ME 486C Capstone Project

Fall 2025

Final Testing Results

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QFD

Quality Function Deployment

Project title: RE Lab Solar Heater
Project leader: Brendan Frazier
Date: 10/27/2025

Energy Stored	Efficient Insulation	Thermostat	[redacted]	Flow Rate	Heat exchanger	Life expectancy	Cost
0							
0	0						
+	0	-					
+	+	-	[redacted]				
+	+	0	[redacted]	0			
+	+	0	[redacted]	0	0		
+	+	0	[redacted]	+	0	0	
+	+	0	[redacted]	+	+	0	-

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

5	3	1	0
Strong	Moderate	Weak	None

1: low, 5: high — Competitive evaluation (1: low, 5: high)

	Customer importance rating	Engineering Requirements (How's) → / Customer Requirements - (What's) ↓	Energy Stored	Efficient Insulation	Thermostat	[redacted]	Flow Rate	Heat exchanger	Life expectancy	Cost	Mounting system	Weighted Score	Solar Water Rating	Solar Air Rating	Vacuum Tube Solar Collector Kit Rating	4000 Series Artica Solar Air Heater	Hybrid Solar rating
		Desired direction of improvement (↑,0,↓)	↑	↑	↓	[redacted]	↑	↑	↑	↓	↓						
1	5	System must reduce heating load by 30% during worst case months (compared to baseline method)	5	5	0	[redacted]	4	5	0	0	0	50	4	3	5	4	5
2	5	System must operate in winter conditions	5	5	0	[redacted]	5	3	1	0	3	55	3	3	5	4	5
3	5	System must use RE solar as primary input	5	5	0	[redacted]	4	3	0	0	5	65	5	5	5	5	3
4	3	Installation must not require major mods to building	0	1	0	[redacted]	2	0	0	3	5	24	2	3	3	4	5
5	5	System must be safe and comply with codes	3	3	3	[redacted]	3	3	3	0	5	70	5	5	4	5	5
6	3	System must have minimal maintenance	1	1	1	[redacted]	2	5	5	1	4	36	3	4	4	5	5
7	3	Payback period must be under 10 yrs	5	5	3	[redacted]	2	5	3	5	4	66	5	5	1	3	4
8	1	System must have ability to include temp. and performance monitoring and visual indicator of operation status	3	0	5	[redacted]	4	3	0	0	1	12	5	5	4	4	5
9	3	System must not overheat or cause interior overheating	5	0	5	[redacted]	4	3	0	0	2	45	5	5	4	4	5
		Technical importance score	126	111	47	[redacted]	114	112	44	27	111	818	37	38	35	38	42
		Importance %	15%	14%	6%	[redacted]	14%	14%	5%	3%	14%	100%					
		Units	kWh	R Value	Watts	[redacted]	m^3/sec	Joules	Years	$	Kilograms						
		Target	30 kWh	10 R-Value	10 W	[redacted]	0.1 m^3/s	5 MJ	10 yrs	$3,000	20 kg						
		Priorities rank	1	5	7	[redacted]	3	4	8	9	6						

Figure 1: QFD

Calvin Schenkenberger

DESIGN REQUIREMENTS

Customer Requirements

1. Reduce Heat Load by 30%
2. Function in Winter
3. Utilize Only Renewable Energy
4. No Significant Modifications
5. Comply with all Relevant Codes (ASHRAE, Electrical, Plumbing, and Solar Standards)
6. Minimal Maintenance
7. 10 Year Payback Period
8. Visual Indicators of Status
9. Integrated Monitoring System
10. Cannot Overheat Building

Engineering Requirements

1. Energy Storage
2. Sufficient Insulation
3. Thermostat Control
4. Flow Rate
5. Life Expectancy
6. Cost
7. Mounting Weight

