Salt River Project (SRP) Thermal Mass

Cooling Load/Sensible and Latent Heat Analysis

ME476C Section 1

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Contents

Introduction

Air conditioning is a large contributor to the energy demand in Maricopa County. The overarching goal of this project is to create a thermal mass that charges during the Salt River Project (SRP) off peak hours, and discharges cool air during peak hours. This will decrease the demand for energy during peak hours, and save SRP as well as customers money.

To calculate the cooling load (Q), the 1997 ASHRAE cooling load method is used to determine the smallest and largest possible values of Q based on the types of materials homes are built of. These calculations are done in Excel. [1] This is then compared to numbers found by the National Renewable Energy Lab (NREL).

Once the amount of energy necessary to keep the house cool during peak hours is determined, the next step is determining the mass and volume of the material needed to absorb adequate heat from the house during that time, effectively keeping it cool. This report answers the question of how much material we will need for the design, as well as how much it will cost.

This analysis then provides a MATLAB function that inputs material specific properties such as the specific heat and heat of fusion and uses heat transfer formulas to determine the amount of material needed to keep the house cool. The values for Q found previously are inputted into the MATLAB code, which can then be quickly applied to a variety of materials to compare the mass and volume needed to keep a house cool. This then influences the size of the system, as well as the price.

Assumptions

Part 1. Cooling Load

The peak hours for SRP can be found at the SRP time of use plan. [2] The peak hours are between 2-8PM.

The formulas from the ASHRAE handbook are given below to calculate the cooling load in BTU/hr. This can then be converted into energy by multiplying Q by the number of hours that the system is running.

$$Q_{roof} = U_{roof} * A_{roof} * CLTD_{corrected}$$ ***Equation 1***

$$Q_{windows} = U_{windows} * A_{windows} * CLTD_{corrected}$$ ***Equation 2***

$$Q_{walls} = U_{walls} * A_{walls} * CLTD_{corrected}$$ ***Equation 3***

$$Q_{total} = Q_{roof} + Q_{windows} + Q_{walls}$$ ***Equation 4***

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

$$TM = T_{max} - (\frac{DR}{2})$$ ***Equation 6***

Where

Q = cooling load (BTU/hr)

U = coefficient of heat transfer (Btu/hr*ft^2*F)

A = area (ft^2)

$CLTD$ = cooling load temperature difference (F)

$CLTD_{corrected}$ = CLTD adjusted for indoor and outdoor temperatures (F)

TR = indoor room temperature (F)

TM = mean outdoor temperature (F)

T_{max} = max outdoor temperature (F)

DR = daily range (F)

The cooling load is calculated in Excel. The initial data is given below with the majority of the values coming from the 1997 ASHRAE handbook based on the Phoenix Sky Harbor airport. The average area of the exterior walls on a home is from the Siding Authority estimator. [3] The average roof surface area is found from BFM roofing estimates. [4]

Table 1. ASHRAE Data

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	0.074	Btu/h*ft^2*F
U Roof	0.066	Btu/h*ft^2*F
U Windows	0.55	Btu/h*ft^2*F

The CLTD values for each wall, window, and roof are determined for different materials by the authors of the 1997 ASHRAE handbook. These values are copied over into Excel for the peak hours from 2-8PM (given in the 24 hour clock as 14-20) for each side of the wall, the roof, and windows. The values are given below.

