NORTHERN ARIZONA UNIVERSITY

ME 476C Capstone Project

Summer 2025

RE Lab Solar Heater

Jacob Apodaca

Brendan Frazier

Tyler Hedgecock

Joseph Meza

Calvin Schenkenberger

Northern Arizona University

Flagstaff, AZ 86001

Project Description

Primary Goal

- Implement a solar water or air heater to provide heat to the Renewable Energy Lab to offset the current, nonrenewable, method of heating.

Important

- Reduce total non-renewable energy usage by NAU
- Help achieve NAU carbon neutrality plan
- Keep stored batteries above 40 °F

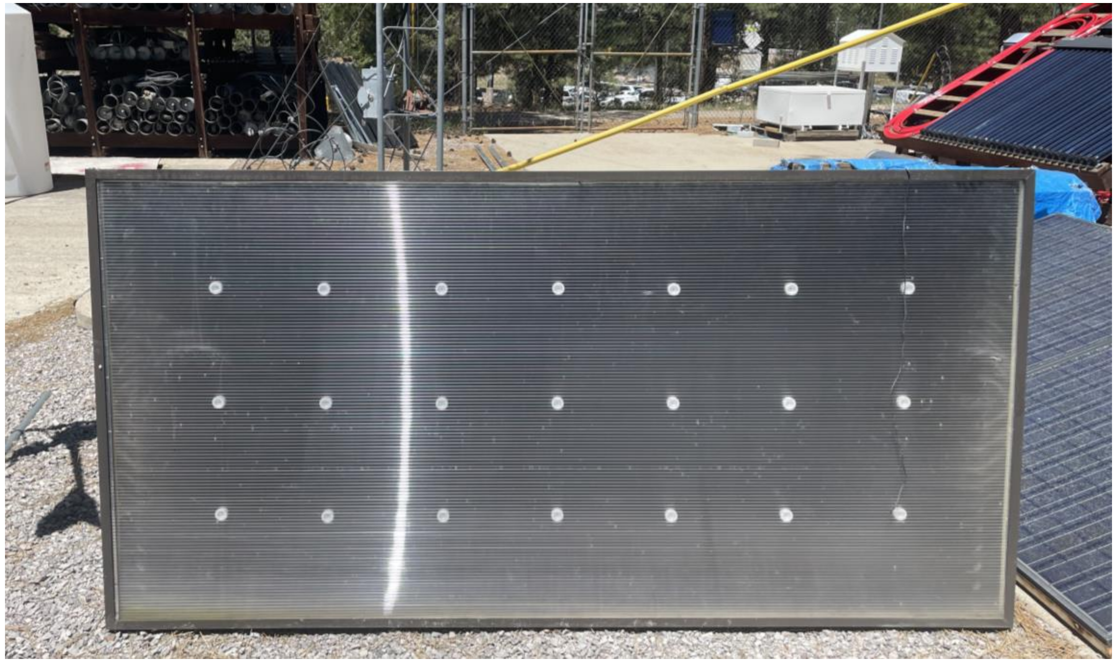


Figure 1: Air-Based Solar Thermal Panel

Brendan Frazier

Functional Decomposition: Black Box Model

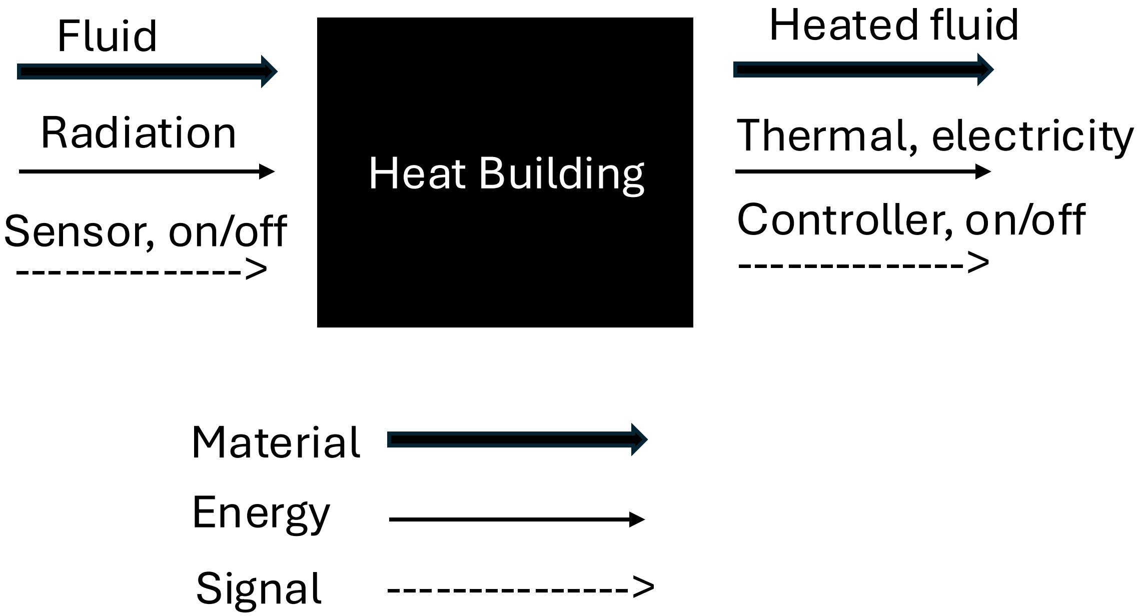


Figure 2: Black Box Model

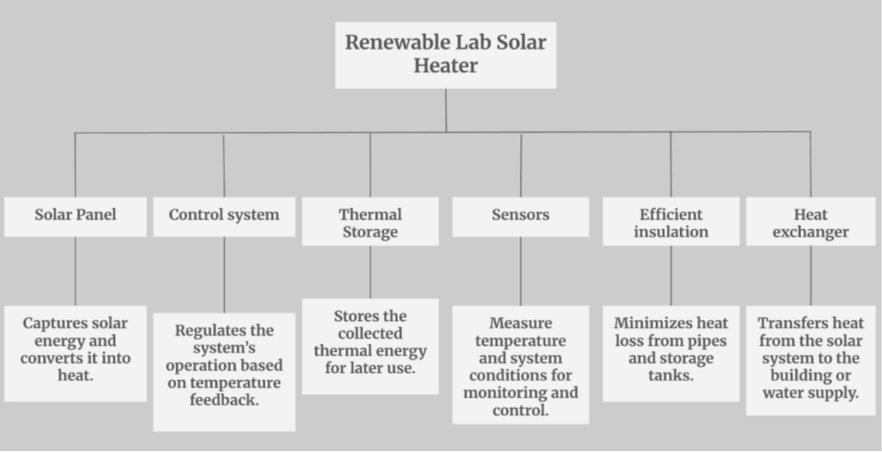
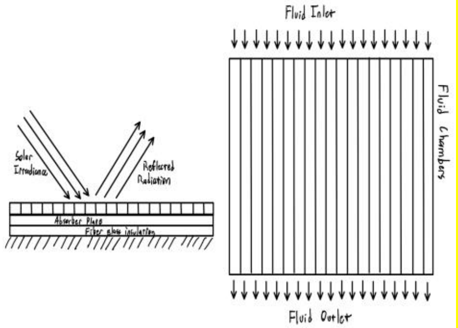
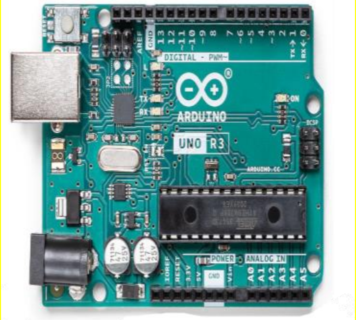
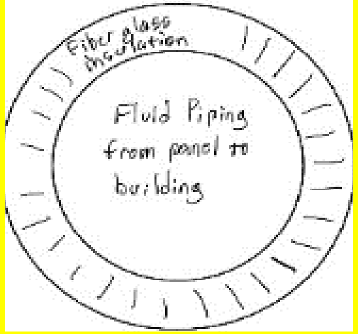
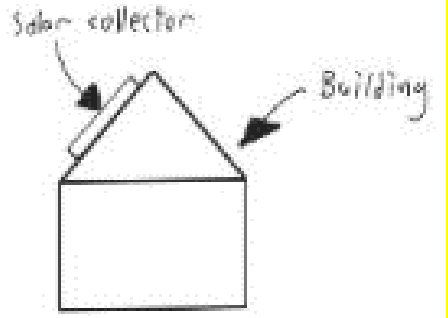
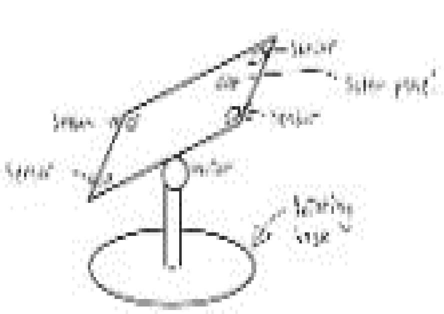
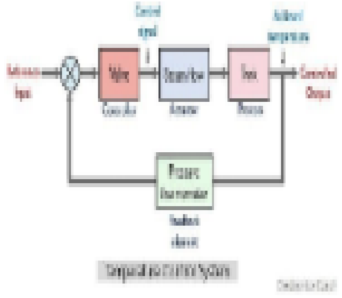
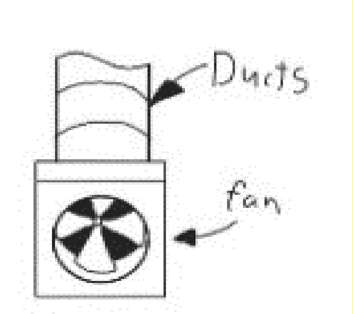
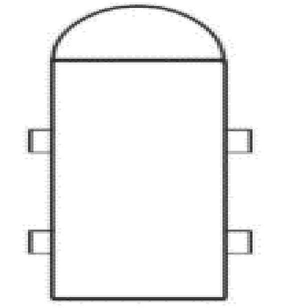
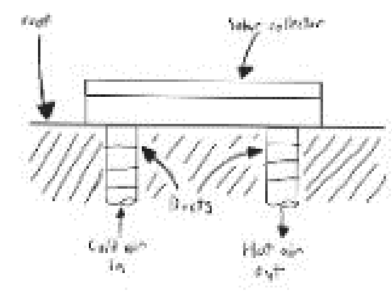