Jacob Apodaca

Testing Summary

Table 1: Testing Plan Summary

Experiment	Relevant DRs	Testing Equipment Needed	Other Resources
EX1 - Output Temperature	CR1, CR2, CR3, CR8, CR9, CR10, ER1, ER2, ER3	HW Anemometer	A good sunny day
EX2 - Flow Rate	CR1, ER1, ER4	Vane / HW Anemometer	NA
EX3 - Wind Loading	ER5, ER6, ER7, CR5	NA	Flagstaff airport weather data
EX4 – Voltage Drop	CR5, CR10, ER3, ER6	Multimeter	NA
EX5 – Air Leak Test	ER6, CR9, ER2	Fog Machine	NA
EX6 – Water Leak Test	CR6, ER7, ER5	NA	A rainy day
EX7 – Weather Data Collection	ER5, ER7	NA	NREL and NWS weather data
EX8 – Performance Test	CR1, CR2, CR7, CR8, CR10, ER5, ER6	HW Anemometer and RTD	EX1 temperature data

Tyler Hedgecock

Experiment 1 – Temperature Test

Summary: Determine any major heat losses through the ducting system. This can occur through leaks in the duct (checked in EX5) and with poor or lacking insulation. This test requires temperature measurements to be taken every 30 minutes with a record of the solar irradiation at the time of recording. These temperature measurements are taken at each of the 3 vents.

Procedure:
- Take temperature data at the outlet using a hotwire anemometer
- Temperature data collection done over constant interval
- Postprocessing observation of any major heat losses

Results:
- Max Irradiation: 522 W/m^2
- Vent 1 Max Temp: 89.0°F
- Vent 2 Max Temp: 109.4°F
- Vent 3 Max Temp: 104.5°F
  - 4.5% drop in temp from vent 2 to 3