Table 2. CLTD Values

	CLTD values (F)					
Hour	Roof 14	Wall 16 North	Wall 16 East	Wall 16 South	Wall 16 West	Windows (Conduction Load)
14	32	9	26	11	11	13

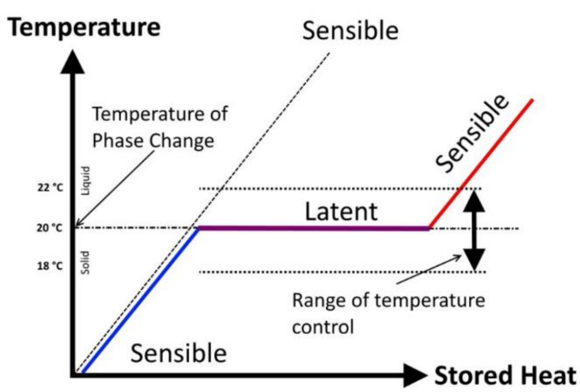
15	36	10	28	14	12	14
16	39	11	30	17	14	14
17	42	13	31	20	17	13
18	44	14	31	23	20	12
19	45	16	32	25	25	10
20	45	17	32	27	30	8

Table 3. CLTD Values

	CLTD values (F)					
Hour	Roof 1	Wall 1 North	Wall 1 East	Wall 1 South	Wall 1 West	Windows (Conduction Load)
14	88	27	31	42	11	13
15	88	29	30	59	12	14
16	83	29	30	73	14	14
17	73	28	28	80	17	13
18	60	29	25	79	20	12
19	43	27	20	62	25	10
20	26	17	14	32	30	8

Part 2. Latent and Sensible Heat of Materials

The following diagram shows a general phase change diagram, as well as the equations for latent and sensible heat.



Graph 1. Phase Change Diagram [5]

$Latent\ Heat = \ q = m * c$ ***Equation 7***

$Sensible\ Heat = q = m * C * \Delta T$ ***Equation 8***

$D = m/V$ ***Equation 9***

Where

q = heat (kJ)

m = mass (kg)

c = heat of fusion (kJ/kg)

C = specific heat (kJ/kg*C)

T = temperature (C)

V = volume (m^3)

D = density (kg/m^3)

The following data is collected for water and concrete. These are found in the engineering toolbox. [6]

Table 4. Material Properties

	Water	Concrete
Heat of fusion (kJ/kg)	334	n/a
Specific heat (kJ/kg)	4.184	1
Temperature of fusion (C)	0	1200
Density	(varies for temp)	2300
Cost ($/kg)	0.0002189	0.10

Mathematical Modeling/Software Calculations

Part 1. Cooling Load in Excel

Excel is used to calculate the cooling load using the assumptions. The following table is created by taking the CLTD values and using ***equation 5*** and ***equation 6*** to find CLTD corrected, then ***equation 1*** to find the value of Q for the roof that allows the smallest amount of heat in. This is repeated for the roof that lets in the most heat to find the max Q value.

Table 5. Roof Calculation in Excel

Min Roof - Assume Roof 14			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	32	45.5	5105.1
15	36	49.5	5553.9
16	39	52.5	5890.5
17	42	55.5	6227.1
18	44	57.5	6451.5
19	45	58.5	6563.7
20	45	58.5	6563.7
Total			42355.5

Similar calculations are used to find Q for the windows using ***equation 2.*** An example of these calculations are given below.

Table 6. Window Calculation in Excel

Min Windows (Conduction Load)			
Hour	CLTD (F)	CLTD corrected (F)	Q (Btu/hr)
14	13	26.5	1457.5
15	14	27.5	1512.5
16	14	27.5	1512.5
17	13	26.5	1457.5
18	12	25.5	1402.5
19	10	23.5	1292.5
20	8	21.5	1182.5
Total			9817.5

Similar calculations are used to find Q for the walls facing North, East, South, and West using ***equation 3***. An example for the North and East walls are given below. For more details on all the walls for the minimum and maximum calculations, look at the Excel document.