Figure 3: Functional Decomposition

Jacob Apodaca

Concept Generation: Air Subsystems

Table 1: Air-Based Concept Variants

	Solar Panel	Sensors	Control System	Thermal Insulation	Thermal Storage	Heat Exchanger
1						
2						

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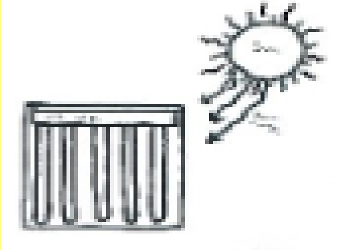
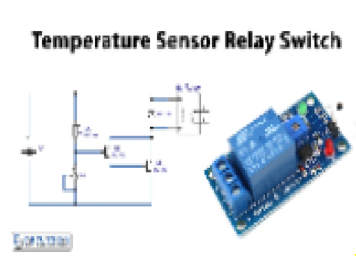
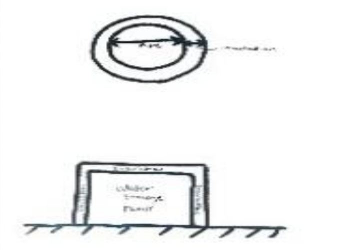
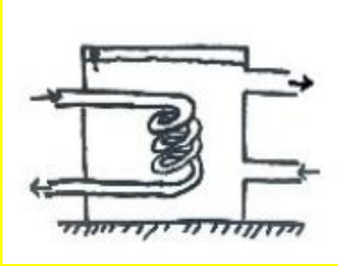
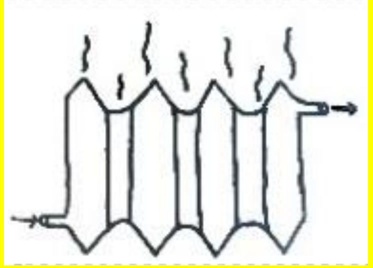
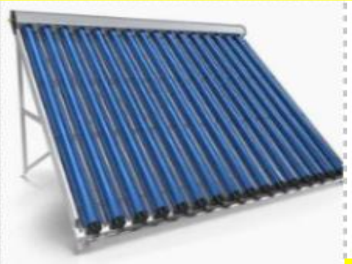
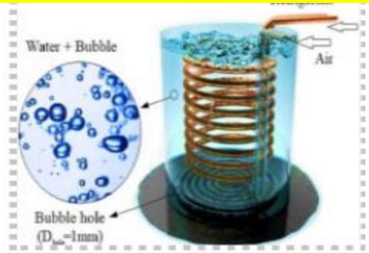
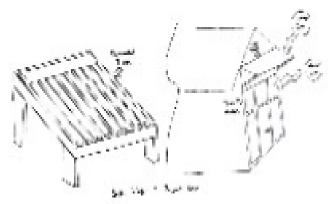
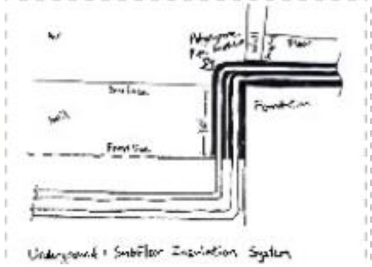
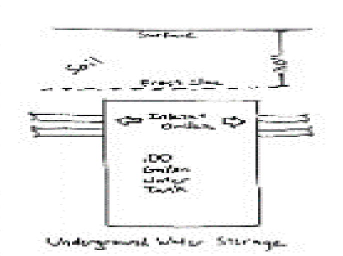
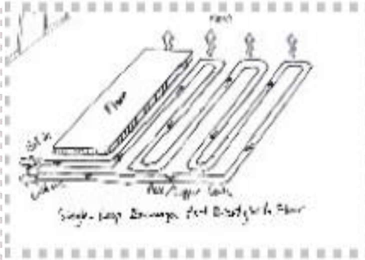
Tyler Hedgecock

Concept Generation: Water Subsystems

Table 2: Water-Based Concept Variants

	Solar Panel	Sensors	Control System	Thermal Insulation	Thermal Storage	Heat Exchanger
1						
2						
3						

Joseph Meza

Concept Advantages and Disadvantages

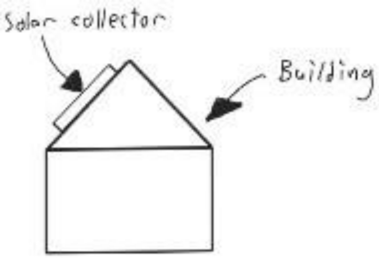


Figure 4: Solar Air collector on top of building

Pros:
- Takes up no space on ground
- Greater sunlight view factor

Cons:
- Difficult winter maintenance
- Mildly invasive

Figure 5: Smart Thermostat

Pros:
- Wifi capabilities built in for remote access

Cons:
- Expensive (minimum $70)
- Gets outside temperature readings from local weather station rather than system readings

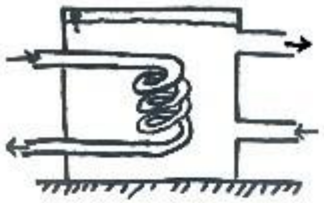


Figure 6: Storage tank with CFWH

Pros:
- High efficiency
- High thermal capacity

Cons:
- Additional cost
- Requires additional insulation
- Requires an additional pump

Figure 7: T-Type Thermocouple

Pros:
- Stable type of thermocouple
- Can be used during colder temperatures

Cons:
- Small voltage output
- Improper installations can lead to errors for the system
- Prone to corrosion

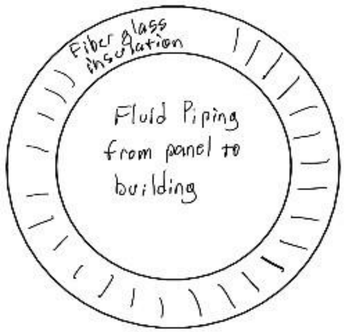


Figure 8: Fiberglass pipe insulation

Pros:
- Protects exposed pipes from winter conditions.
- Mitigates unwanted heat losses

Cons:
- Unable to be used in other system areas that require additional insulation

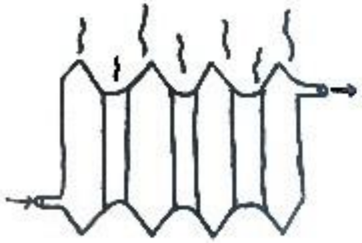


Figure 9: Radiator inside of building

Pros:
- Provides heat for the building throughout the day.

Cons:
- Tends to take up space in a small area within the building
- Takes up electricity and can increase cost.