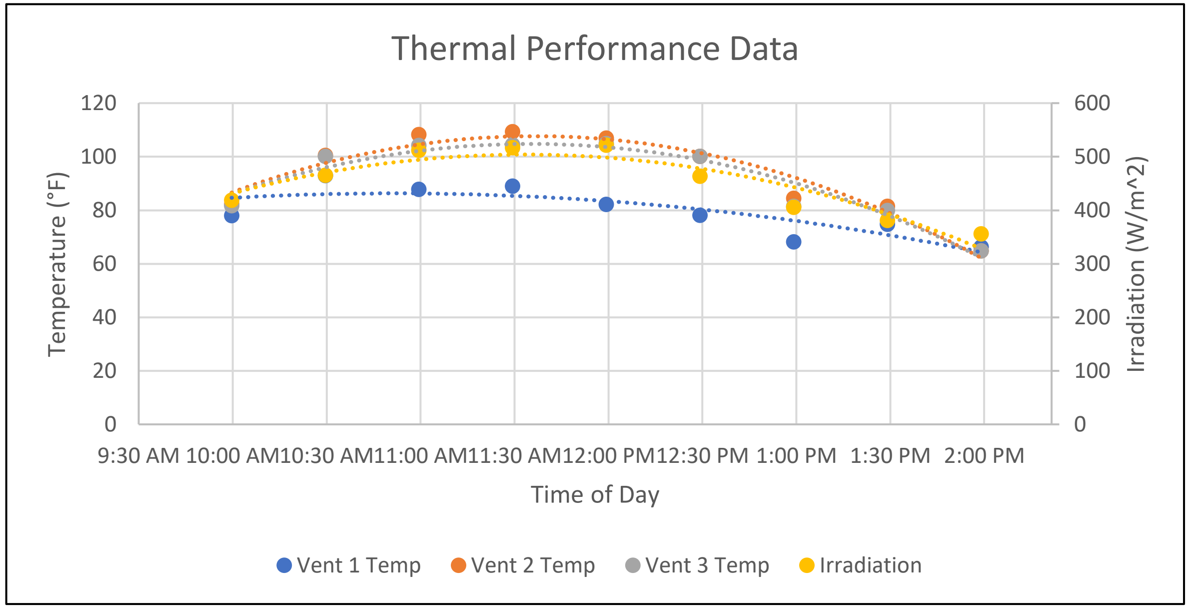

Figure 2: Thermal Performance Plot

Brendan Frazier

Experiment 1 – Temperature Test

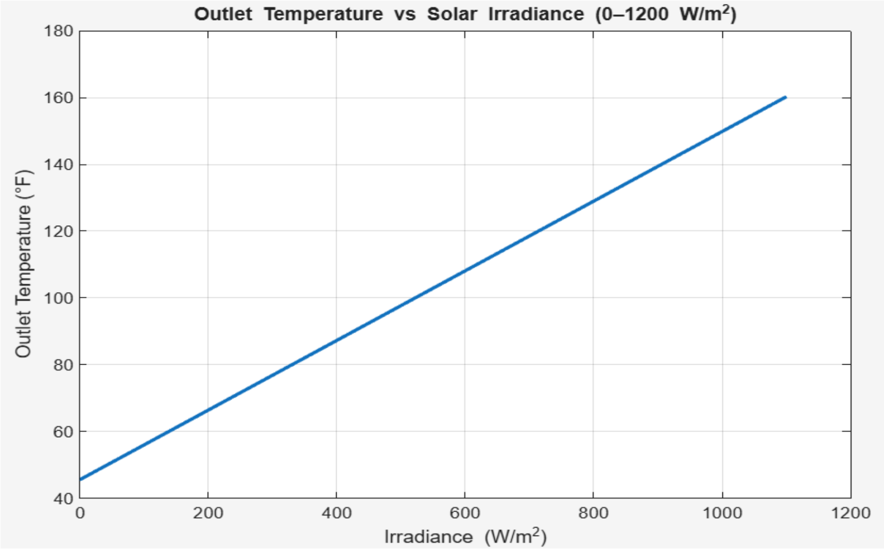

Figure 3: Output Temp Based on Irradiation

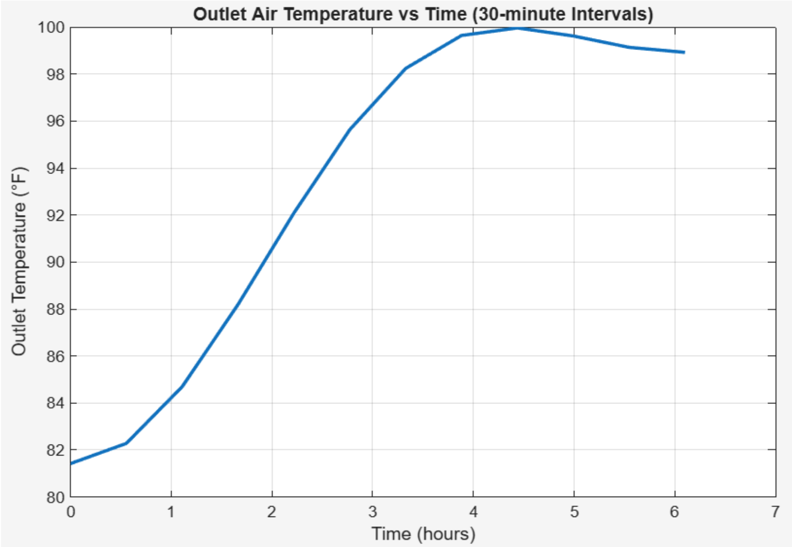

Figure 4: Output Temp Based on Time of Day

MATLAB Simulation (Temperature)

- Figure 3 presents an output temperature of 100.4°F at 522 W/m^2 (8.2% difference from testing)
- Figure 4 shows temperature across the solar window of the RE lab with a peak irradiation of 522 W/m^2. Max output temperature of 100°F (8.6% difference from testing)

Experiment 2 – Flow Rate Test

Summary: Due to the ductwork system, it is likely that the volumetric flow rate will drop before reaching the output vents. To find the volumetric flow rate an anemometer will be used at all inputs and outputs. This test also verifies if the fans have a flow rate near the same value as stated in the spec. sheet which is 190 CFM. This test will also allow us to calculate the supplied heat load using the sensible heat formula.

Procedure:
- Hold anemometer at inputs and outputs
- Record data
- Calculate flow rate using speed and cross-sectional area of the ducts

Results:
- Front Room Input ≈ 115 CFM
- Main Room Input ≈ 143.5 CFM
- Vent 1 output (front room) ≈ 160.5 CFM
- Vent 2 output (main room) ≈ 53 CFM
- Vent 3 output (main room) ≈ 100.5 CFM