Table 7. Wall Calculation in Excel

Min North Wall - Assume Wall 16				Min East Wall - Assume Wall 16			
Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)	Hour	CLTD (F)	CLTD corrected (F)	Qdot (Btu/hr)
14	9	22.5	657.675	14	26	39.5	1154.585
15	10	23.5	686.905	15	28	41.5	1213.045
16	11	24.5	716.135	16	30	43.5	1271.505
17	13	26.5	774.595	17	31	44.5	1300.735
18	14	27.5	803.825	18	31	44.5	1300.735
19	16	29.5	862.285	19	32	45.5	1329.965
20	17	30.5	891.515	20	32	45.5	1329.965
Total			5392.935	Total			8900.535

The final Q is found by adding together all of the Q values for the walls, windows, and roof using ***equation 4.***

Table 7. Q Values by hour

Total Min Qdot		Total Max Qdot	
Hour	Q (Btu/hr)	Hour	Q (Btu/hr)
14	9807.13	14	90

15	10515.54	15	99
16	11085.98	16	109
17	11630.65	17	119
18	12004.66	18	128
19	12299.16	19	139
20	12423	20	149
Average	11395.16	Average	119

Values of q are calculated by multiplying each Q value for the hour by one hour, then adding it up at the end. This is converted between units to be used in the calculations for latent and sensible heat in MATLAB.

Table 8. Excel Sum Q Values

Max Q Values (Btu)		Max Q Values (kJ)		Max Q Values (kWh)	
Roof	62327.1	Roof	65755.091	Roof	18.26
Windows	9817.5	Windows	10357.463	Windows	2.88
Walls	41214.3	Walls	43481.087	Walls	12.08
Total	113358.9	Total	119593.64	Total	33.22
Min Q Values (Btu)		**Min Q Values (kJ)**		**Min Q Values (kWh)**	
Roof	42355.5	Roof	44685.053	Roof	12.41
Windows	9817.5	Windows	10357.463	Windows	2.88
Walls	27593.12	Walls	29110.742	Walls	8.09
Total	79766.12	Total	84153.257	Total	23.38

Part 2. Latent and Sensible Heat in MATLAB

There are two MATLAB files used for the latent and sensible heat calculations. The first is a function that uses equation 7, equation 8, and equation 9 to determine how much heat the material is releasing when being cooled. These equations are rearranged by adding together the latent and sensible heat, and rearranging to solve for the mass, giving the following equation.

$m = Q/(C * \Delta\mathrm{T} + \mathrm{c})$ ***Equation 10***

In MATLAB, this equation is shown below, as well as the formula that converts that mass into volume using ***equation 9.***

```
Mass = EnergyValues./(SpecificHeat*dT+HeatofFusion); %kg
Volume = Mass/MinDensity;
```

The function also checks if the material is a phase change material by checking if the heat of fusion occurs within the temperature change. If it does not, then it automatically sets the heat of fusion to 0.

```
if (LowestTemp > TempofFusion) || (TempofFusion > RoomTemp)
    HeatofFusion = 0;
end
```

The function then produces a variety of graphs and tables displaying information regarding the mass, volume, and price of material needed. The MaterialPropertiesDriver.m calls on the function MaterialProperties by giving information about the material and plugging it into the function. Using the assumptions for the values found above, the following code is produced for water. The same is done for concrete, see the **Appendix** for more details..

```
%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)
```

The minimum and maximum energy requirements are determined based on the cooling load calculations, and plugged into MATLAB through the following:

```
LowestTemp = -1; %deg C
MinEnergyRequirement = 84153; %kJ
MaxEnergyRequirement = 119593; %kJ
```