Calvin Schenkenberger

Concept Generation: Full Assemblies

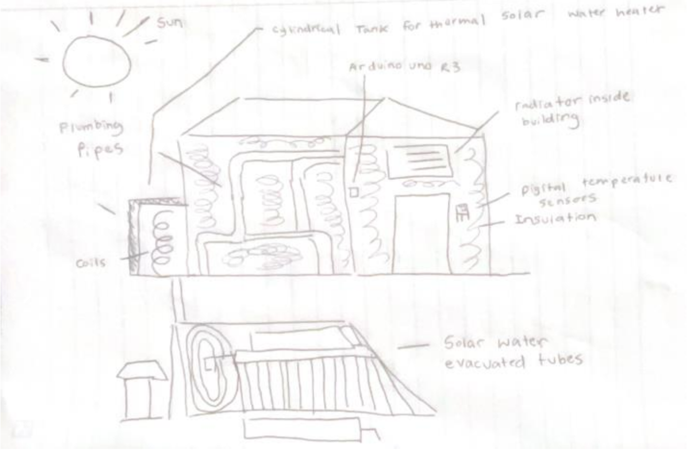


Figure 10: Full Design #1

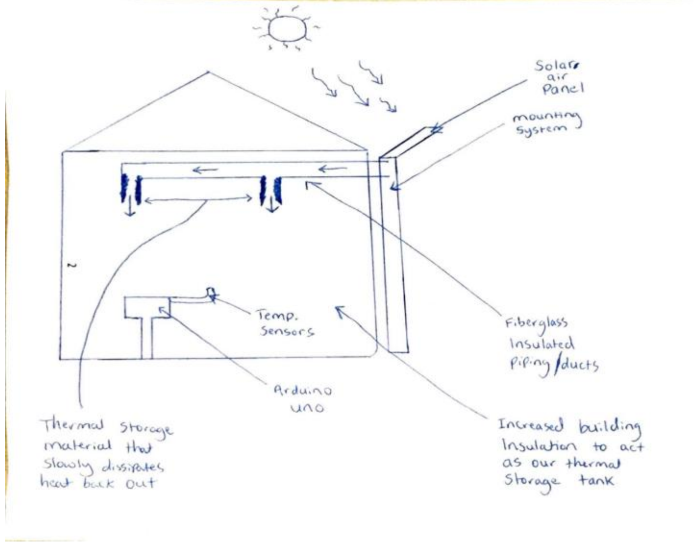


Figure 11: Full Design #4

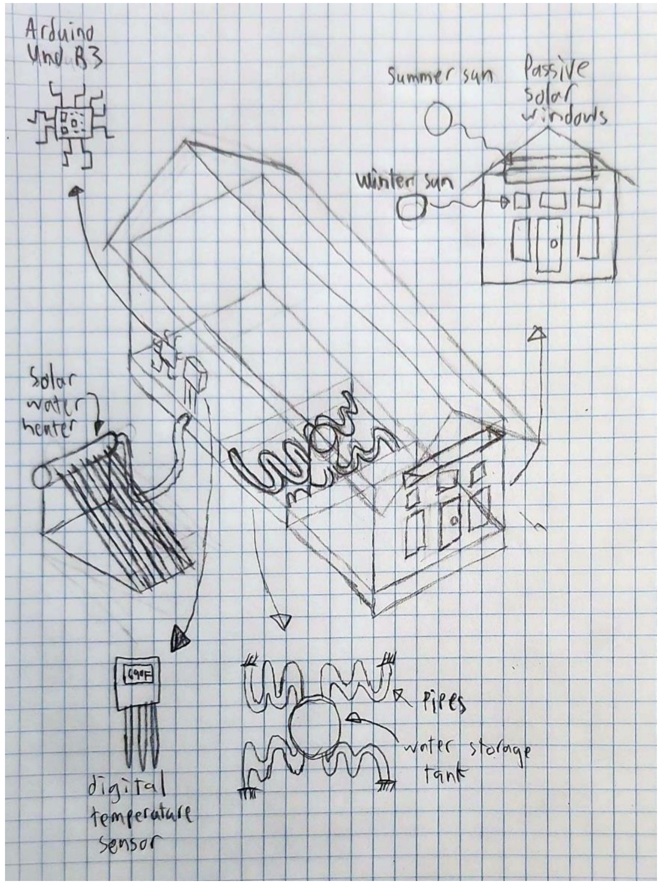


Figure 12: Full Design #3

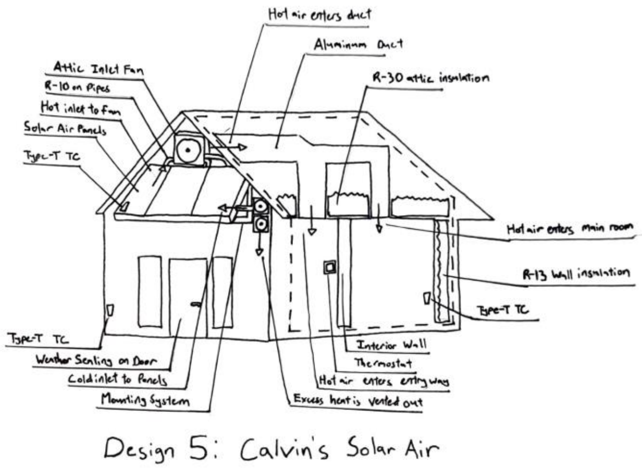


Figure 13: Full Design #5

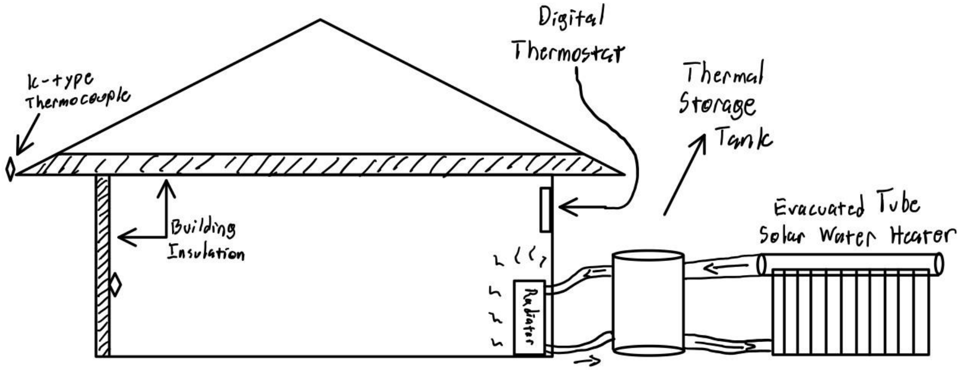


Figure 14: Full Design #2

Jacob Apodaca

Concept Advantages and Disadvantages

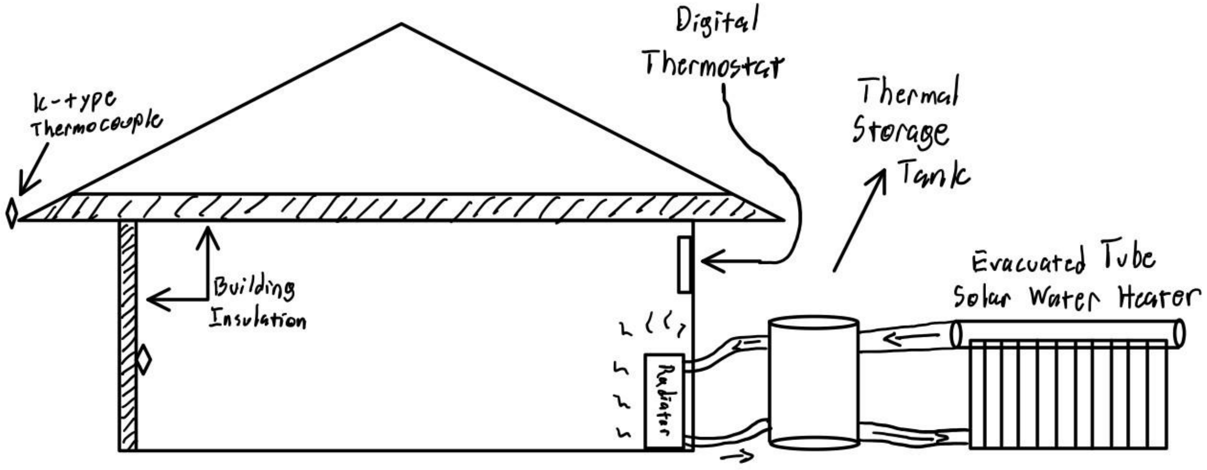


Figure 15: Finalist Design (Water)

Pros:
- Digital thermostat provides wide controls over how and when the system is operating
- Large water storage tank will provide adequate heat storage for overnight use

Cons:
- Harder to disperse the heat without additional internal fans and circulation
- Takes up space
- No additional indoor insulation
- Thermocouple recalibration requirements
- Use of water could lead to unavoidable maintenance

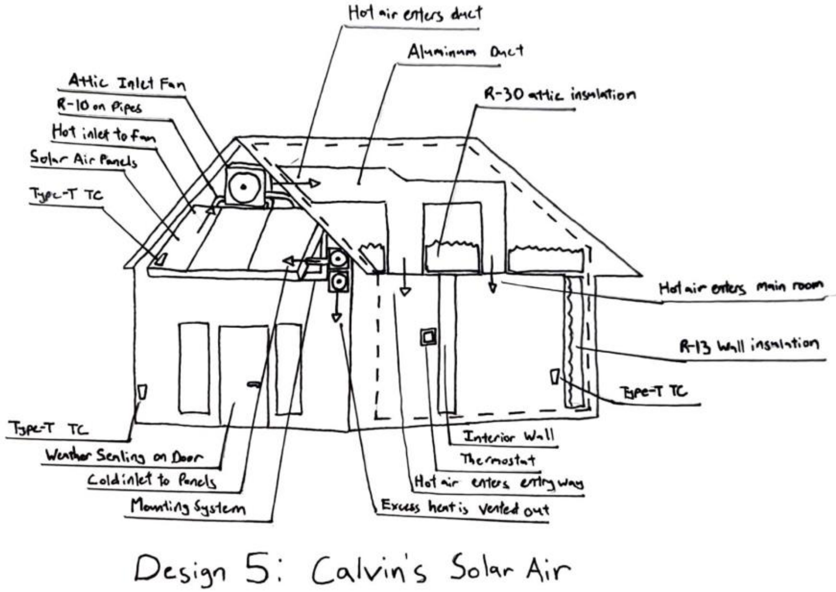


Figure 16: Finalist Design (Air)

Pros:
- Wall insulation can maintain stable temperatures
- Fans can circulate heat
- Temperature can be adjusted through thermostat
- Compact

Cons:
- Mounting system might be heavy
- No backup heat storage

Fluid and Pipe Analysis Literature Review

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Pipe Fluid Flow Analysis

Assumptions:

-Incompressible

-Fully Developed Flow

-S.S. Flow

-1m height of EVC Tubes

-Vol. Flow Rate (Q) provided by manufacturer

EVC Tube Solar Collector CV [26]

$$\dot{m} = Q \cdot \rho = 0.11\ \frac{L}{min} \cdot \frac{1min}{60\ sec} \cdot \frac{1\ m^3}{1000\ L} \cdot 997\ \frac{kg}{m^3} = 0.001827\ \frac{kg}{s}$$