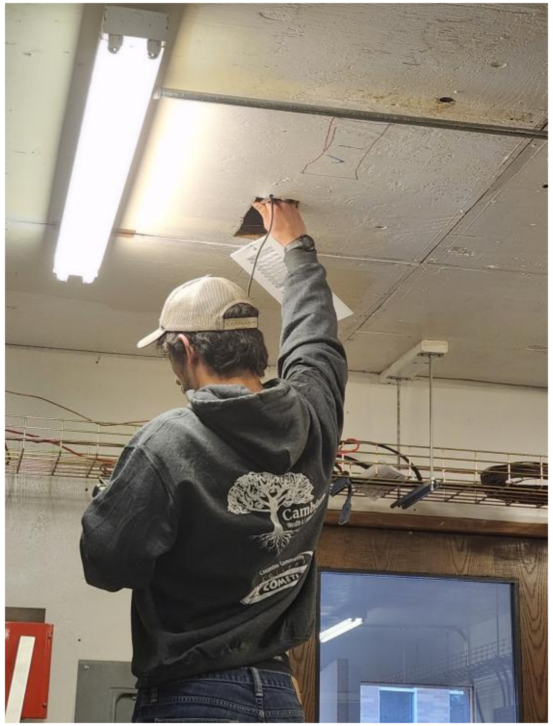

Figure 5: Vent 2 output flow rate test

Experiment 3 – Wind Loading

Table 2.2 Values (approximate) of surface roughness length for various types of terrain

Terrain description	z_0 (mm)
Very smooth, ice or mud	0.01
Calm open sea	0.20
Blown sea	0.50
Snow surface	3.00
Lawn grass	8.00
Rough pasture	10.00
Fallow field	30.00
Crops	50.00
Few trees	100.00
Many trees, hedges, few buildings	250.00
Forest and woodlands	500.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

Figure 6: Surface Roughness Approximation

Correlation Dependent on Surface Roughness
The following form for this type of correlation was proposed by Counihan (1975):

$$\alpha = 0.096 \log_{10} z_0 + 0.016(\log_{10} z_0)^2 + 0.24 \qquad (2.38)$$

Figure 7: Surface Roughness Correlation

Summary: Need a 30 Year Wind analysis to prove reliability of mounting system under possible wind loads

Procedure:

- Collect windspeed data from NCEI
- Sort by maximums for each year
- Find Surface Roughness Correlation
- Solve for windspeed at RE Lab using Power Law
- Find Dynamic Pressure
- Solve for Drag and Lift
- Find Maximum Resultant Wind Load

2.3.4.2 Power Law Profile

The power law represents a simple model for the vertical wind speed profile. Its basic form is:

$$\frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^{\alpha} \qquad (2.36)$$

Figure 8: Power Law

Calvin Schenkenberger

Experiment 3 – Wind Loading

Assumptions:
a = 0.56
z = 15 ft
zr = 33 ft
ρ = 0.0019 slugs/ft^3
Sdrag = 18.35 sqft
Slift = 26.21 sqft
C = 0.767

