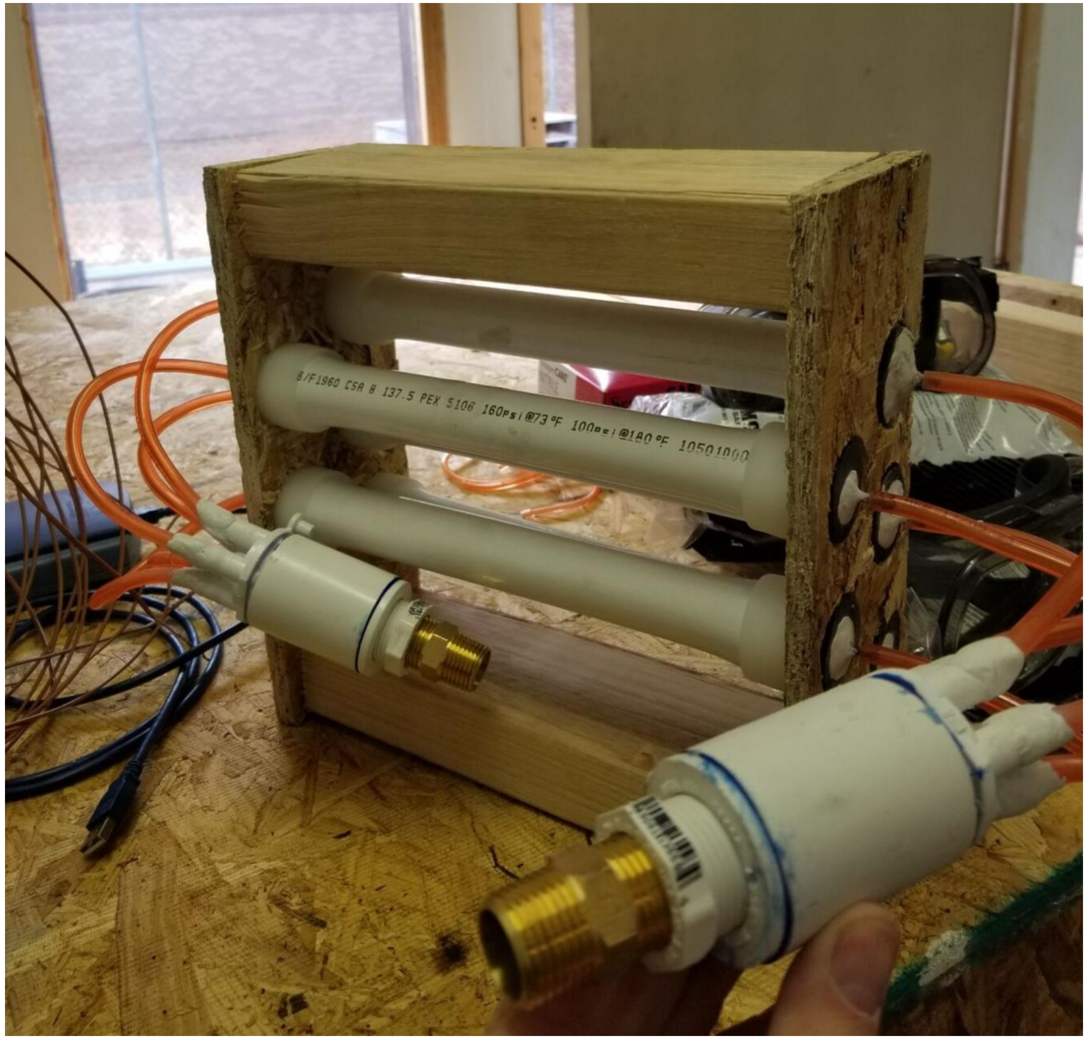
Design	Scores
Datum: Baltimore Air Coil- TSU-M Ice Chiller Thermal Storage Unit	25
Micro PCM Panel	29
Radiant Cooling	22
In-House Thermal Storage	26
Pipe System for AC/Thermal Conditioning in Pipe	19
CO2 Coolant: Underground Refiridgeration System	23
Underground Convection System	25
Water Cycle	23
Puffy Cement	27

CRITERIA DESCRIPTION	Saves Power because it doesn't use prime time power	How Hot/Cold will it make the house of the customer	How efficient is it	Does it need monthly/yearly/Every 5 year maintance. Refills, Parts, Repairs, Ease of Access,	How well does it ease the load off of the grid during peak time, use power during low	Is it realizstic for the average home buyer, new build vs pre-existing structure,	Does it explode, catch fire, freeze someones hand if touched	
	Power Saving	Comfort Level	Efficiency	Level of Maintenance	Grid Assistance	Cost	Safety	WEIGHTED SCORE
WEIGHT	7	4	5	1	6	3	2	28
	24%	14%	19%	4%	22%	10%	7%	100%

Max Score	Max2	Max 3	Max 4	Max 5
29	27	26	25	23
Micro PCM Panel	Puffy Cement	In-House Thermal Storage	Underground Convection System	Water Cycle & CO2 Coolant: Underground Convection System

Concept Evaluation Decision Matrix

Concept Selection- Water Bars



Essentially ice suspended in the air

- There is not a better material that exist that is a better functioning TES for cold storage
- PEX-A is designed to last and survive the risks of using ice and water.

Concept Selection- Concrete Block

Building a house with a wall for cold TES

- Can double a building material
- Can double as art/ décor
- Would require a construction business model that is supported by energy saving incentives.

Project Management

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Schedule

Gantt Chart

SRP Thermal Mass

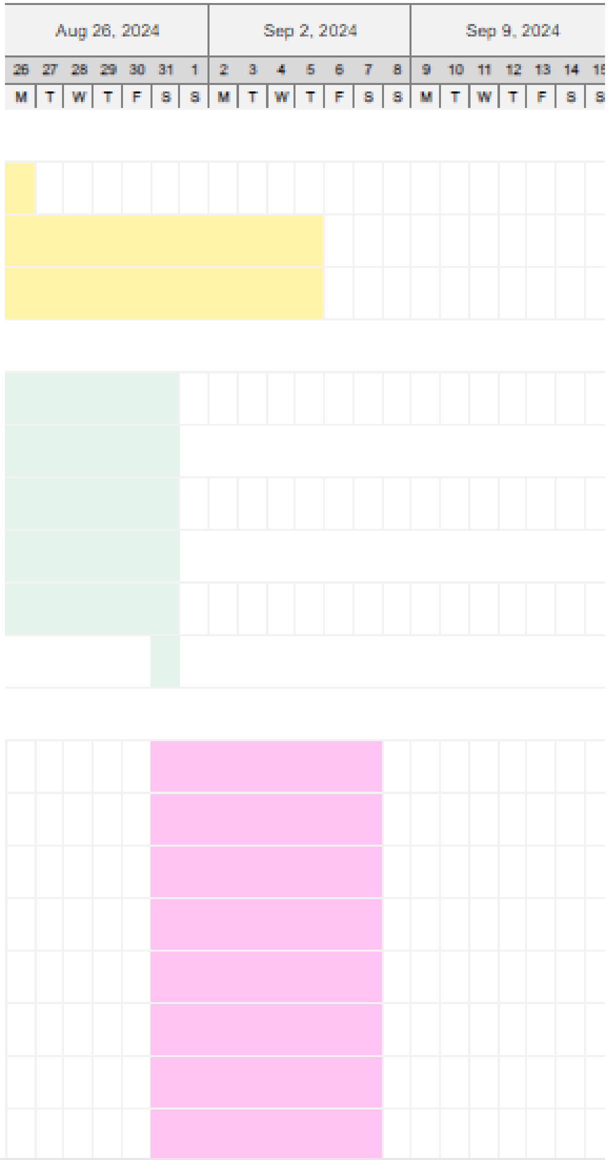
SRP | Project lead

Project start: **Thu, 8/1/2024**

Display week: **5**

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

	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 comp	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/solut	Maciej	100%	8/31/24	9/7/24
	Show image of top-level CAD/engineerin	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 a	Maciej/Steven	100%	8/31/24	9/7/24
	Cooling Load/Mass of Materials Needed	Courtney	100%	8/31/24	9/7/24
	Summarize conditions that led to your 'lo	Courtney	100%	8/31/24	9/7/24
	NPV	Maciej	100%	8/31/24	9/7/24