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) = 0.001827\ \frac{kg}{s} \cdot 4.184\ \frac{J}{g \cdot {}^\circ C} \cdot (100^\circ C - 20^\circ C) = 611.53\ W$$

$$u = \frac{Q}{A} = \frac{0.11\ \frac{L}{min} \cdot \frac{1min}{60sec} \cdot \frac{1000000mm^3}{1L}}{1452.2mm^2} = 1.262\ \frac{mm}{s} = 0.0012\ \frac{m}{s}$$

$$Re = \frac{u \cdot D \cdot \rho}{\mu} = \frac{1.262\ \frac{mm}{s} \cdot \frac{0.001m}{1mm} \cdot 43mm \cdot \frac{0.001m}{1mm} \cdot 997\ \frac{kg}{m^3}}{5 \cdot 10^{-4}\ \frac{N \cdot s}{m^2}} = 108.206$$

$$f_{lam} = \frac{64}{Re} = \frac{64}{108.206} = 0.5915$$

$$h_L = f_{lam} \cdot \frac{L}{D} \cdot \frac{u^2}{2g} = 0.5915 \cdot \frac{((2.0066m \cdot 30) + 2.61366m) \cdot 0.0012\ \frac{m}{s}}{43mm \cdot \frac{1m}{1000mm} \cdot 2 \cdot 9.81\ \frac{m}{s^2}} = 0.053m$$

$$h_{Lm} = K \cdot \frac{u^2}{2g} = 4\left(1.5 \cdot \frac{\left(0.0012\ \frac{m}{s}\right)^2}{2 \cdot 9.81\ \frac{m}{s^2}}\right) = 4.128 \cdot 10^{-7}m$$

$$h_{LT} = h_L + h_{Lm} = 0.053m + 4.128 \cdot 10^{-7}m = 0.0530004\ m$$

$$P = \rho \cdot g \cdot h = 997\ \frac{kg}{m^3} \cdot 9.81\ \frac{m}{s^2} \cdot 1.0530004\ m = 10298.9\ Pa$$

Thermal Performance Literature Review

[1] N. Mendes, G. Oliveira, and H. De Araújo, "BUILDING THERMAL PERFORMANCE ANALYSIS BY USING MATLAB/SIMULINK." Accessed: Oct. 14, 2024. [Online]. Available: https://publications.ibpsa.org/proceedings/bs/2001/papers/bs2001_0473_480.pdf

[2] Y. Choi, M. Mae, and H. Bae Kim, "Thermal performance improvement method for air-based solar heating systems," *Solar Energy*, vol. 186, pp. 277–290, Jul. 2019, doi: https://doi.org/10.1016/j.solener.2019.04.061.

[3] C. Ghiaus and I. Hazyuk, "Calculation of optimal thermal load of intermittently heated buildings," *Energy and Buildings*, vol. 42, no. 8, pp. 1248–1258, Aug. 2010, doi: https://doi.org/10.1016/j.enbuild.2010.02.017.

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[10] T. L. Bergman, *Fundamentals of Heat and Mass Transfer, 8th Edition*. New York: John Wiley & Sons, Incorporated, 2016.

Thermal Performance Analysis

Assumptions and Conditions

- ASHRAE Solar Irradiation Data
- Both air and water have inlet temperature of 300 Kelvin (27 Celsius)
- Simulation run during solar noon with minimal cloud cover (maximum solar irradiation)