Maximum Allowable Force on Panels: 1450 lbs

Results:
Maximum Force on Panels: 992 lbs

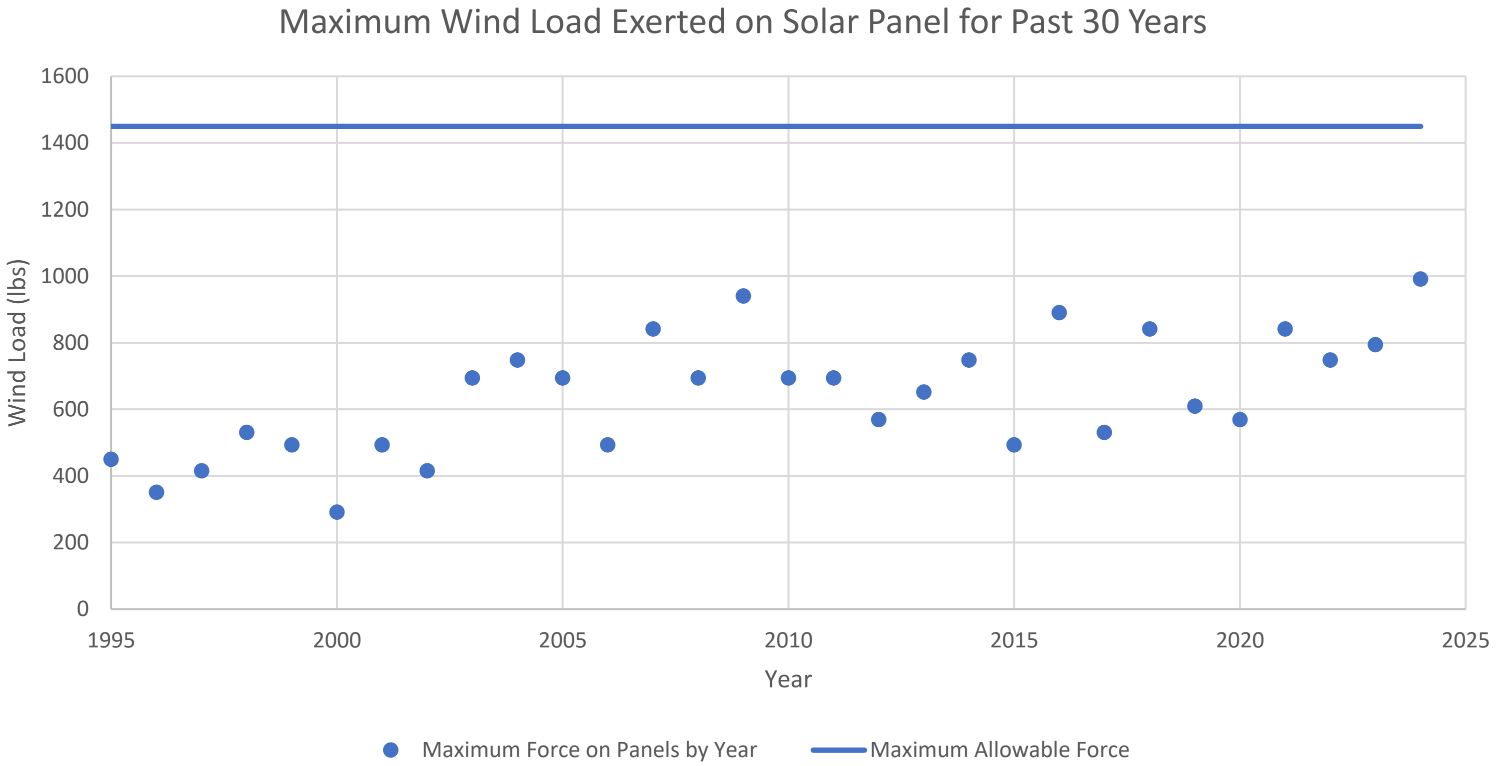

Figure 8: Wind Loading Chart

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Experiment 4 – Voltage Drop Test

Summary: Voltage drop occurs due to wire gauge size and length of wires. To determine the volt drop from the power supply (i.e. batteries) to the fans we will measure the voltage at different points along the electrical system to find the percentage of voltage drop which should be around 2%.

Procedure:

- Obtain multimeter
- Measure voltage at batteries
- Measure voltage at first j-box
- Measure voltage at second j-box (in attic)
- Measure voltage at fans

Results:

- Voltage at batteries **12.84V**
- Voltage at j-box **12.72V**
- Voltage at attic j-box **12.57V**
- Voltage at fans **12.39V**
- Percent voltage drop **≈3%**