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NAU

Budget

ME486C_SRP_Team_Budget			
Total	Income	Expenses	Total
Initial Budget	$ 5,000.00	$ 1,754.57	$ 3,245.43
Donated	$ 500.00	$ 251.00	$ 249.00
Budget	$ 5,500.00	$ 2,005.57	$ 3,494.43

*Budget might be a subject to some additional expenses towards the testing procedures

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NAU

Bill of Materials

Assembly Name	Thermal Energy Storage	Total Parts	136
Assembly Number	1	Parts Acquired	136
Date of Approval	N/A	Parts Donated	15
		Parts Purchased	136
Total Cost	$ 1,754.57	Part Status (Purchased)	100%
		Parts Status (On-Hand)	100%
Item no.	Catalog #	Vendor Name	Description

Size	Qty	Price	Total Cost	#On-Hand?	#Purchased?

https://nau0.sharepoint.com/:x:/r/sites/ME476C557/Shared%20Documents/General/Fall%20%2724_Semester2/ME476C_Bill_Of_Materials.xlsx?d=w4ae5d006d8a94ad6bc5e627131f3a406&csf=1&web=1&e=MuU2si

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Design Validation/Prototyping

Failure Modes and Effects Analysis

Copper Pipe
- Burst
- Loss of fluid
- Exposure to high pressure

Water
- Contamination
- Rapid decay of Thermal Efficiency

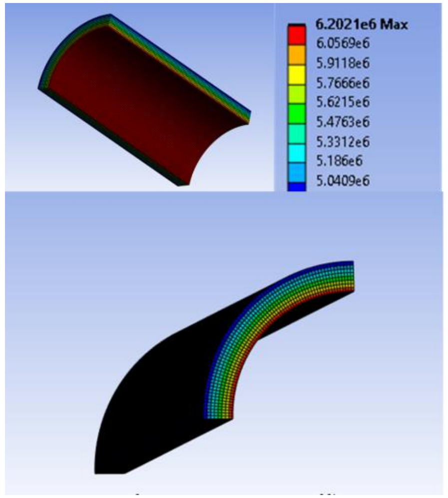
Concrete
- Erosion
- Structural Integrity Compromised and Moisture Damage

Ethylene/Propylene Glycol
- Contamination
- Reduced Heat Transfer

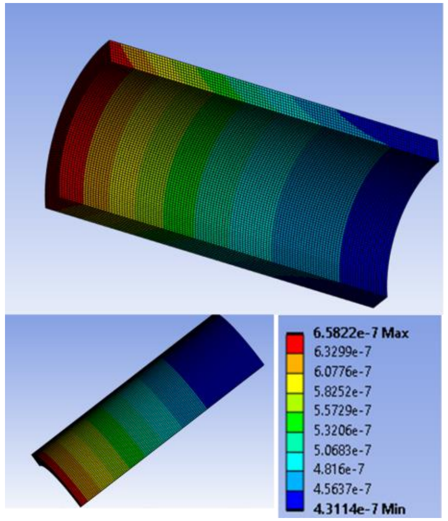
Buckling Failure of Internal Pipe

FMEA

Failure modes are listed and imagined for all possible failures. Here, the mode of highest risk is ice expansion in the casing. Pex A is designed to expand at the same rate as the water. The freezing effect will risk the copper tube being crushed.



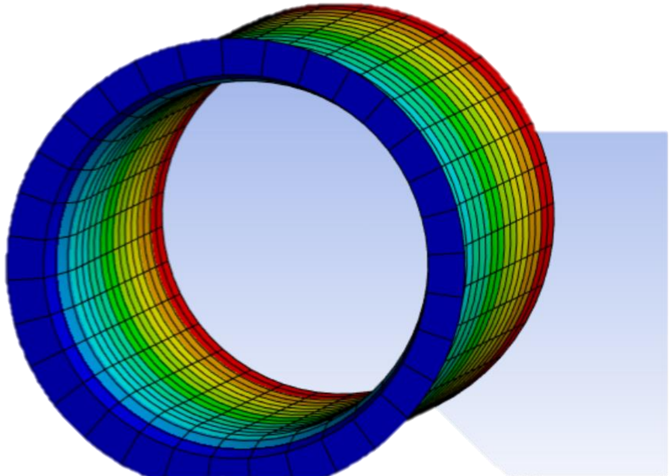
Von Mises Stress (Pa)



$$\sigma_t = \frac{p_i r_i^2 - p_o r_o^2 - r_i^2 r_o^2 (p_o - p_i)/r^2}{r_o^2 - r_i^2}$$

$$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2 + r_i^2 r_o^2 (p_o - p_i)/r^2}{r_o^2 - r_i^2}$$

Deformation (m)



Initial Prototyping

Do we want to proceed with PCM?
Will it help us cool down the houses?

Experimental Setup:

- ABS pipe (2 in diameter, 2 ft long) capped with JB weld and hose clamps
- 3 Copper tubes (0.5 in diameter, 2 ft long)
- Tee fittings on ends with barbed fitting for tubing from a hydraulic bench
- Thermocouples on both ends, spaced by nipples and fittings

Mixture:

$$Cal_2 * 6H_2O + MgCl_2 * 6H_2O$$

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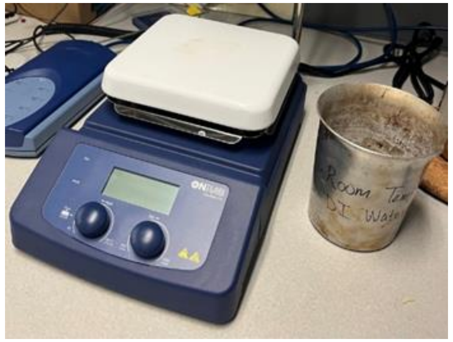
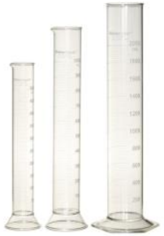
Experimental Design & Method

Data Acquisition:

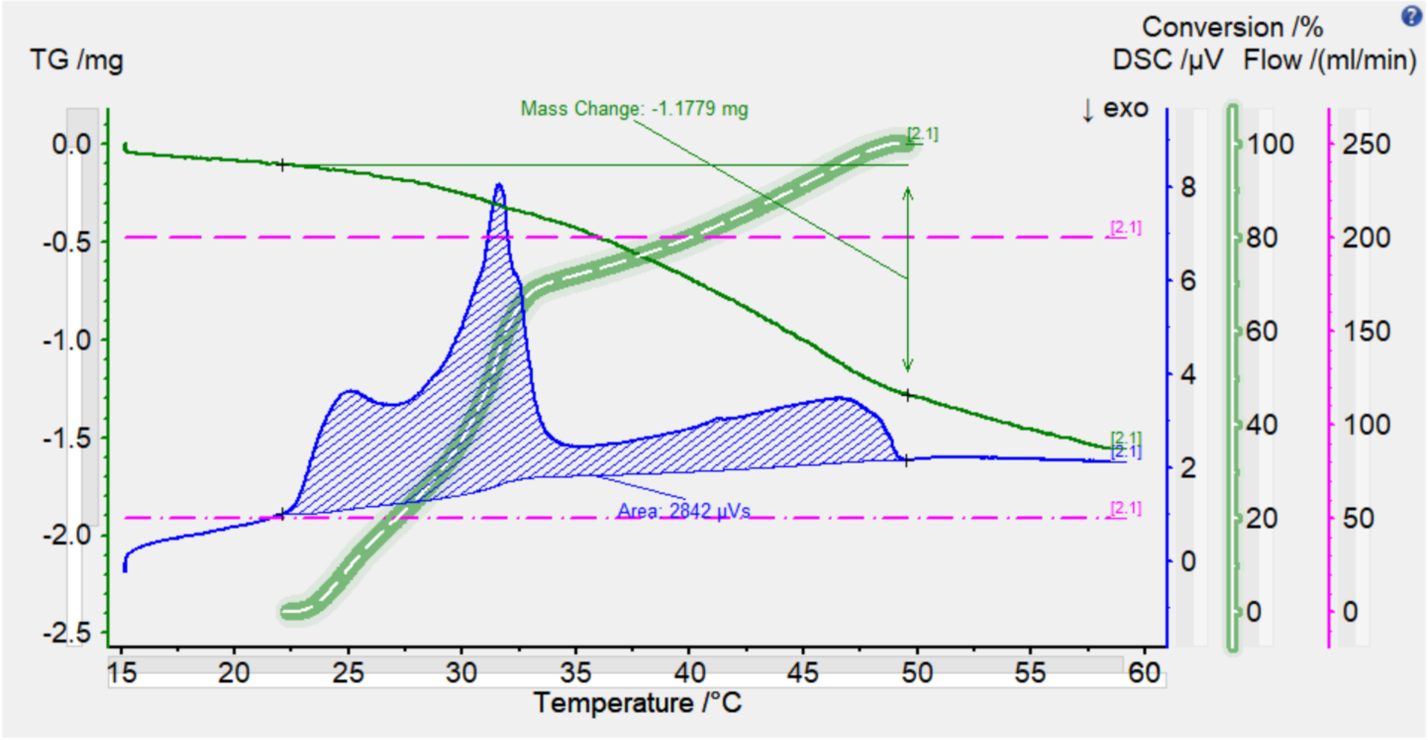
- Pico Data Logger
- K-Type Threaded Thermocouples
- Bucket-Timer Test
- Hydraulic Bench
- Graduated Cylinder