Results/Diagrams

Part 1. Cooling Load

Table 9. Cooling Load Results

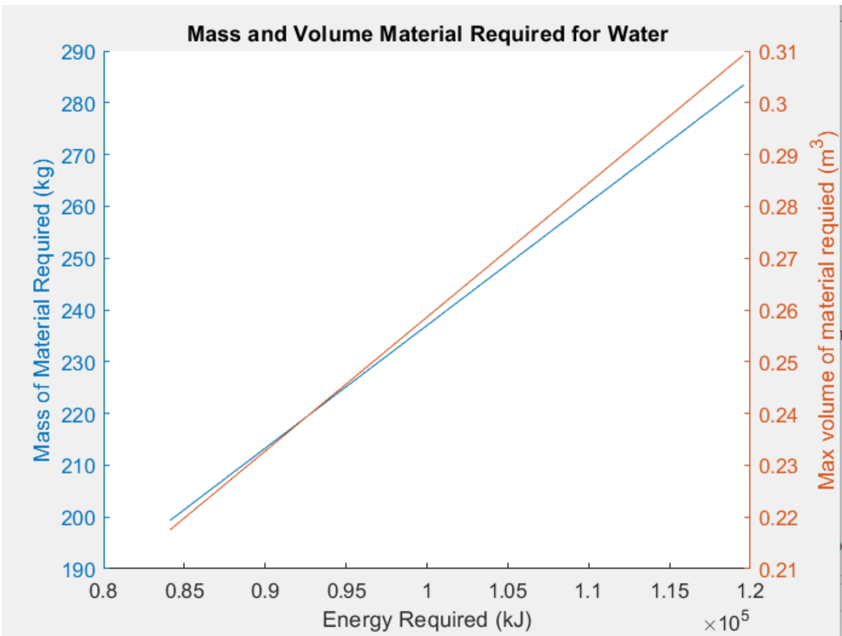
Max Q Values (Btu)	**Max Q Values (kJ)**	**Max Q Values (kWh)**
113358.9	119593.64	33.22
Min Q Values (Btu)	**Min Q Values (kJ)**	**Min Q Values (kWh)**
79766.12	84153.257	23.38
Max Qdot Values (Btu/h)	**Max Qdot Values (kJ/h)**	**Max Qdot Values (kW)**
16194.12857	17084.80564	4.745646463
Min Qdot Values (Btu/h)	**Min Q Values (kJ/h)**	**Min Qdot Values (kW)**
11395.16	12021.8938	3.339321441