Figure 9: Multimeter Voltage Test at First J-Box

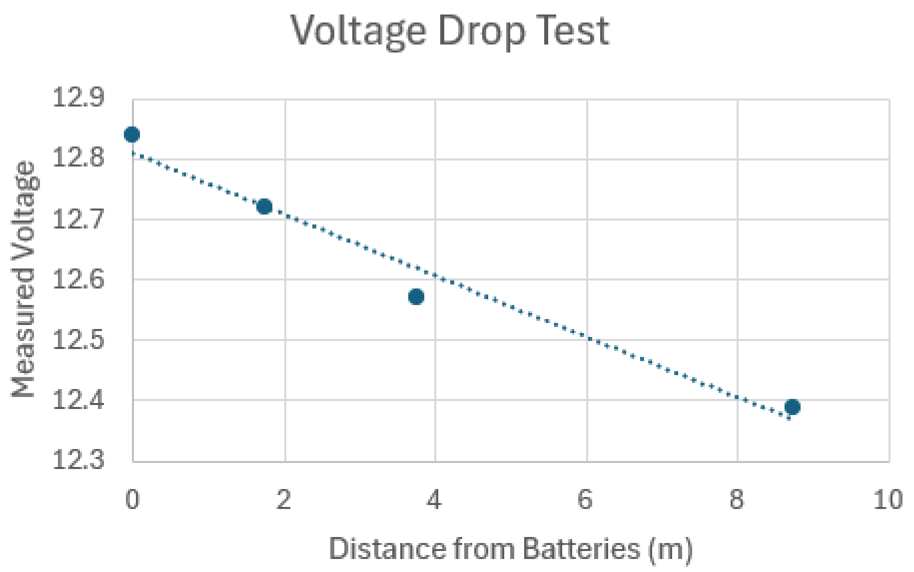

Figure 10: Voltage Drop Plot

Jacob Apodaca

Experiment 5 – Air Leakage Test

Summary: The ducting system of the Solar Air Heater was tested for air leaks by pushing smoke through the ducts using a fog machine and visually checking all seams, joints, screw holes, and transitions for escaping smoke.

Procedure:

- Connect smoke machine to the main inlet duct
- Inspect duct joints, seams, bends, roof penetrations, and connection points
- Record any visible smoke escaping the system
- Re-seal or repair any identified leak locations

Results:

- Smoke traveled through the system smoothly with no major leakage observed
- Minor leakage was detected at a few screw holes which were subsequently marked for resealing
- Overall duct system demonstrated strong integrity with no significant airflow losses

Figure 11: Fog to Input Duct

Figure 12: Fog to output Duct

Figure 13: Air Duct Sealant

Joseph Meza

Experiment 6 – Water Leak Test

Summary: During a rainy day all points of possible leakage will be monitored for water leakage. This includes lag screws mounting points, boot flashing, cover plates on panels, and any other point of leakage. This experiment is primarily visually confirmed with the only calculation being the volume of water across workspace.

Procedure:

- Every 30 minutes conduct visual inspection of attic
- After storm check solar panels for internal water
- Calculate total volume of water during storm

Results:

- During storm, no water leakage observed in attic
- Total rain fall resulted in 52.5 gallons over 18 hours