USB TC-08 Thermocouple Data Logger general specifications	
Number of channels (single unit)	8
Maximum number of channels (using up to 20 TC-08s)	160
Conversion time	100 ms per thermocouple channel + 100 ms for cold junction compensation (CJC can be disabled if all channels used as voltage inputs)
Temperature accuracy	Sum of ±0.2% of reading and ±0.5 °C
Voltage accuracy	Sum of ±0.2% of reading and ±10 μV
Overvoltage protection	±30 V
Maximum common-mode voltage	±7.5 V
Input impedance	2 MΩ
Input range (voltage)	±70 mV
Resolution	20 bits
Noise-free resolution	16.25 bits
Thermocouple types supported	B, E, J, K, N, R, S, T
Input connectors	Miniature thermocouple

Data & Results

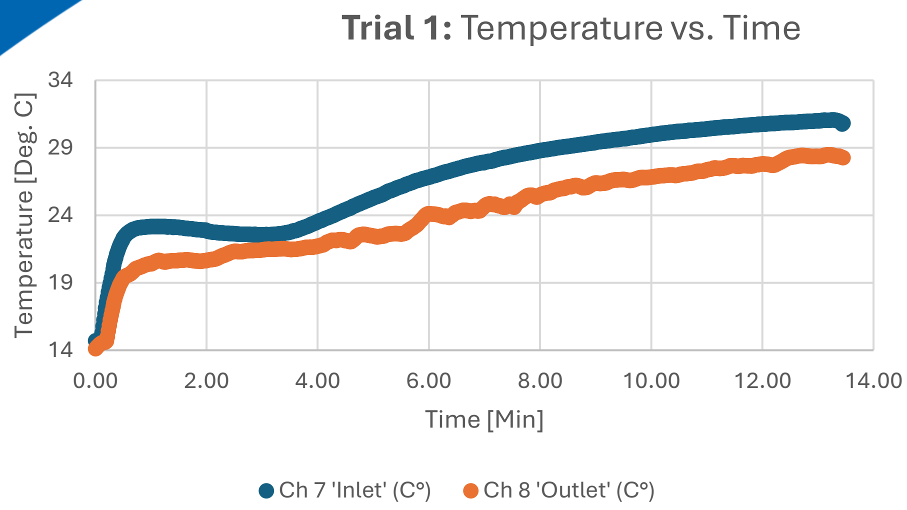


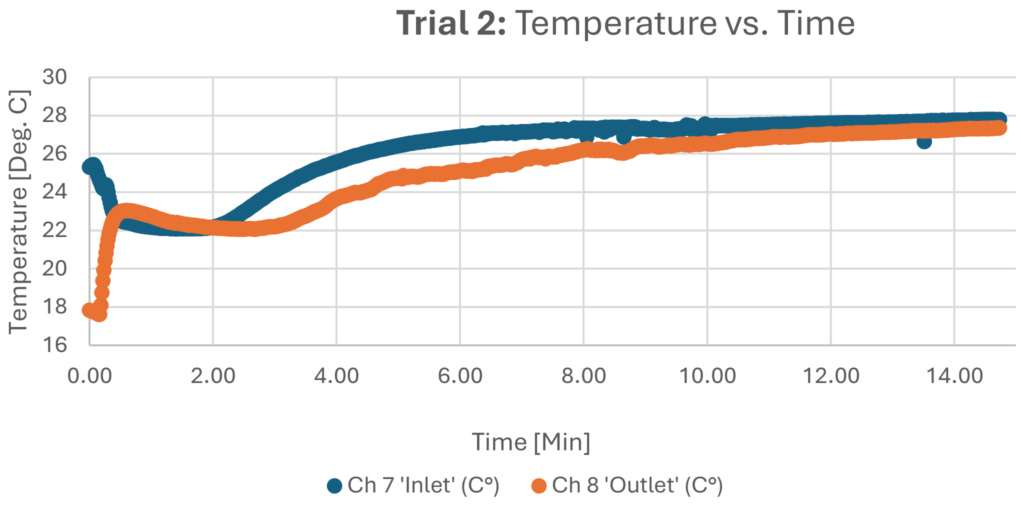
Q = 2842 uVs * 0.0012656 J/uVs = 3.57 J

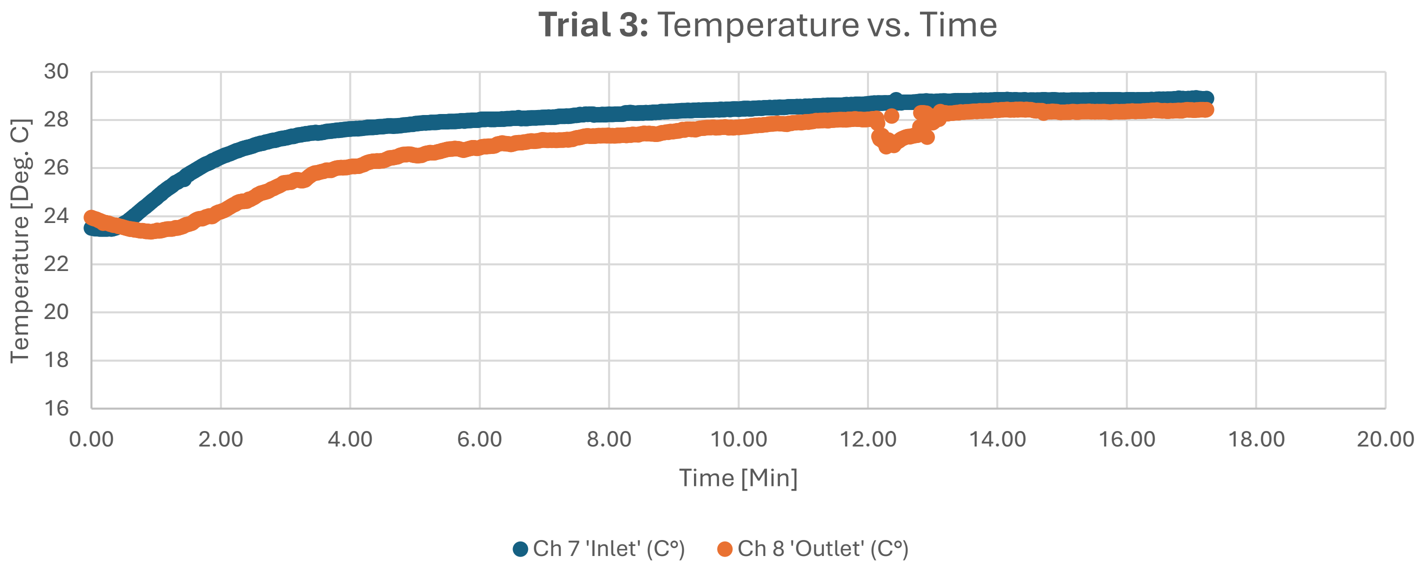
Qmelt = 3.57 J / .0229 g = 156 J/g (error due to mass loss) - Latent heat

Data & Results

Temperature vs. Time Plots:



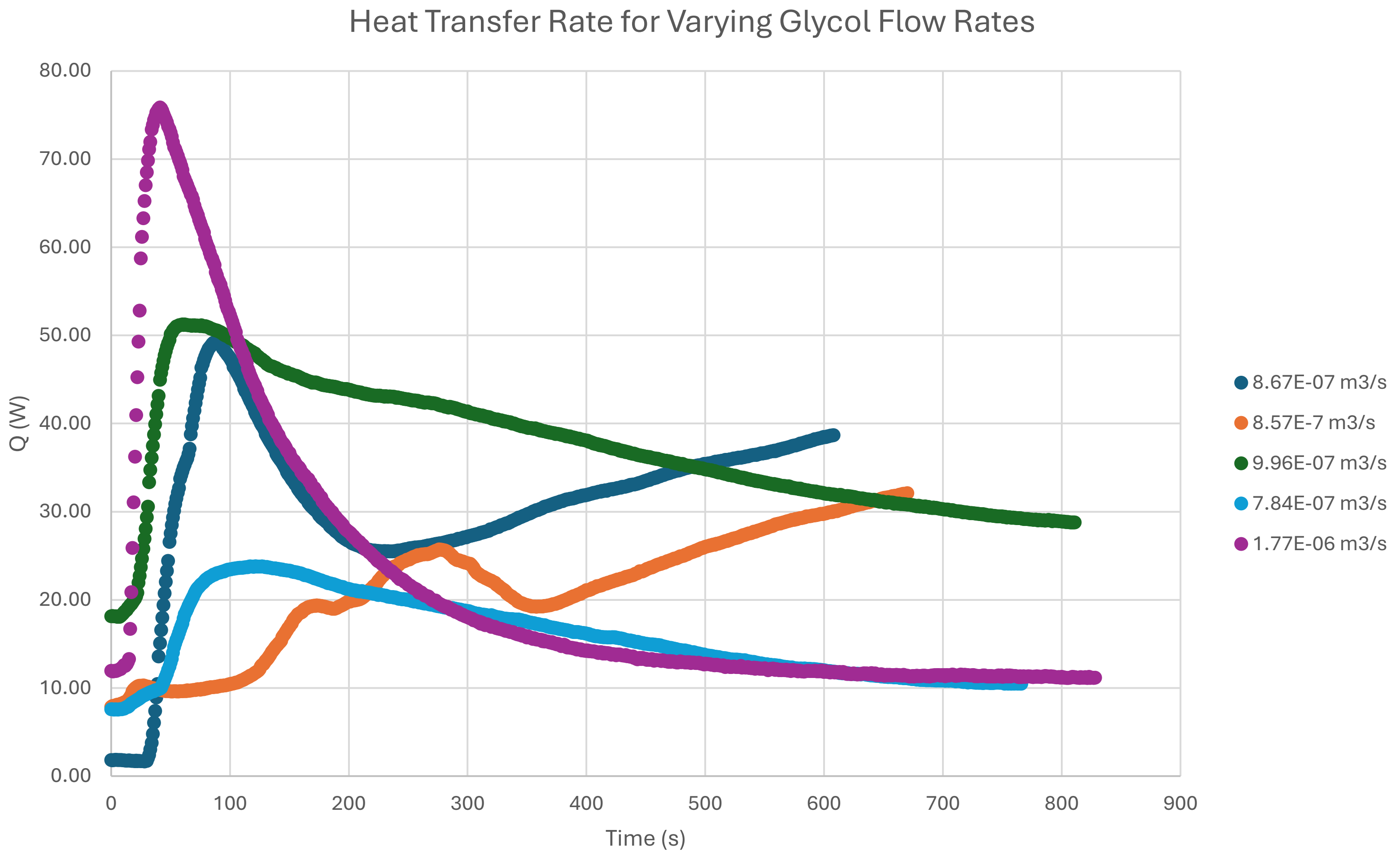




- Consistently has a difference of approximately 2 °C from inlet to outlet as material phase changes
- Phase change occurrence visible as lines intersect.