Fundamental Heat Transfer Equations

$$q_r = A_s \varepsilon \sigma (T_s^4 - T_{surr}^4)$$

$$q_{conv} = hA_s(T_{mo} - T_{mi})$$

$$q_{cond} = kA(T_1 - T_2)$$

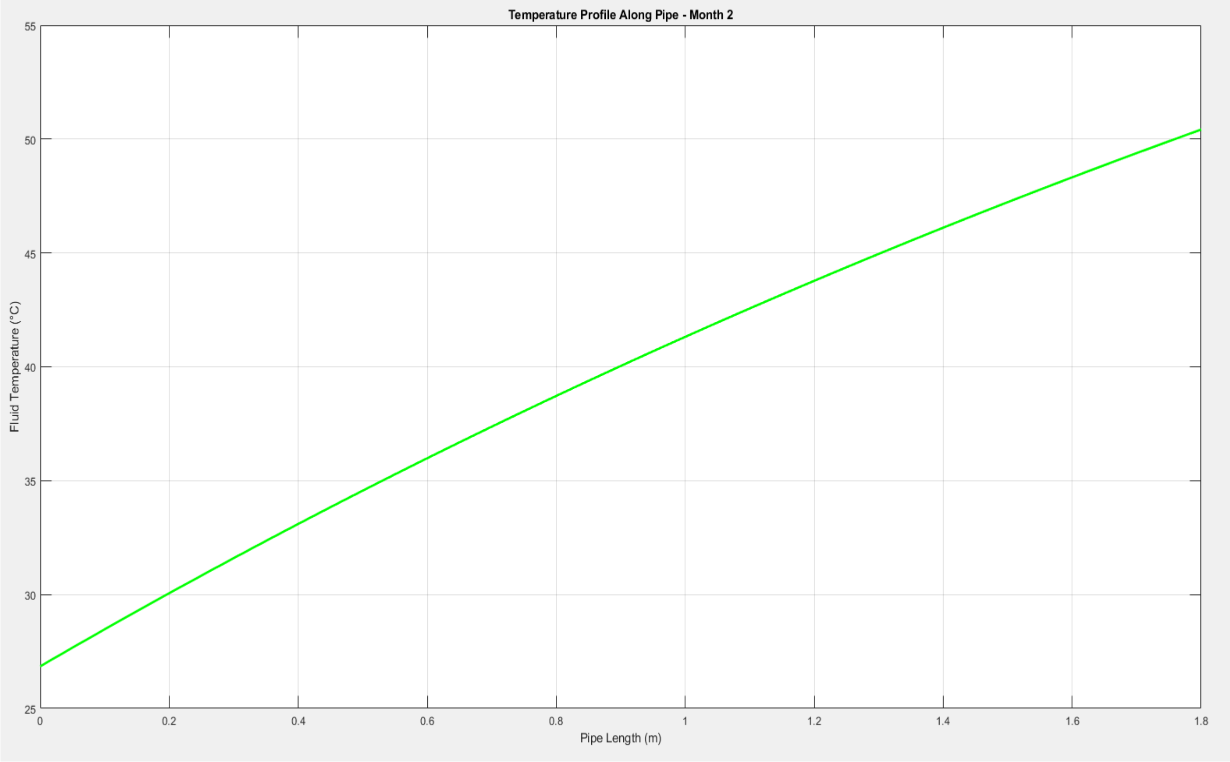
Solution Equations

$$\overline{Nu} = 0.023 * Re^{0.8} * Pr^{0.4}$$

$$T_{out} = T_{in} + \frac{hA_s(T_{inner} - T_{in})}{\dot{m}c_p}$$

Brendan Frazier

Water Performance



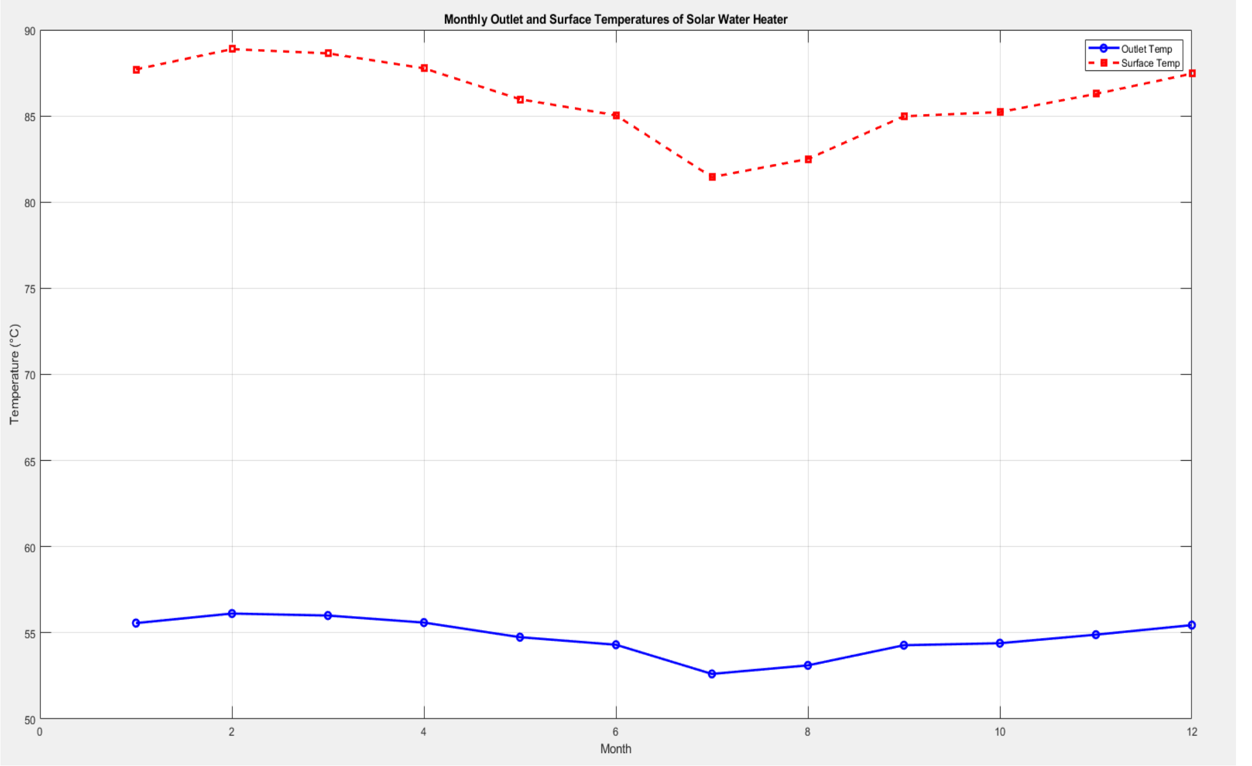


Figure 17: Water Temperature Profile

Figure 18: Water Outlet Temperature

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Air Performance

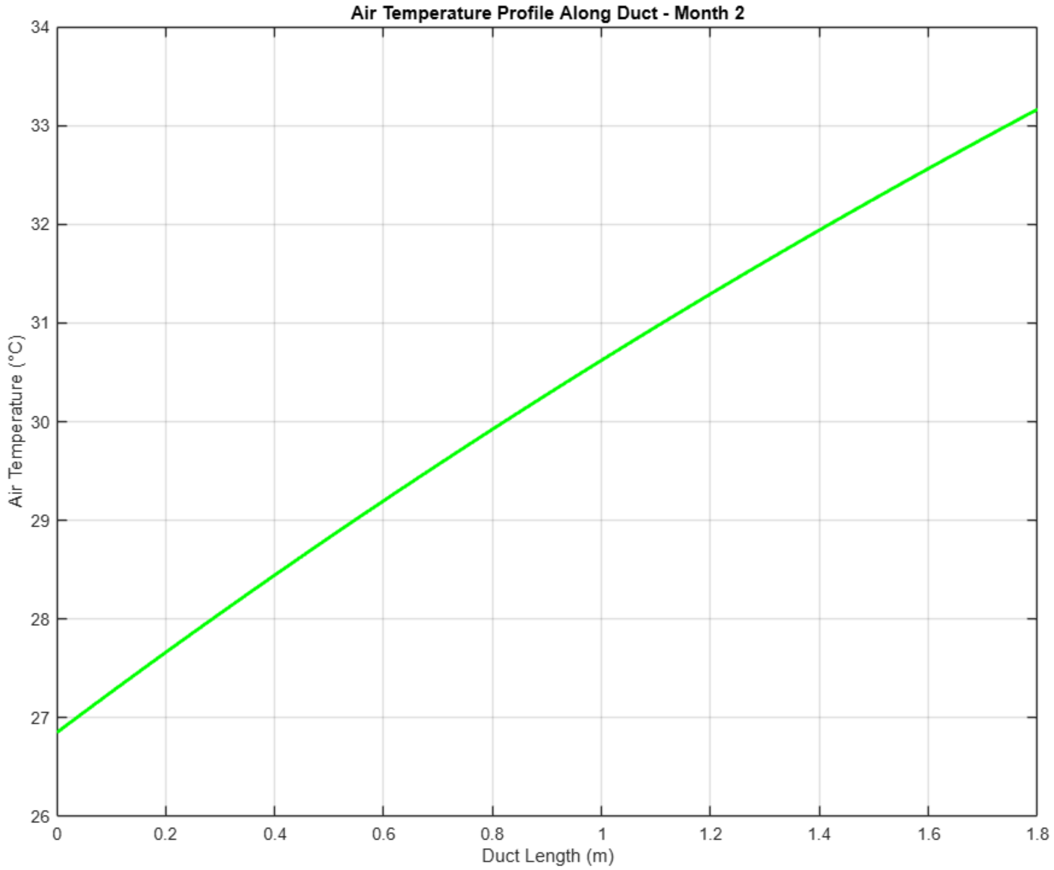

Figure 19: Air Temperature Profile

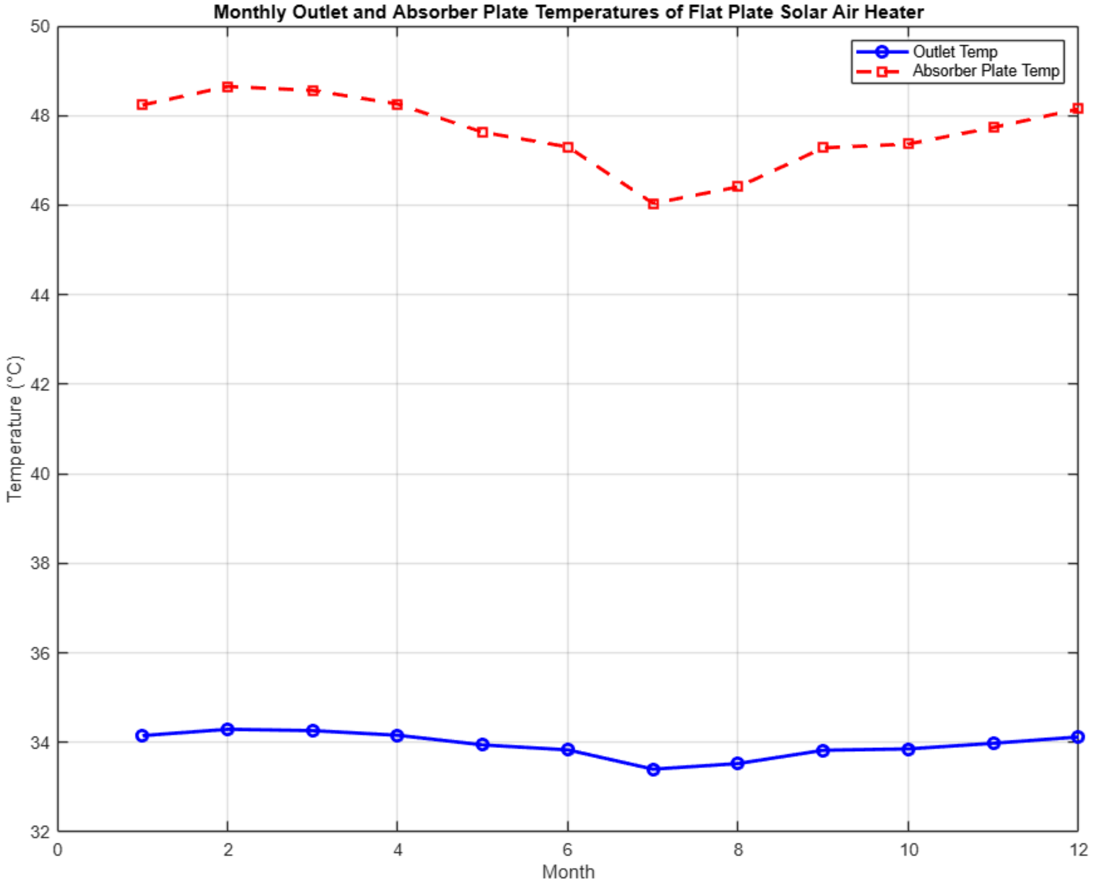

Figure 20: Air Outlet Temperature

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Brendan Frazier

Heat Exchanger Literature Review

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[17] “Learn about hybrid water heaters: Energy-efficient heating.,” Zenith, https://zenithheater.com/hybrid-water-heater/ (accessed Jul. 15, 2025).

Heat Exchanger Analysis

Assumptions:

1. Neglect Kinetic and Potential Energy, KE = 0 and PE = 0 (Fan).
2. No work on the system, W_CV = 0 (Fan and heat exchanger)
3. Ideal gas model, Q_cp = 1.005 kJ/Kg*K (Fan).
4. Steady state (Both devices).
5. No heat transfer, Q_CV = 0 (pump)

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$ [13]

Q_CV = rate of heat transfer (W)
W_CV = amount of work (W)
m_dot = mass flow rate (kg/s)
h = enthalpy (kj/kg)

V = velocity (m/s
g = gravity (9.81 m/s^2)
z = height (m)