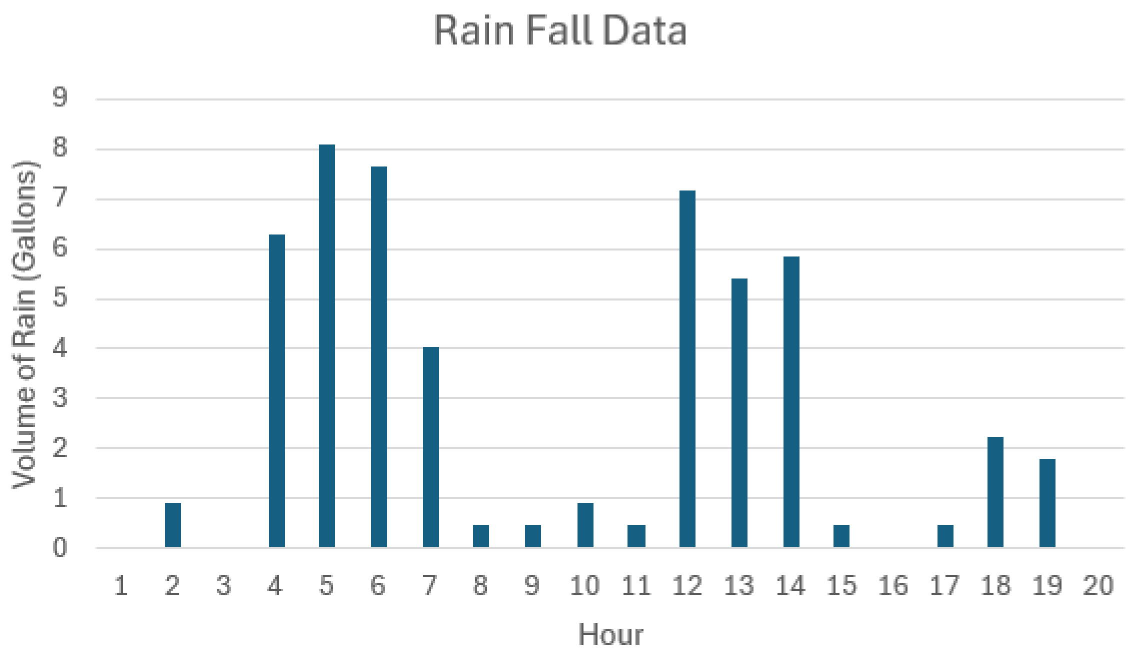

Figure 14: Rain Fall Data Plot

Brendan Frazier

Experiment 7 – Weather Data Collection

Summary: Analyze annual weather patterns in Flagstaff, AZ. Measuring tools are not necessary, however data from the NREL and NWS websites will be needed. Variables that can be ignored are heat losses due to conduction and non-uniform snow weight.

Procedure:

- Annual solar irradiance, precipitation, and snow fall data from NREL and NWS websites.
- Calculate the solar energy absorbed by the solar panels, load for snow fall, and volume of rain in gallons.
- Plot all three values on histograms.

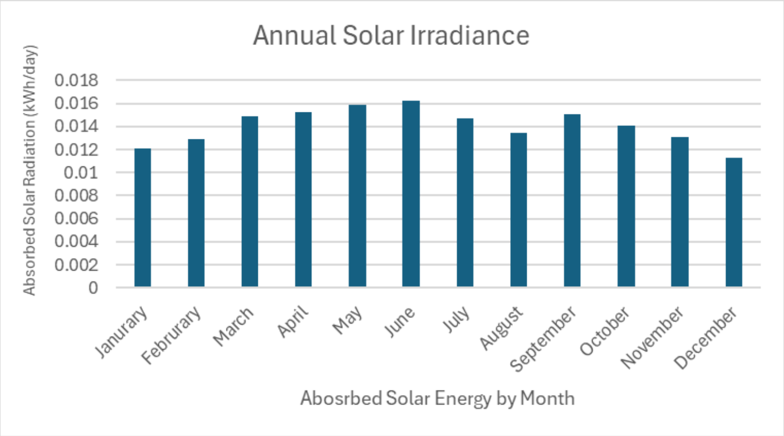

Figure 15: Annual Solar Irradiation

Results:

- <u>Precipitation:</u>
  - Maximum: 399.787 gallons (July 2013)
  - Minimum: 76.302 gallons (June 2015)
- <u>Snow Fall:</u>
  - Maximum: 2941.125 lb (February 2019)
  - Minimum: 0.4125 lb (September 2013)
- <u>Solar Irradiance:</u>
  - Maximum: 0.016241 kWh/day (June)
  - Minimum: 0.011289 kwh/day (December)