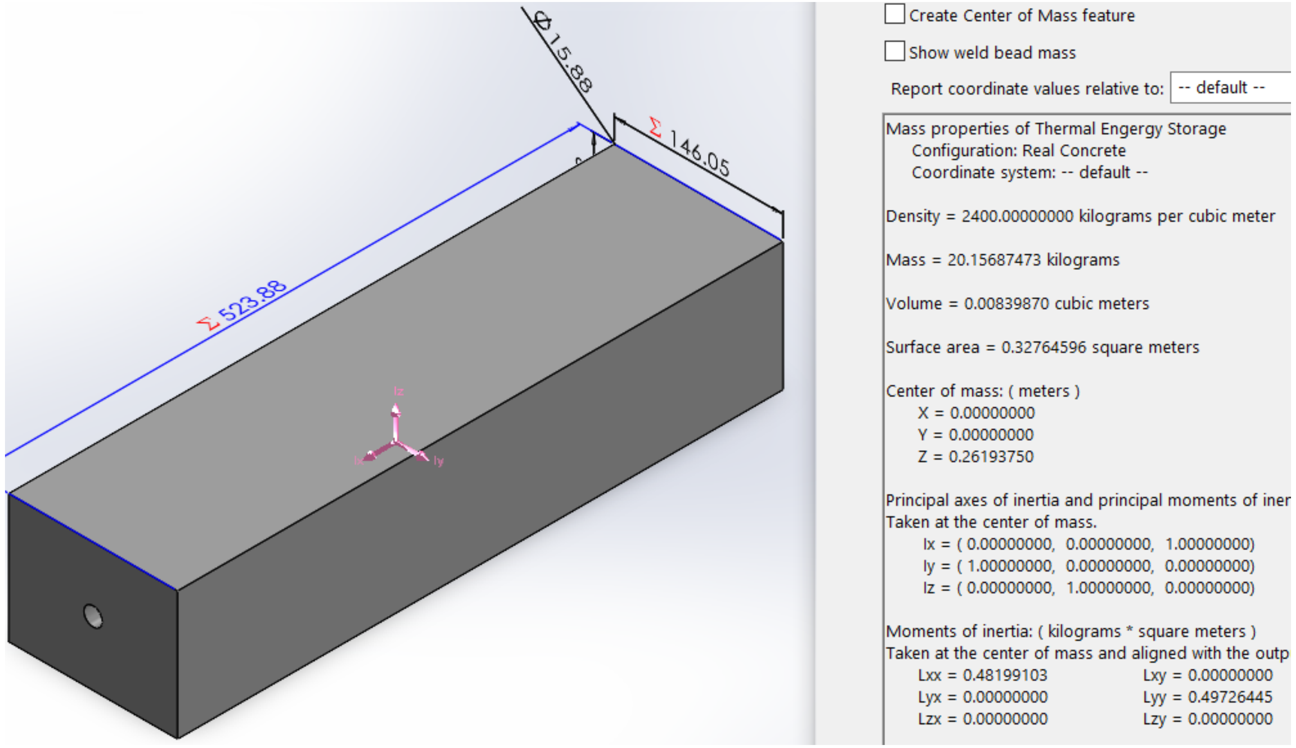
Results - Concrete Charging

Courtney



- Optimal Flow Rate: 9.96E-07 $\frac{m^3}{s}$
- Q=30 W

Volumes and Masses

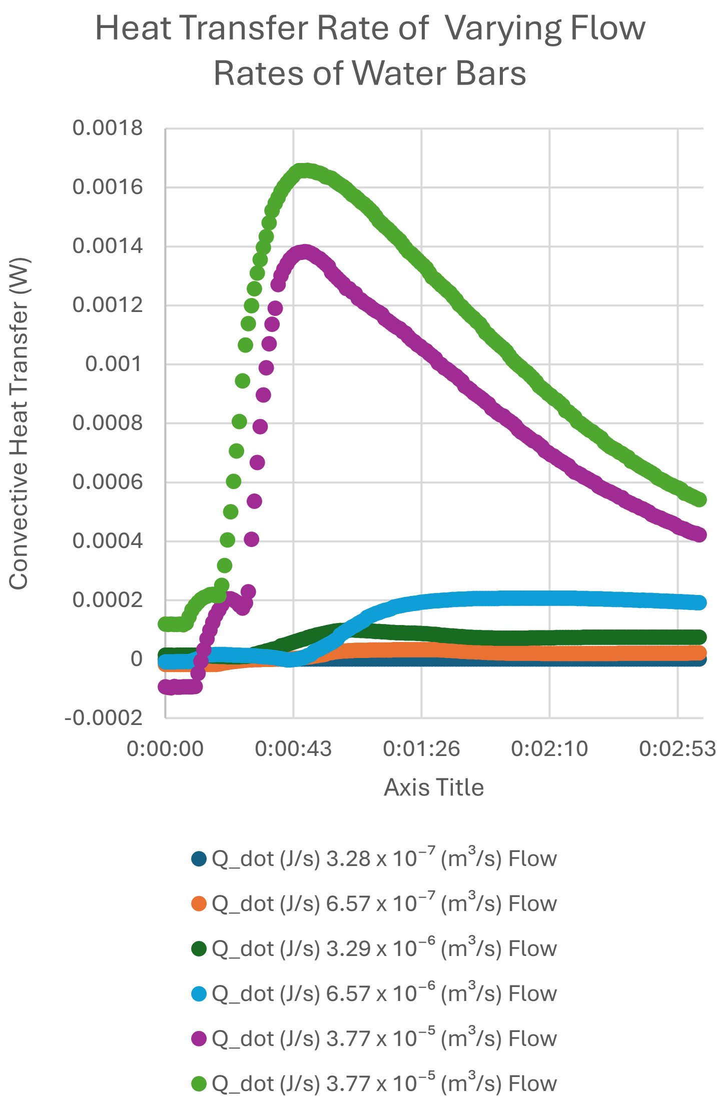


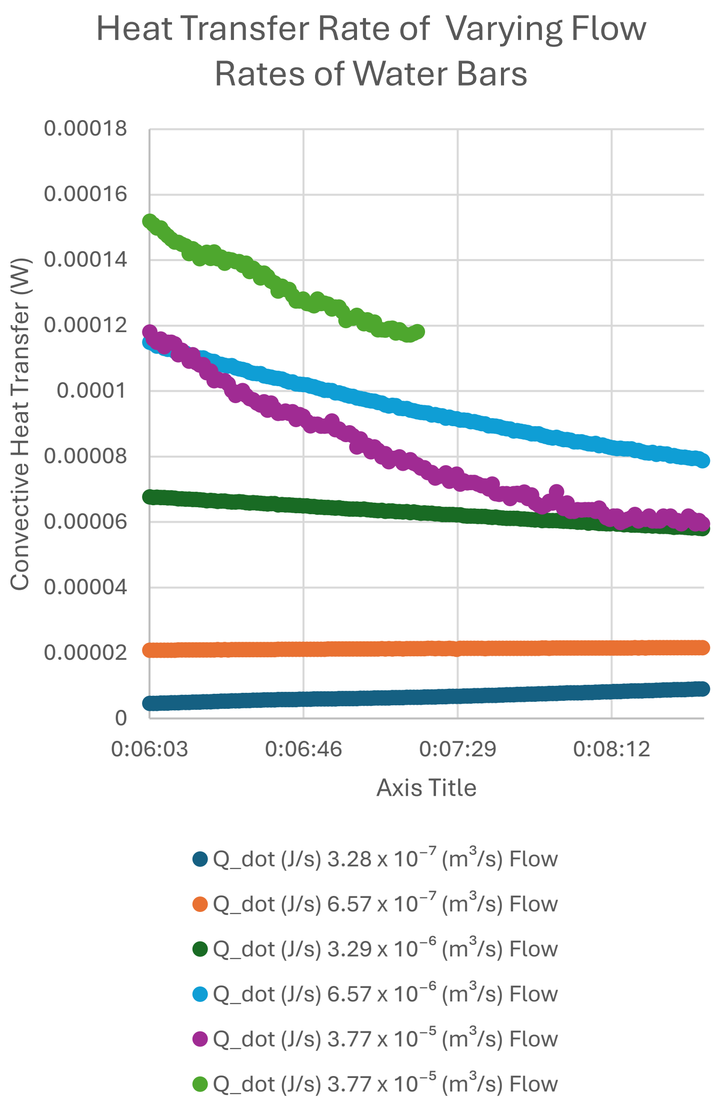
The specific heat of concrete: $880 \frac{J}{kg*°C}$.

From 15°C to -5°C will require 355 kJ. At the optimal flow rate this means 3.29 hours to be prepared to cool a room.

Steven

Results – Water Bar Charging





3.77 x 10^{-5} (m^3/s) Flow proves to have the greatest heat transfer

After a short time, the laminar flow in the pipe does not allow for mixing and higher heat transport.

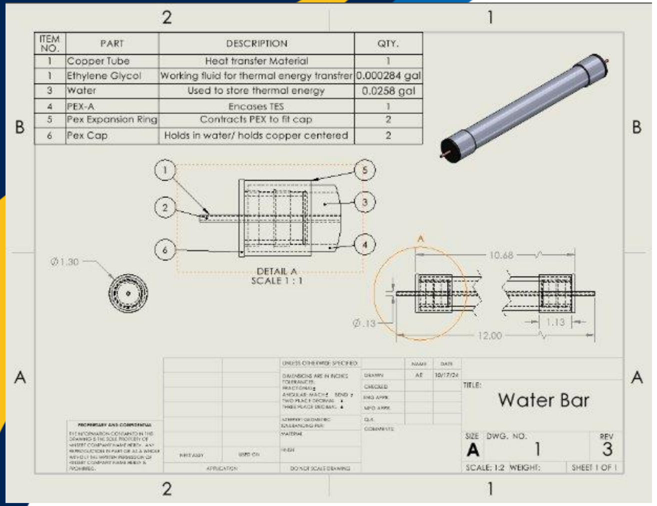
Final Hardware

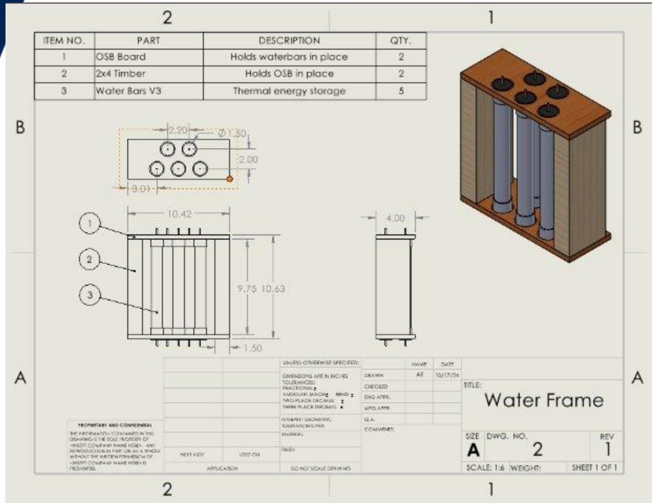
Manufacturing Plan

33% Build					
Manufactured Item	**Picture**	**Components**	**Manufacture Steps**	**Expected Time (hours)**	**Percent of Project**
Test Box (80%)		2x4 inch beams	Cut plywood	1	2.0%
		Plywood	Cut 2x4 in beams	1	2.0%
		Insulation	Connect plywood to beams	5	10.0%
		Hot glue	Glue insulation onto sides	0.5	1.0%
		Glue spray			0.0%
		Screws			0.0%
Concrete Block (75%)		Concrete	Construct the wooden container	4	8.0%
		Water	Add the copper wire to the center	0.5	1.0%
		2x4 in beams	Pour concrete	0.5	1.0%
		Copper wire	Hit out the bubbles	3	6.0%
			Remove from wooden container	0.1	0.2%
Water bars (50%)		PEX pipes	Apply cap to one end of PEX pipe	0.3	0.6%
		Water	Insert the copper pipe through the one PEX pipe	0.1	0.2%
		Copper wire	Use glue to seal one end	0.1	0.2%
		PEX caps	Add water to the inside of the PEX pipe	0.1	0.2%
		Glue	Add cap to the other end	0.2	0.4%
			Glue the other end	0.1	0.2%
			Total	16.5	32.9%