Pump Analysis:

$$V_2 = \frac{\dot{m}v}{A} = 0.00134 \text{ m/s}$$

$$\dot{W}_{CV} = \dot{m}\left[(h_1 - h_2) - \left(\frac{V_1^2 - V_2^2}{2}\right) + g(z_1 - z_2)\right]$$

$$= -612.2\text{W}$$

$$T_3 = \frac{\dot{Q}_{CV}}{\dot{m}c_p} + T_2$$

$$= \frac{251.03W}{\left(0.001827\frac{kg}{s} \cdot 4184\ \frac{J}{Kg{\cdot}°C}\right)} + 100°C$$

$$= 232.84°C$$

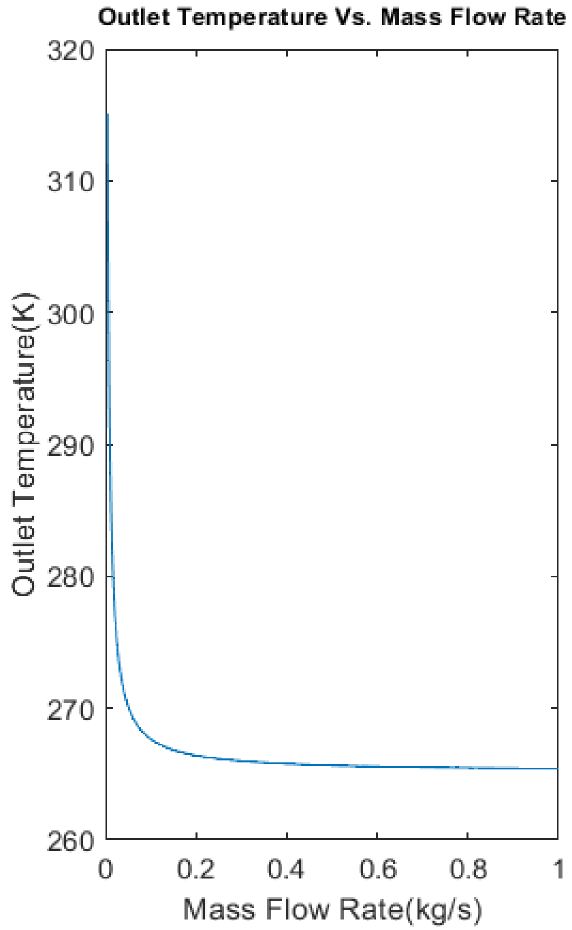

Figure 21: Fan Analysis

Tyler Hedgecock

Heat Load Literature Review

[26] “ThermoPowerTM 30 Tube Evacuated Tube Solar Collector,” SunMaxx Solar - Solar Hot Water Systems, Aug. 22, 2023.
[27] T. L. Bergman, "Chapter 12: Radiation," in Fundamentals of Heat and Mass Transfer, 8th Edition. New York: John Wiley & Sons, Incorporated, 2016.
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Calvin Schenkenberger

Heat Load

Calculate the hourly heat required to maintain the solar shack at or above 40 °F

Methods:
- Manual Measurements and Analysis
- eQUEST Schematic Design Wizard

Assumptions:
- Symmetrical
- Some eQUEST defaults

Equations:
- $A = L * W$
- $\Theta = \tan^{-1}(a/b)$
- $Qs = 1.08 * CFM * \Delta T$ (Sensible heat formula)

Variables:
- Qs = Btu/h
- $CFM = ft^3/m$
- ΔT = °F


Figure 22: Attic Insulation

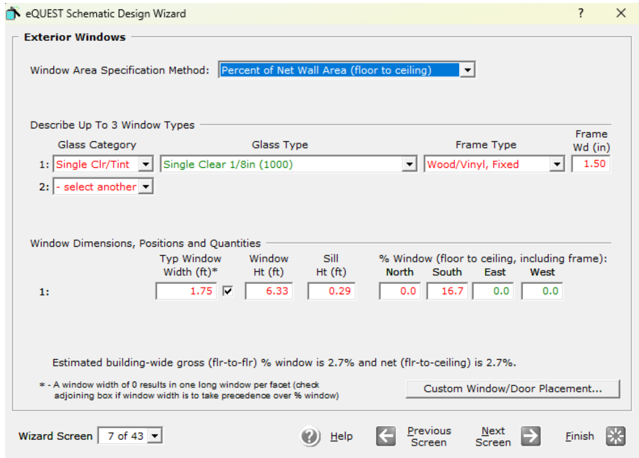

Figure 23: eQUEST Schematic Design Wizard

Figure 24: 25 Watt Light


Figure 25: Measurement

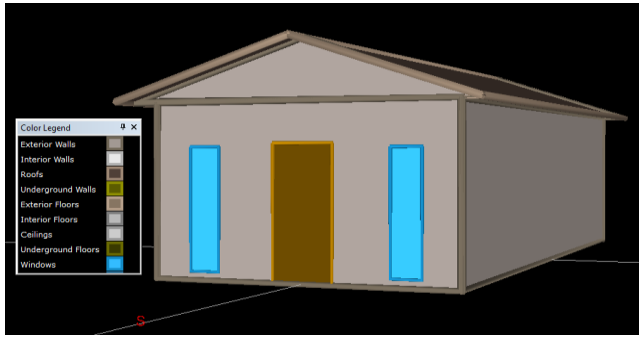

Figure 26: Generated 3D Model

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Calvin Schenkenberger

Heat Load

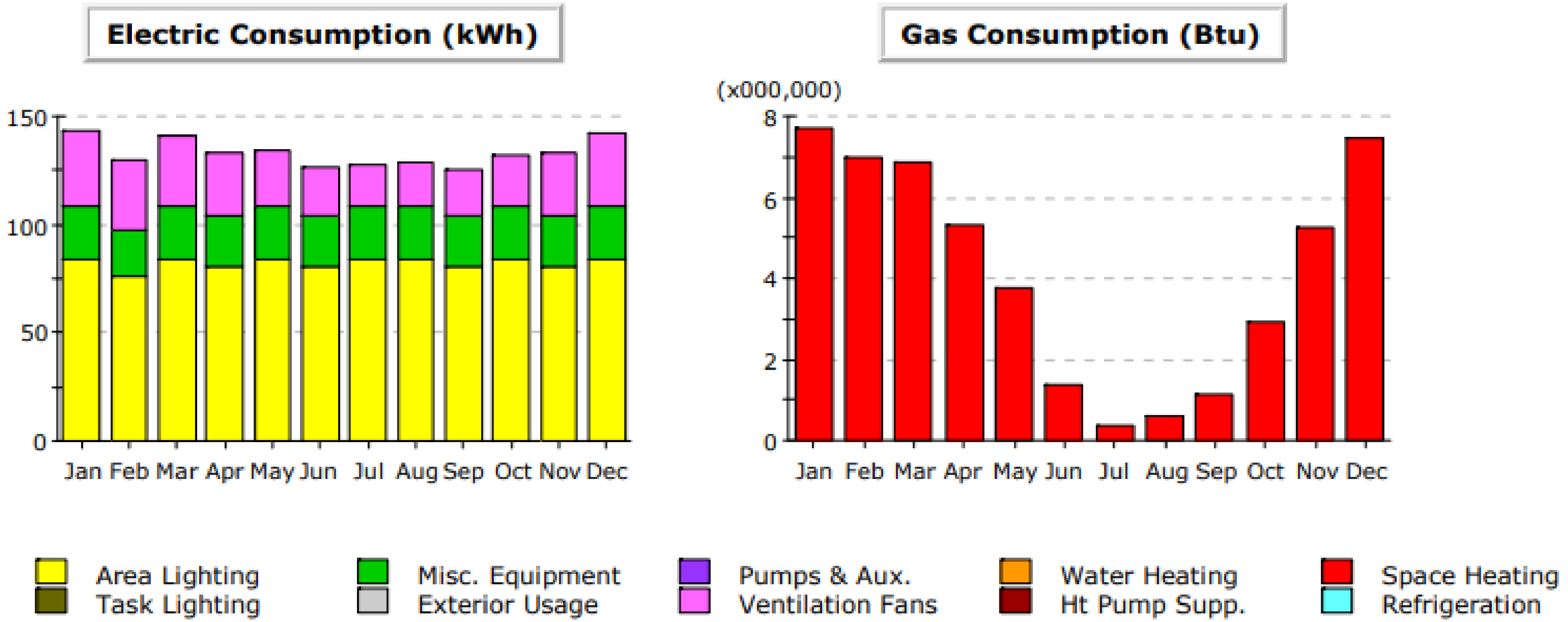

Figure 27: Summary of Energy Consumption

Peak consumption: 7.68MMBtu = **10.32 KBtu/h**

Thermal Battery Literature Review

[13] A. S. Barrak, A. A. Saleh, and Z. H. Naji, “Energy saving of Air Conditioning System by oscillating heat pipe heat recovery using binary fluid,” *2019 4th Scientific International Conference Najaf (SICN)*, pp. 178–183, Apr. 2019. doi:10.1109/sicn47020.2019.9019354

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Thermal Battery

Assumptions:

- The **thermal conductivity (k)** of water is assumed to be **0.6 W/m·K**, representing liquidwater at room temperature.
- The **heat transfer area (A)** is approximated as **0.05 m²**, assuming contact between the heating coil and water.
- The **thermal path thickness (x)** is **0.1 m**, representing the distance heat travels through the water.
- The **initial water temperature** is assumed to be **20°C**, simulating a cold start before heating.
- The **heat source temperature** is set to **80°C**,which is safe and efficient for solar-heated water.
- The **specific heat capacity (cp)** of water is**4186 J/kg·K**, a universal constant for water.
- The **volumetric flow rate** is assumed to be **3 liters per minute**, with a total simulation time of **3600 seconds (1 hour)**.
- 45.2 megajoules 1 hour of heating