Part 2. Sensible and Latent Heat

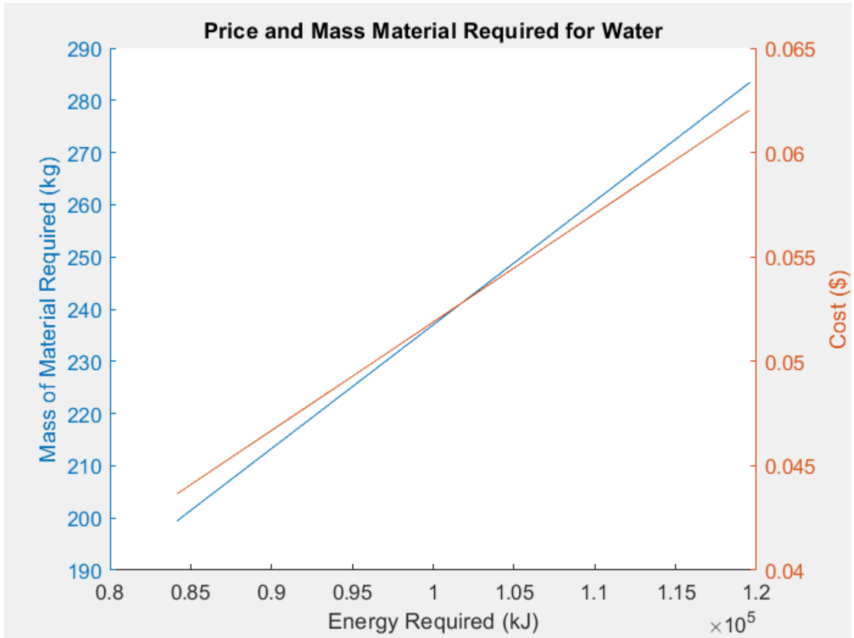
Table 10. Water Results

Mass and Volume Requirements for Energy Requirements Water

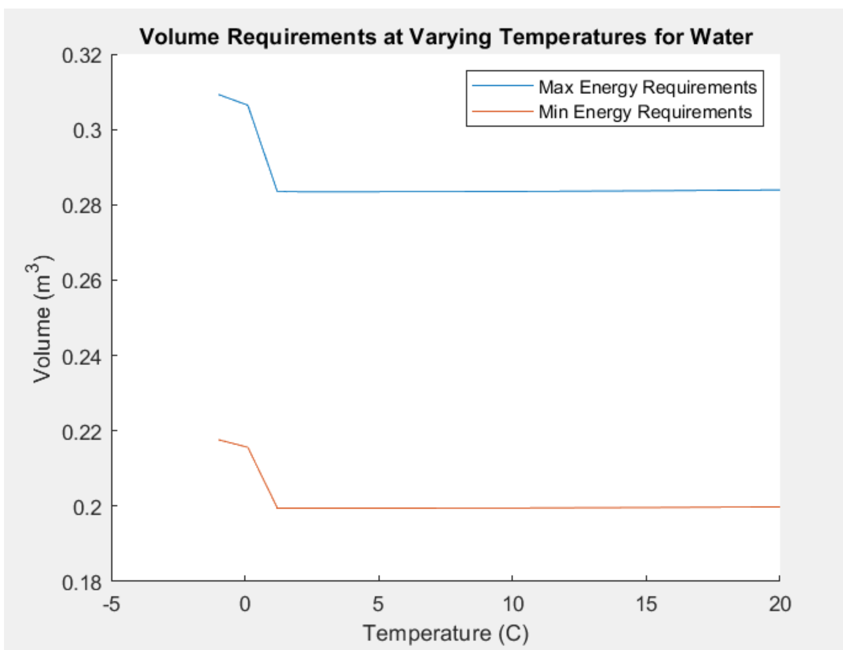
Energy Requirmenets (kJ)	Mass Required (kg)	Volume Required (m^3)	Latent Heat Storage (kJ)	Sensible Heat Storage (kJ)
84153	199.45	0.21763	66616	17537
86018	203.87	0.22245	68093	17926
87884	208.29	0.22728	69569	18314
89749	212.71	0.2321	71046	18703
91614	217.13	0.23693	72522	19092
93479	221.55	0.24175	73999	19481
95345	225.97	0.24657	75475	19869
97210	230.39	0.2514	76952	20258
99075	234.82	0.25622	78428	20647
1.0094e+05	239.24	0.26104	79905	21035
1.0281e+05	243.66	0.26587	81382	21424
1.0467e+05	248.08	0.27069	82858	21813
1.0654e+05	252.5	0.27552	84335	22201
1.084e+05	256.92	0.28034	85811	22590
1.1027e+05	261.34	0.28516	87288	22979
1.1213e+05	265.76	0.28999	88764	23368
1.14e+05	270.18	0.29481	90241	23756
1.1586e+05	274.6	0.29963	91717	24145
1.1773e+05	279.02	0.30446	93194	24534
1.1959e+05	283.44	0.30928	94671	24922