Manufacturing Plan Full Link

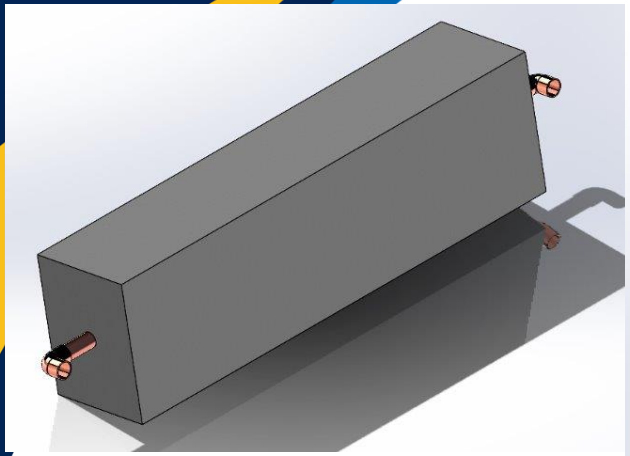
CAD

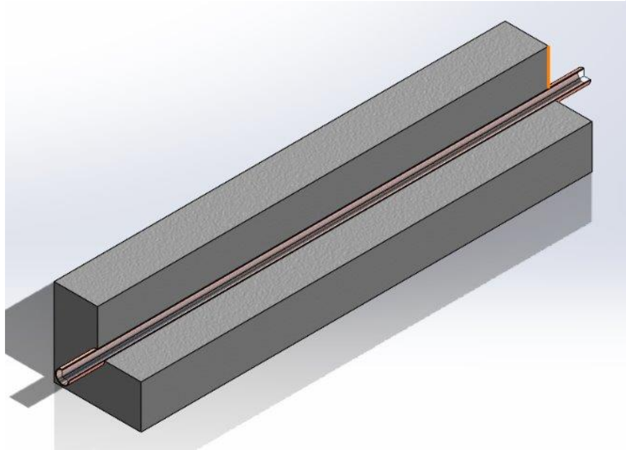


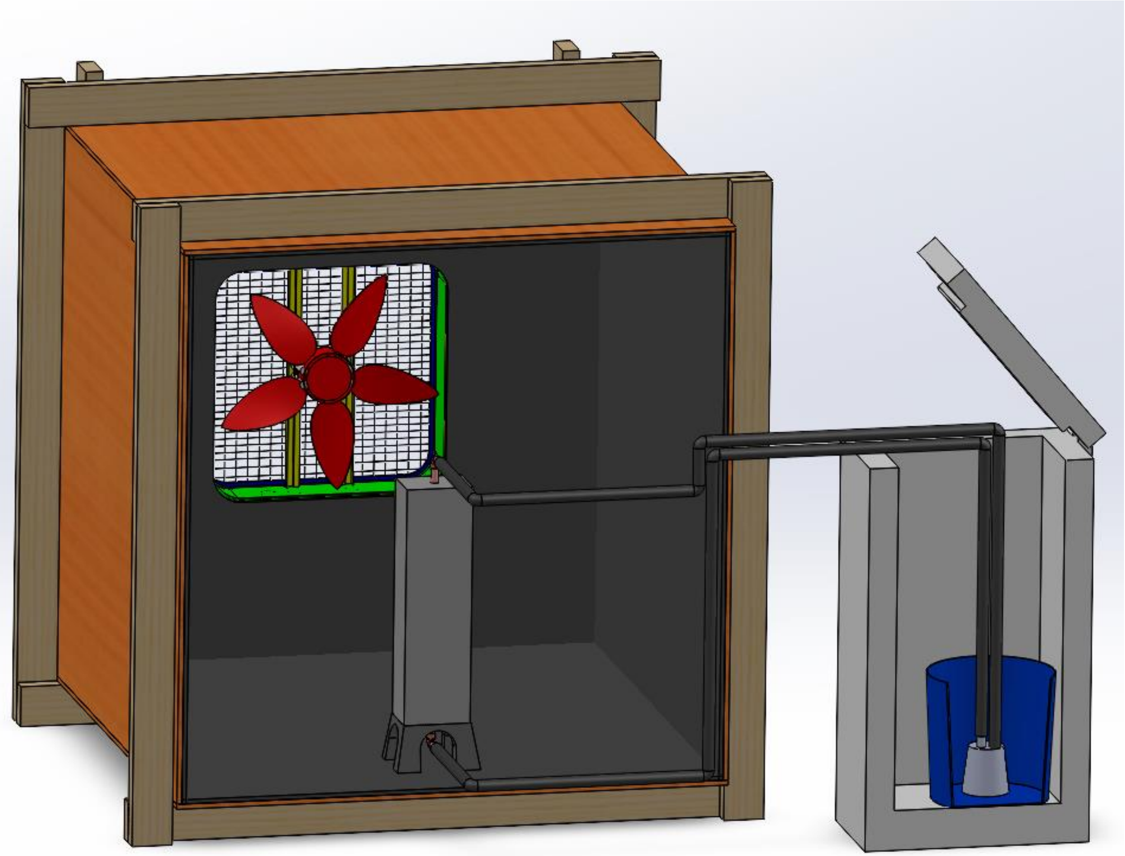


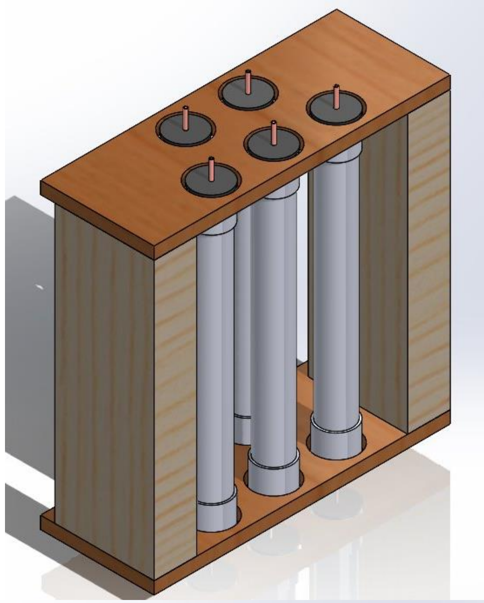
Here will be drawing of the test box and walls that make up the box. Also here will be the updated drawing of the concrete mass