Heat loss Analysis

$$Q_{loss} = \frac{k \cdot A \cdot \Delta T}{x}$$

$$Q = m \cdot C_p \cdot \Delta T$$

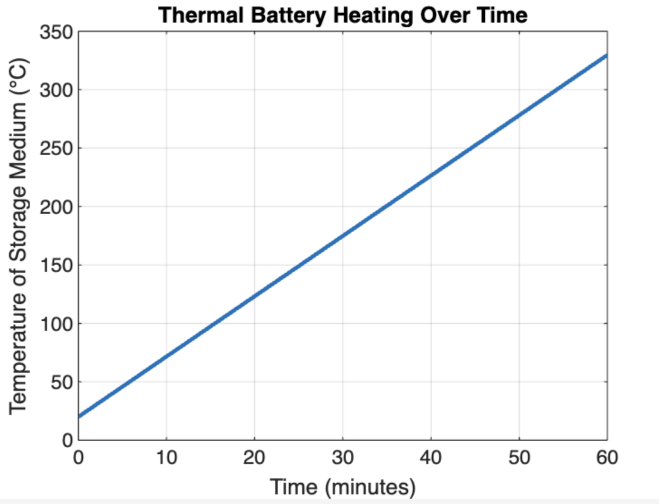

Figure 28 Thermal Battery heating over an hour

Joseph Meza

Summary of Calculations

Table 1: All Engineering Calculations

Variable	Equations	Results	Units		Variable	Equations	Result	Units
Heat Load	eQUEST	10.32	KBtu/h		Mass flow rate	$\dot{m} = Q \cdot \rho$	0.001827	kg/s
Water Out Temp.	$T_{out} = T_{in} + \frac{hA_s(T_{inner} - T_{in})}{\dot{m}c_p}$	~55	Celsius		Vel. of water	$u = \frac{Q}{A}$	1.262	mm/s
Air Out Temp.	$T_{out} = T_{in} + \frac{hA_s(T_{inner} - T_{in})}{\dot{m}c_p}$	~34	Celsius		RE's #	$Re = \frac{u \cdot D \cdot \rho}{\mu}$	108.206	N/A
Radiation Absorption	$G_{abs} = \alpha G cos(90 - \theta)$	152.14	W/m^2		F.F. lam. flow	$f_{lam} = \frac{64}{Re}$	0.5915	N/A
Water Pwr Out	$P = Q * A * \alpha$	11.7	kWh/day		Major hl	$h_L = f_{lam} \cdot \frac{L}{D} \cdot \frac{u^2}{2g}$	0.053	m
Heat Exchanger	$Q = m \cdot C_p \cdot \Delta T$	4.545	MJ		Minor hl	$h_{Lm} = K \cdot \frac{u^2}{2g}$	4.128*10^-7	m
					Total hl	$h_{LT} = h_L + h_{Lm}$	0.053	m
					Pressure	$P = \rho \cdot g \cdot h$	10298.9	Pa

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Jacob Apodaca

Pugh Chart

Table 1: Air and Water Based Full Design Concepts

Criteria	Design 1 (Jacob Air)	Design 2 (Brendan Water)	Design 3 (Tyler water)	Design 4 (Joseph water)	Design 5 (Calvin air)	Water Datum	Air Datum
Energy Stored	s	s	+	-	s	Water Datum	Air Datum
Insulating Power	s	-	+	-	+	Water Datum	Air Datum
Head Pressure	s	+	-	+	s	Water Datum	Air Datum
Exchanger Efficiency	+	s	+	s	-	Water Datum	Air Datum
Life Expectancy	-	+	-	+	+	Water Datum	Air Datum
Cost	+	+	-	+	+	Water Datum	Air Datum
Total	+1	+2	0	+1	+2	Water Datum	Air Datum

Water Datum:
Vacuum Tube Solar Collector Kit [26]

Air Datum:
Artica 4000 Series Solar Air Heater [37]

Brendan Frazier

Design Selection

Table 1: Decision Matrix

Criterion	Weight	Design 2 (Water)	Design 5 (Air)
Energy Stored	25%	21.2	19
Insulating Power	20%	13.2	14.6
Head Pressure	5%	2.6	3.4
Exchanger Efficiency	15%	11.6	11.2
Life Expectancy	20%	15.4	18.2
Cost	15%	9.8	12.8
Total	100%	73.8	79.2