Graph 2. Mass and Volume Material Required for Water



Graph 3. Mass and Price Material Required for Water

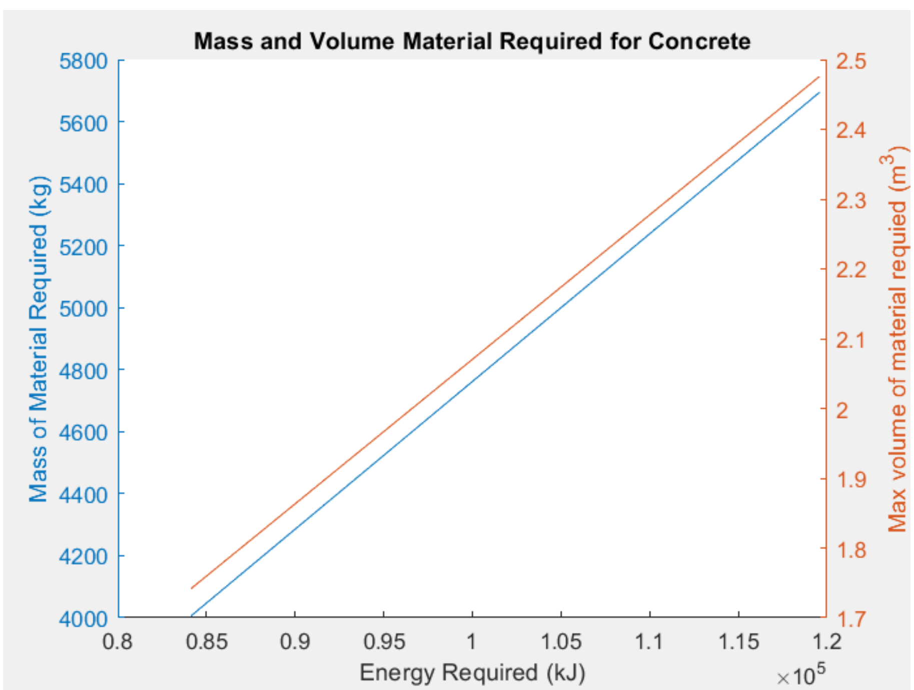


Graph 4. Volume Requirements at Varying Temperatures for Water

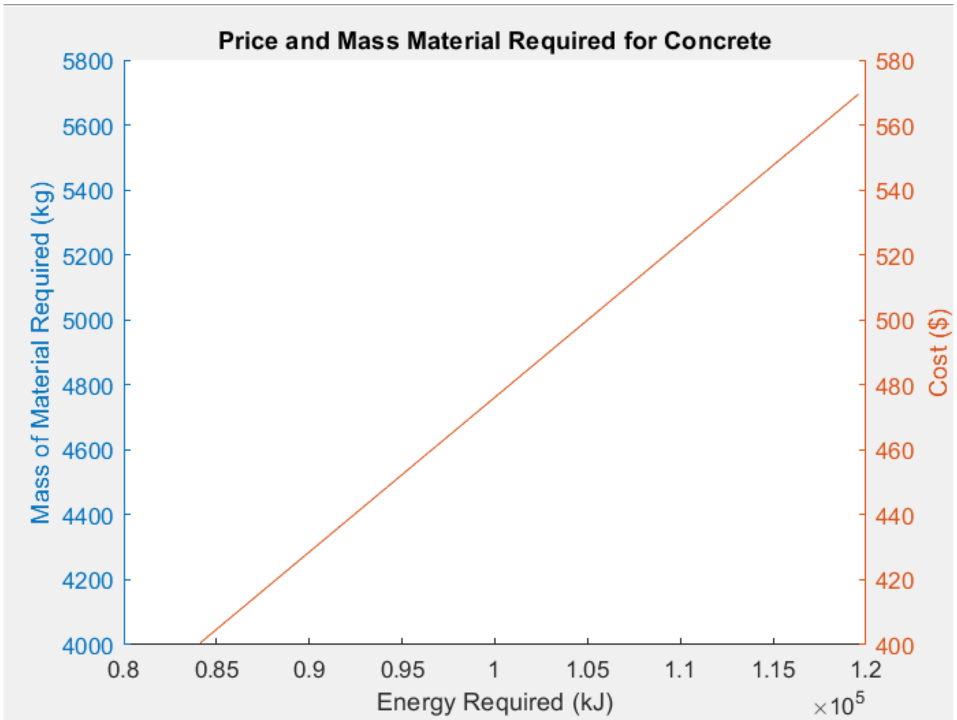
Table 11. Concrete Results

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)
84153	4007.3	1.7423	0	84153
86018	4096.1	1.7809	0	86018
87884	4184.9	1.8195	0	87884
89749	4273.8	1.8582	0	89749
91614	4362.6	1.8968	0	91614
93479	4451.4	1.9354	0	93479
95345	4540.2	1.974	0	95345
97210	4629	2.0126	0	97210
99075	4717.9	2.0512	0	99075
1.0094e+05	4806.7	2.0899	0	1.0094e+05
1.0281e+05	4895.5	2.1285	0	1.0281e+05
1.0467e+05	4984.3	2.1671	0	1.0467e+05
1.0654e+05	5073.2	2.2057	0	1.0654e+05
1.084e+05	5162	2.2443	0	1.084e+05
1.1027e+05	5250.8	2.283	0	1.1027e+05
1.1213e+05	5339.6	2.3216	0	1.1213e+05
1.14e+05	5428.4	2.3602	0	1.14e+05
1.1586e+05	5517.3	2.3988	0	1.1586e+05
1.1773e+05	5606.1	2.4374	0	1.1773e+05
1.1959e+05	5694.9	2.476	0	1.1959e+05



Graph 5. Mass and Volume Material Required for Concrete



Graph 6. Mass and Price Material Required for Concrete

Conclusion and Analysis

The cooling load I calculated can be compared to the cooling load found by the National Renewable Energy Lab (NREL). They found that for hot-dry and mixed-dry climates, the average thermal load per year is 1.83M MBTU/yr. [7]

When converting this down to Btu/hr, this is approximately 208 BTU/hr. Our average minimum calculated load is 11395 Btu/hr, which is significantly higher than their values. However, this could be explained because their value includes the cooler winter months and the power used through the night. Phoenix is on the high end of the hot climate, so accounting for that, our values would be expected to be higher than a mixed climate as well. Our values only account for the peak hours when AC is running at full power.

Through this analysis, it is clear that the price and volume of water is significantly lower than the price that would be required to have adequate cooling capacity with concrete. However, water may have other properties that could be disadvantageous, specifically because it expands. This MATLAB code that I created could also be used to quickly calculate how much it will cost to use other materials if we decide to consider them.