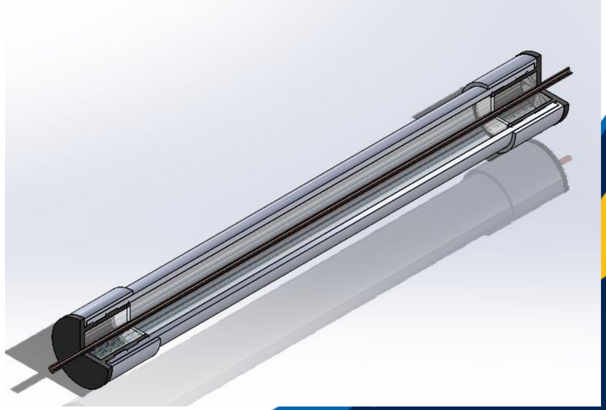
CAD

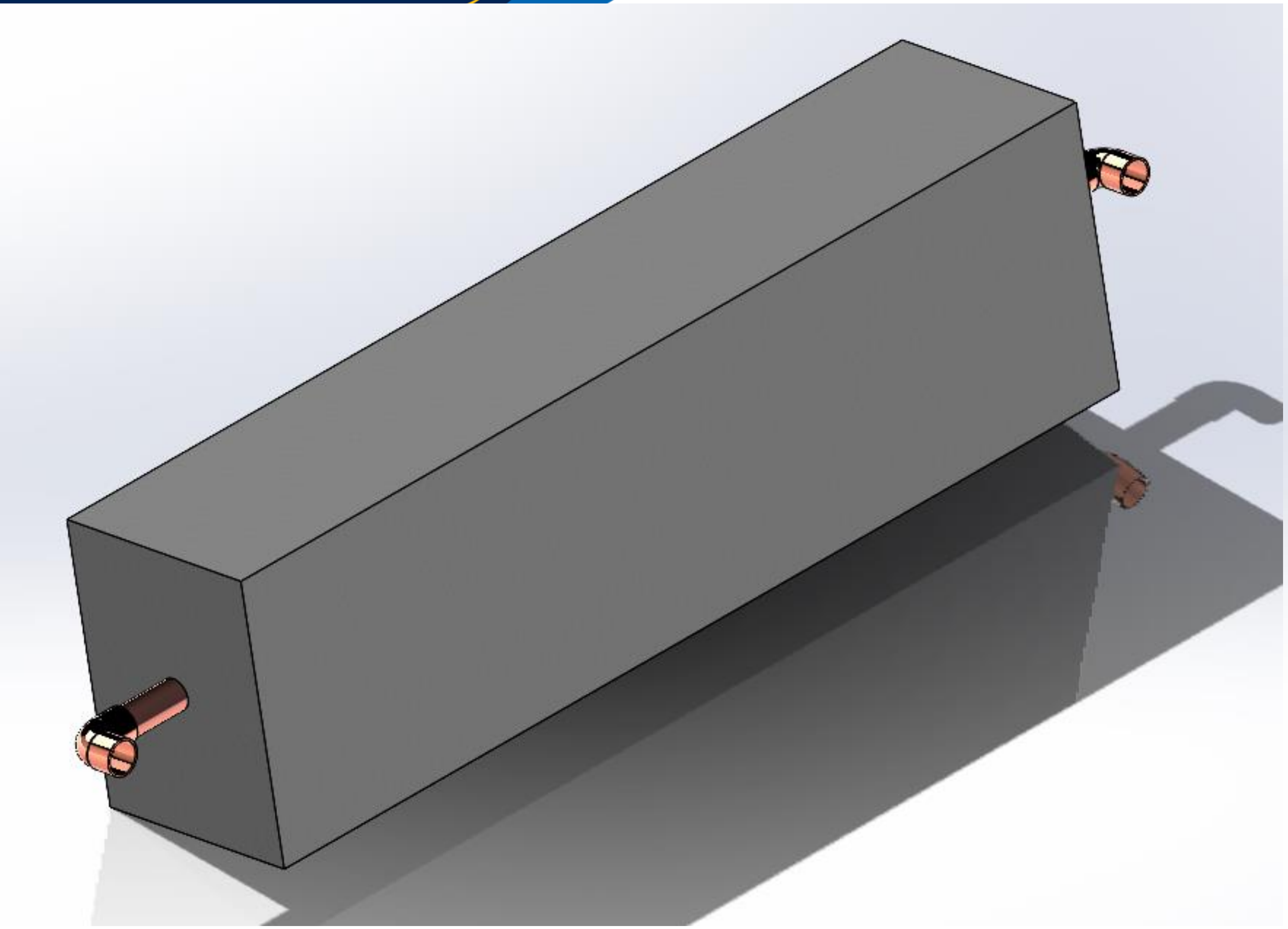


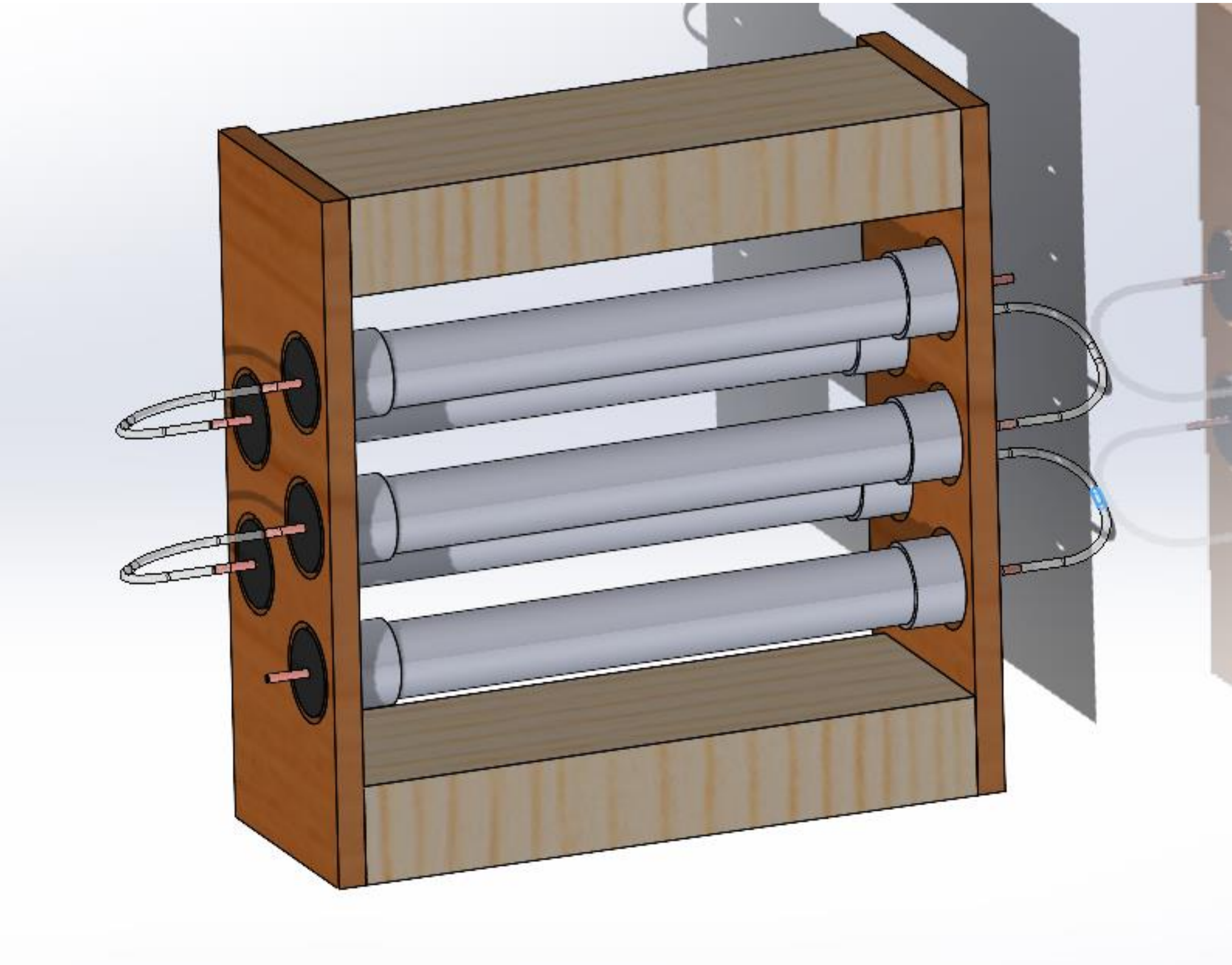


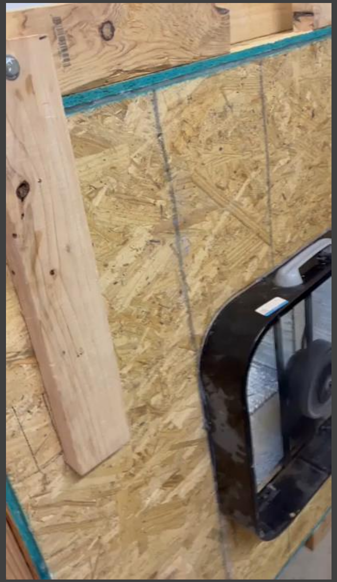




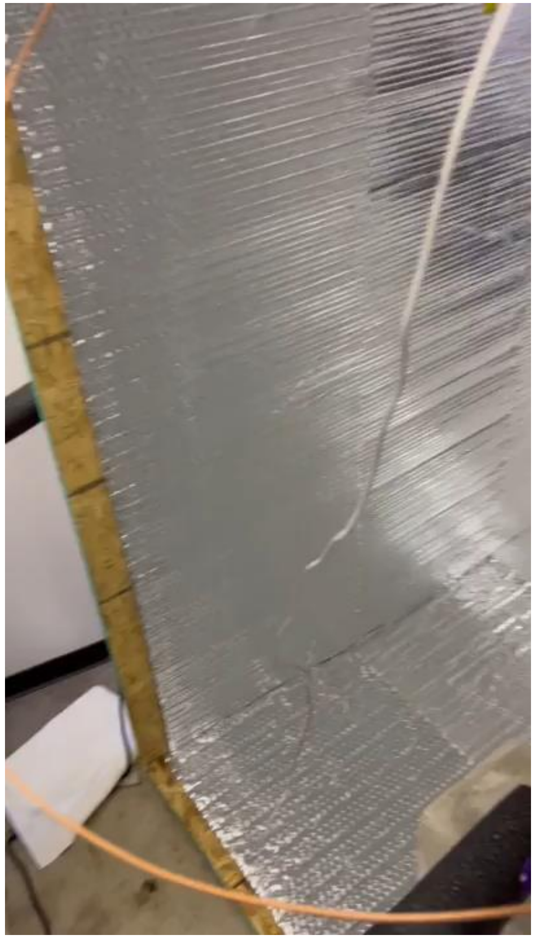


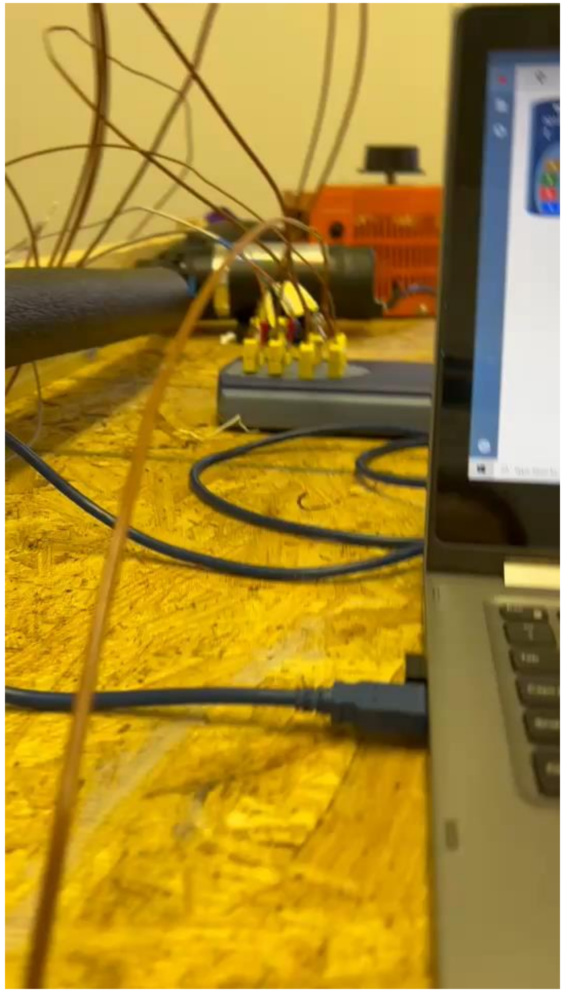


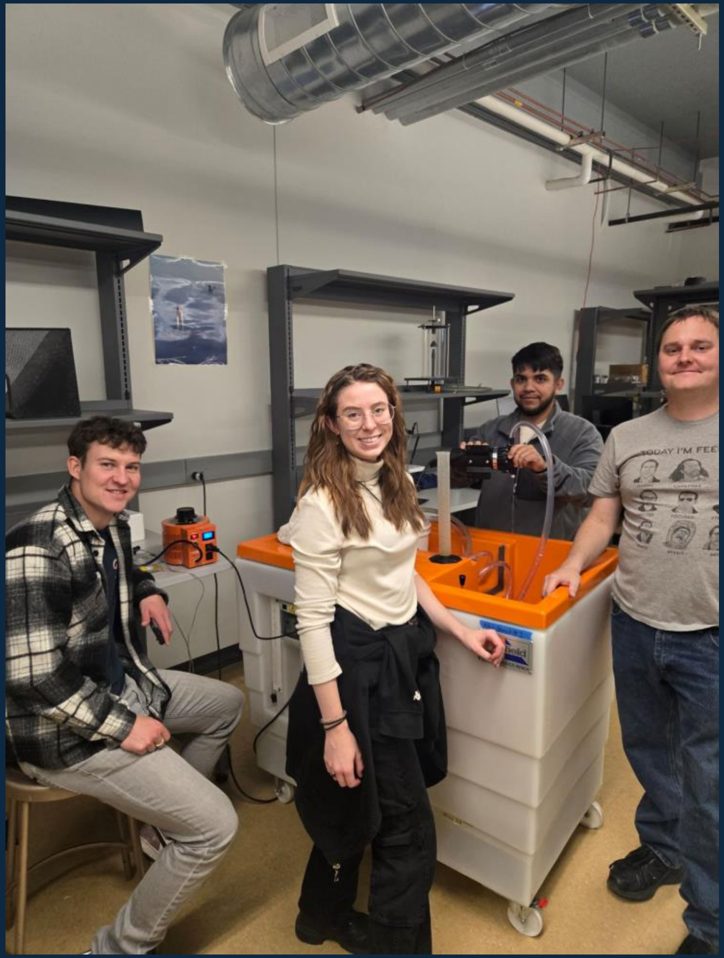




Testing Videos







Testing

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Top Level Testing Summary Table

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	• Thermocouples • Graduated Cylinder • Stopwatch • Pico DataLogger	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	• Thermocouples • Graduated Cylinder • Stopwatch • Pico Data Logger • Drill	Safety equipment working with glycol Solar Shack Dr. Wade's Lab

Detailed Testing Plan

Instrument	Measurement	Resolution	Resolution Uncertainty
Stopwatch	Time	0.01	0.01 s
Graduated cylinder	Volume	2 mL	1 mL
k-type thermocouples/Pico data logger	Temperature	20 bit	7.15E-6 V/bit (quantization error)
RTD thermometer	Temperature	0.01	0.01

Value	Symbol	Depends on Variables
Mass flow rate of glycol	$\dot{m}_{glycol}$	t, V
Heat transfer based on thermodynamic model	$\dot{Q}_{CV}$	t, V, $T_{enter\ \infty}$, $T_{exit\ \infty}$
Heat transfer based on convection	$\dot{Q}_{conv}$	$T_{enter\ \infty}$, $T_{exit\ \infty}$, T_s

Finalized Specification Sheet

Engineering Requirement		Target	Tolerance	Measured/ Calculated Value	ER met? (yes or no)	Client Acceptable (yes or no)
Provide energy during the 4-8pm peak hours	ER1	11kW	+/- 9 kW	Calculated		
Charge thermal mass during non-peak hours	ER2	265257 kJ	+/- 238148 kJ	Calculated		
Reduce costs (Compared to Datum)	ER3	Less than 25.85 ₵/kWh	+/- 5 ₵	Calculated		
Initial Costs (Compared to Datum)	ER4	Less than $5000	+ $0	Measured		

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Finalized Specification Sheet

Customer Requirement		CR met? (yes or no)	Client Acceptable (yes or no)
User Friendly (ease of access & easy to assemble and integrate)	CR1		
Reliability (be able to cool down the house)	CR2		