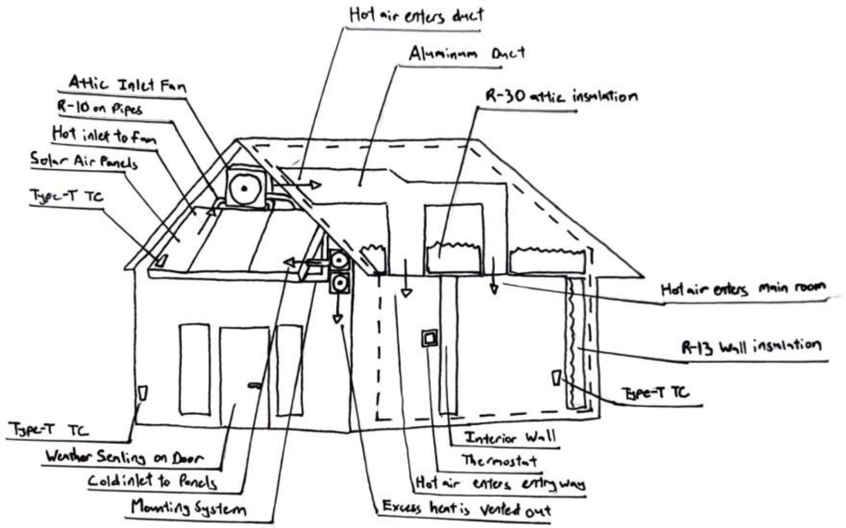


Figure 29: Top Rated Design Concept

Brendan Frazier

CAD Model

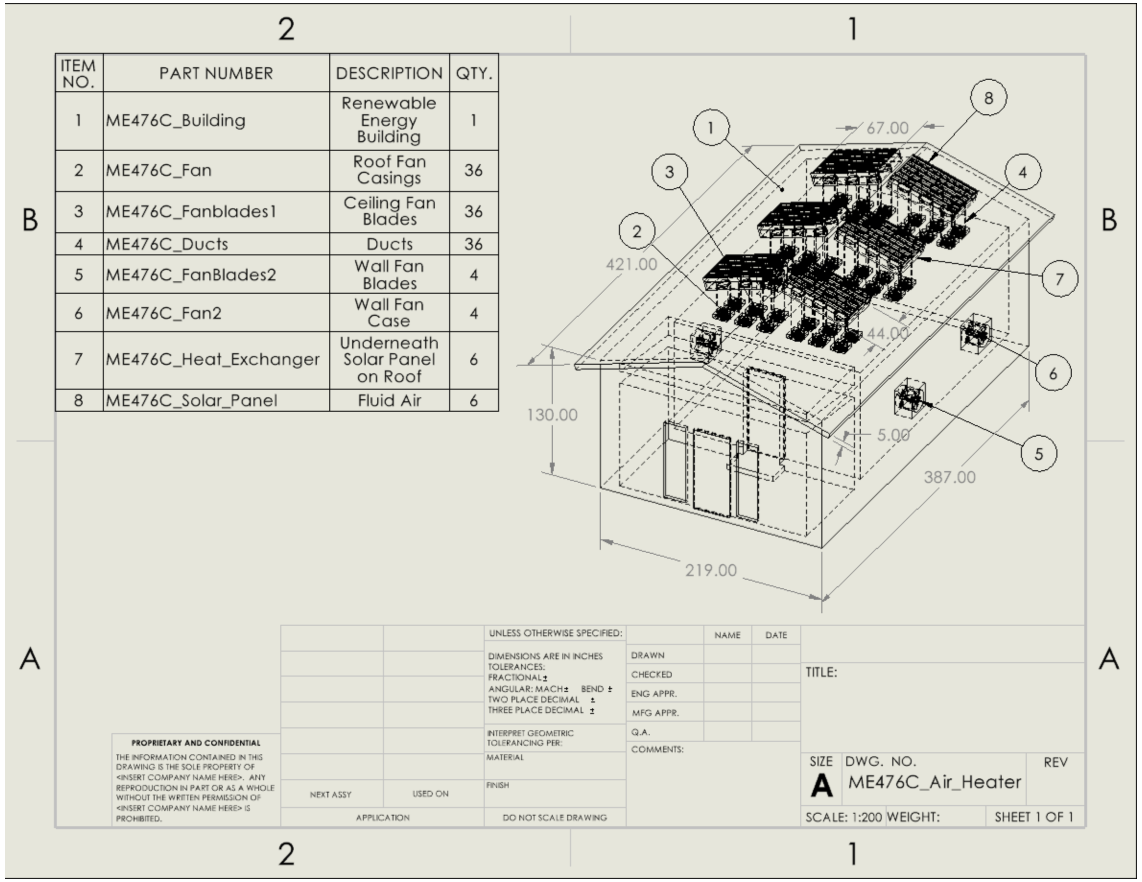


Figure 30: Engineering Drawing of Concept

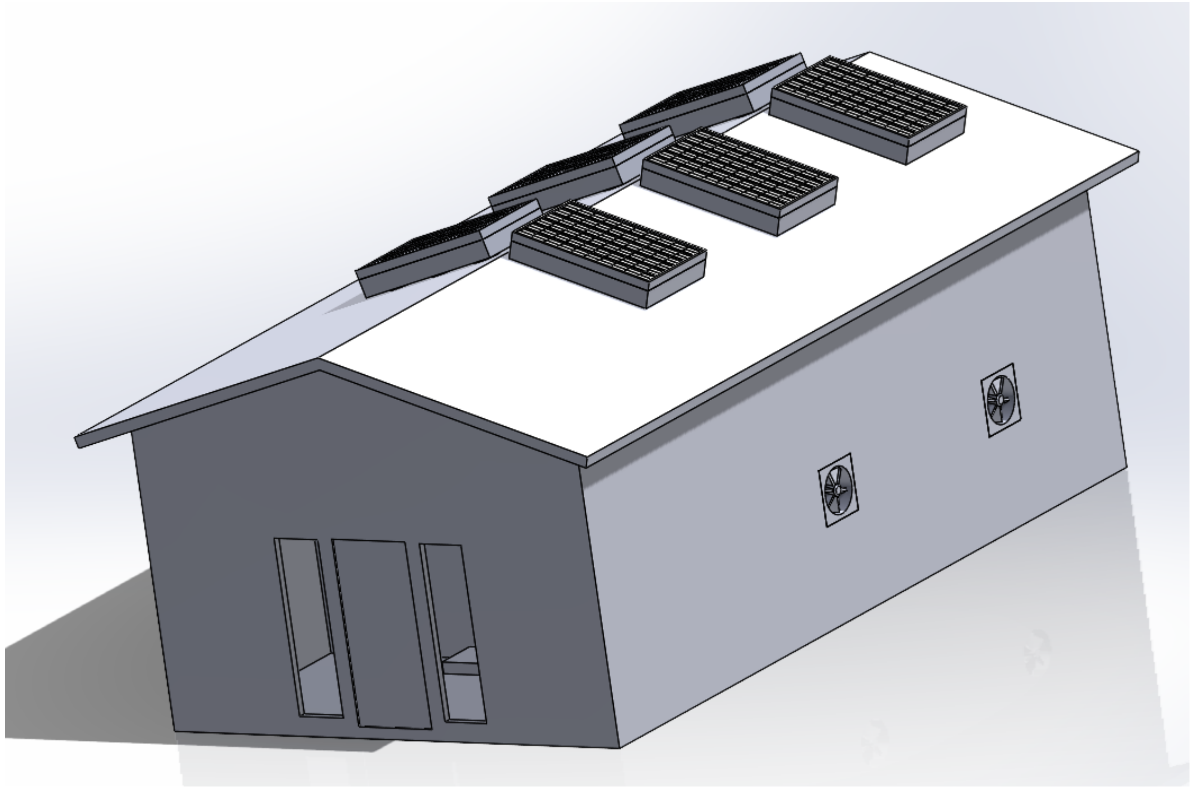
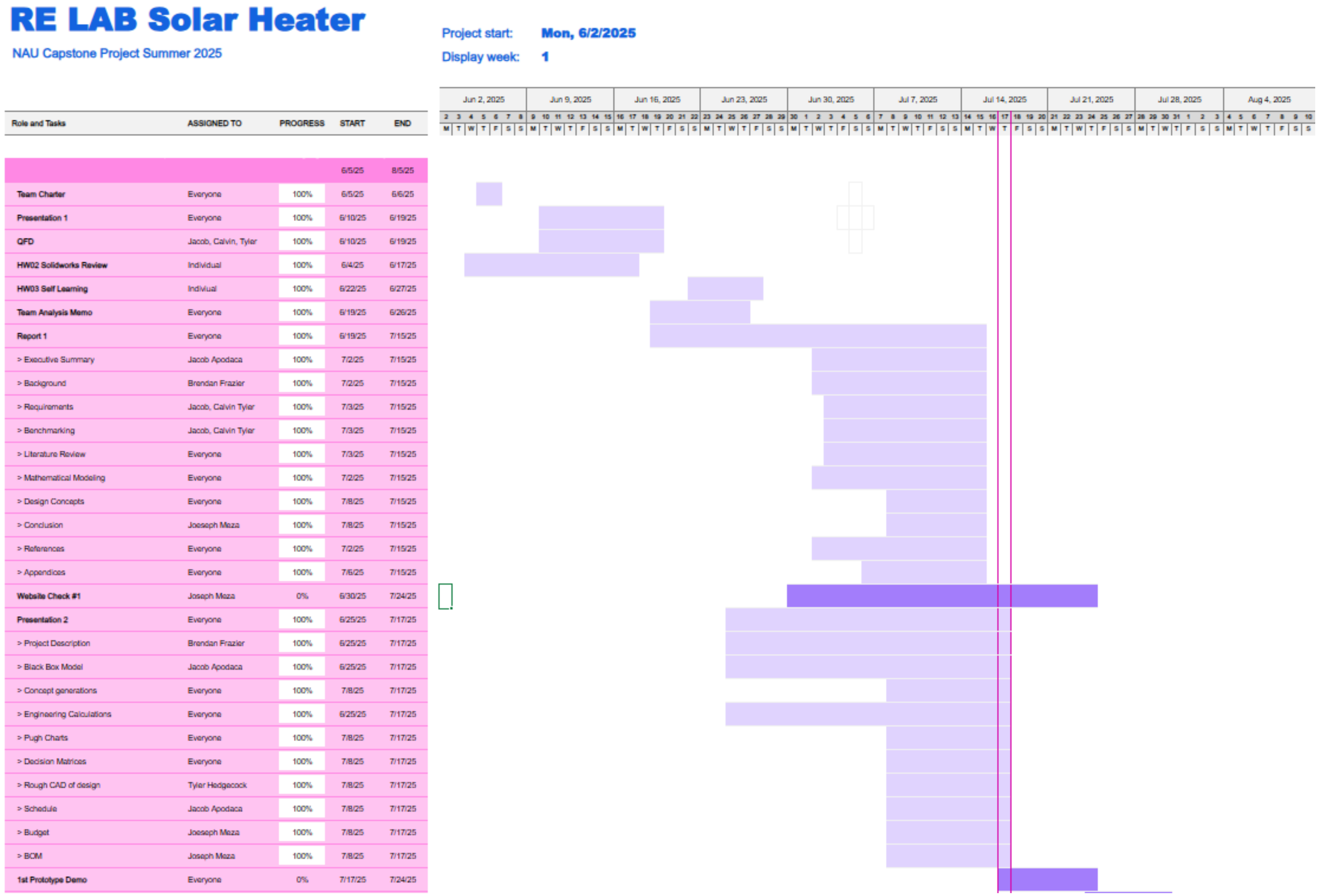


Figure 31: Assembly of Concept

Tyler Hedgecock

WBS: Gantt Chart



RE LAB Solar Heater

NAU Capstone Project Summer 2025

Project start: **Mon, 6/2/2025**

Display week: **1**

Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			6/5/25	8/5/25
Team Charter	Everyone	100%	6/5/25	6/6/25
Presentation 1	Everyone	100%	6/10/25	6/19/25
QFD	Jacob, Calvin, Tyler	100%	6/10/25	6/19/25
HW02 Solidworks Review	Individual	100%	6/4/25	6/17/25
HW03 Self Learning	Indivual	100%	6/22/25	6/27/25
Team Analysis Memo	Everyone	100%	6/19/25	6/26/25
Report 1	Everyone	100%	6/19/25	7/15/25
> Executive Summary	Jacob Apodaca	100%	7/2/25	7/15/25
> Background	Brendan Frazier	100%	7/2/25	7/15/25
> Requirements	Jacob, Calvin Tyler	100%	7/3/25	7/15/25
> Benchmarking	Jacob, Calvin Tyler	100%	7/3/25	7/15/25
> Literature Review	Everyone	100%	7/3/25	7/15/25
> Mathematical Modeling	Everyone	100%	7/2/25	7/15/25
> Design Concepts	Everyone	100%	7/8/25	7/15/25
> Conclusion	Joeseph Meza	100%	7/8/25	7/15/25
> References	Everyone	100%	7/2/25	7/15/25
> Appendices	Everyone	100%	7/6/25	7/15/25
Website Check #1	Joseph Meza	0%	6/30/25	7/24/25
Presentation 2	Everyone	100%	6/25/25	7/17/25
> Project Description	Brendan Frazier	100%	6/25/25	7/17/25
> Black Box Model	Jacob Apodaca	100%	6/25/25	7/17/25
> Concept generations	Everyone	100%	7/8/25	7/17/25
> Engineering Calculations	Everyone	100%	6/25/25	7/17/25
> Pugh Charts	Everyone	100%	7/8/25	7/17/25
> Decision Matrices	Everyone	100%	7/8/25	7/17/25
> Rough CAD of design	Tyler Hedgecock	100%	7/8/25	7/17/25
> Schedule	Jacob Apodaca	100%	7/8/25	7/17/25
> Budget	Joeseph Meza	100%	7/8/25	7/17/25
> BOM	Joseph Meza	100%	7/8/25	7/17/25
1st Prototype Demo	Everyone	0%	7/17/25	7/24/25

Figure 32: Gantt Chart

Project Budget and Overview

Total Budget Available: $1,000 total

- $500 provided by the Renewable Energy Lab
- $500 required to be raised by the team to cover unexpected purchases and extra materials

Anticipated Expenses

- **Solar Collector Materials** (pipes, absorber plate, glazing): **$300**
- **Thermal Storage Tank / Insulated Water Tank**: **$250**
- **Pump, Valves, and Circulation Hardware**: **$200**
- **Mounting Frame and Structural Hardware for Roof**: **$150**
- **Insulation and Sealant Materials**: **$120**
- **Control Unit, Sensors, and Temperature Gauges**: **$100**
- **Miscellaneous and Contingency Funds**: **$180**

- **Total Estimated Expenses: ~ 1300**

Joseph Meza

Fundraising

- **Business Sponsorship:** Approach local hardware or plumbing supply stores in Flagstaff for material donations or small sponsorships.
- **Leads:** Grand Canyon Brewery owner looking to sign a write off
- Raised 63$

Figure 33: Fundraising Flyer at GCB

Joseph Meza

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Thank You
Questions?