The values calculated for the material properties can be considered in the Net Present Value calculations that impact the spider charts. The tool creates an effective way for comparing the properties of materials visually and through tables, and determining which factors lead to the lowest costs.

References:

[1] R. Crawford, K. Herold, A. Jacobi, and T. Kuehn, *1997 ASHRAE Handbook*, I-P. 1997.
[2] "SRP Time-of-Use (TOU) Price Plan | SRP." Accessed: Feb. 03, 2024. [Online]. Available: https://www.srpnet.com/price-plans/residential-electric/time-of-use
[3] "Siding Calculation & Exterior Sq. Ft. Estimation Methods," Siding Authority. Accessed: Apr. 29, 2024. [Online]. Available: https://sidingauthority.com/estimation-calculator/
[4] B. Tarver, "How Much Does the Average Roof Replacement Cost," B&M Roofing | Commercial & Residential Roofing in Colorado. Accessed: Apr. 29, 2024. [Online]. Available: https://bmroofing.com/how-much-does-the-average-roof-replacement-cost/
[5] "Figure 1. Sensible heat vs. latent heat and temperature control during...," ResearchGate. Accessed: Mar. 16, 2024. [Online]. Available: https://www.researchgate.net/figure/Sensible-heat-vs-latent-heat-and-temperature-control-during-the-phase-change-7_fig1_312868057
[6] "Water - Thermophysical Properties." Accessed: Apr. 29, 2024. [Online]. Available: https://www.engineeringtoolbox.com/water-thermal-properties-d_162.html
[7] A. Speake, E. J. H. Wilson, Y. Zhou, and S. Horowitz, "Component-level analysis of heating and cooling loads in the U.S. residential building stock," *Energy Build.*, vol. 299, p. 113559, Nov. 2023, doi: 10.1016/j.enbuild.2023.113559.

Appendix:

```
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
```

```
% 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 = 84153; %kJ
MaxEnergyRequirement = 119593; %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)
```