Safety (safe to keep it in the house)	CR3		
Affordability (Return on investment no longer than five years)	CR4		
Help reach SRP goal to decrease carbon emissions from 2005 levels by 65% by 2035	CR5		
Provide air conditioning through the thermal mass between 4-8 pm	CR6		
Charge the thermal mass during non-peak hours	CR7		
Provide state of the art research/literature review	CR8		
Determine typical SRP electricity use during peak months	CR9		
Provide savings	CR10		
Consider SRP customer rate programs with and without customer-site solar PV generation	CR11		
Provide economic analysis of designs	CR12		
Choose one thermal energy storage solution to build and test	CR13		
Propose a full-scale design	CR14		
Stay within $5000 budget	CR15		

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Future Work

Future Work – Water Bars

Engineer a state-of-the-art heat exchanger outside of the scope of our proof of concept

- Inline static mixing device that will not fail under the crush of ice
- Inner coil mixer that flexes with the freeze (buckling failure analysis
- Would also need to reside in very small diameter

https://www.coleparmer.com/i/koflo-ppt-25-24-p-polypropylene-tube-disposable-static-mixers-1-4-od-1-8-id-24-element/1466904
https://www.youtube.com/watch?v=MJycphczB7s

Future Work – Concrete

Research and Development

- Forms with inserts for the pipe
- Pipe material cost benefit analysis (Aluminum, copper, Pex, PVC)
- Construction integration method study
  - Safety integration (Securing)
  - Load bearing study
  - Condensation mitigation
  - Heat transfer optimization

https://www.houseplans.com/plan/1972-square-feet-3-bedroom-2-bathroom-3-garage-traditional-ranch-cottage-sp265191
https://canel.my.id/
https://www.amazon.com/Concrete-Walkways-Walkway-Rectangular-Textured/dp/B0D9LYKC4S
https://www.johnguest.com/gb/en/resources/blog/plastic-or-copper-pipe-correct-answer

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Thank You!
Questions????

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