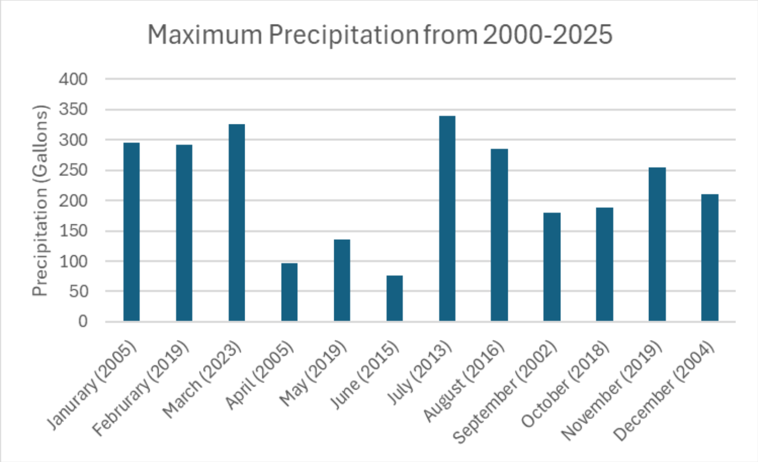

Figure 16: Annual Precipitation

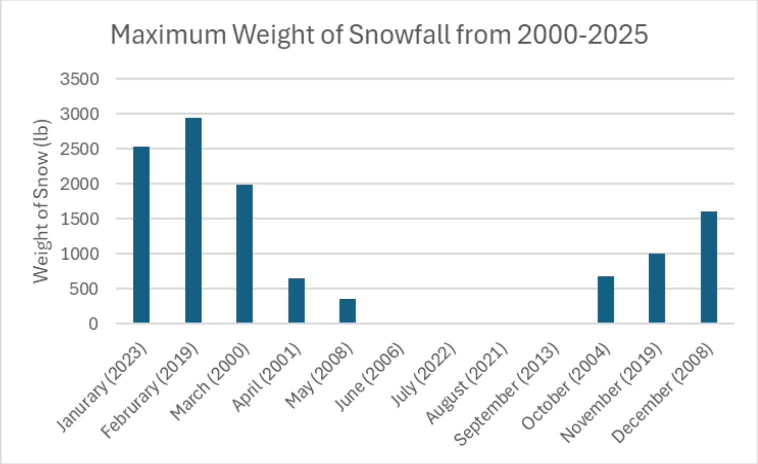

Figure 17: Annual Snow Fall

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Tyler Hedgecock

Experiment 8 – Energy Performance Test

Summary: Performance testing will establish energy input into the building. This will be done using a hot wire anemometer at the outlet of the ducting and using the time rate calculation based on the temperature input to gather the energy supplied. This will be done over any sunny day. The results will be in units of kWh be compared with the building heat load simulation. Based on the established customer requirements, the comparison should indicate that 30% of the total building heat load requirements are equal to that of the energy supplied from the solar panels.

Procedure:
- Take temperature data at the outlet using a hotwire anemometer
- Temperature data collection done over constant interval
- Perform calculation to gather energy supply
- Compare with building heat load simulation

Results:
- Vent 1 Energy Supply: 1.6kWh
- Vent 2 Energy Supply: 3.1kWh
- Vent 3 Energy Supply: 2.9kWh

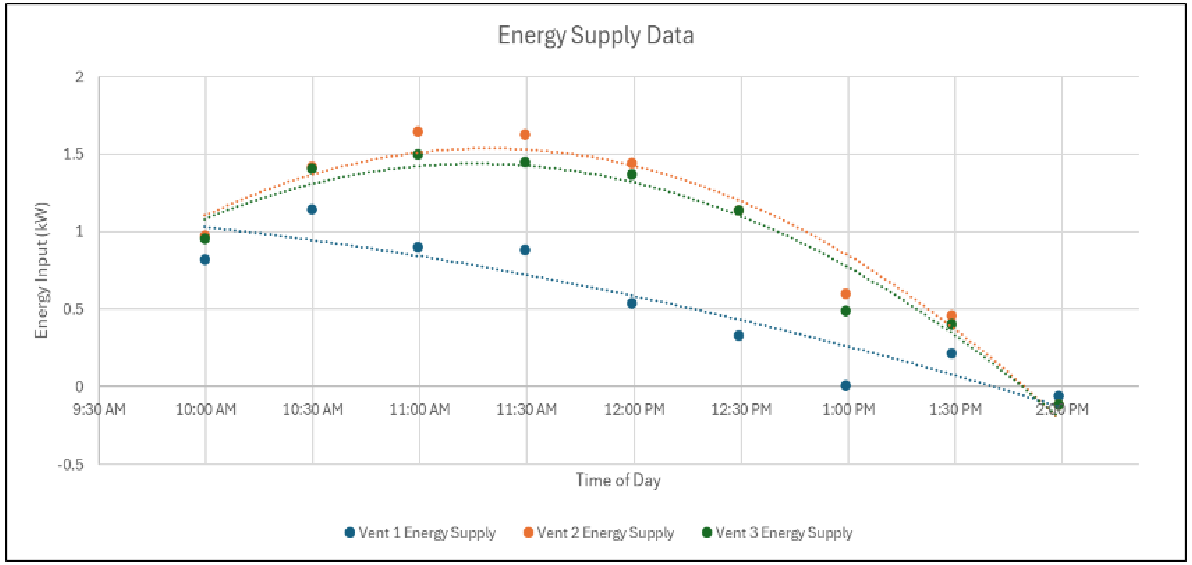

Figure 18: Energy Supply Plot

Experiment 8 – Energy Performance Test

```
--- Building Heatload Coverage with 2 Solar Panels ---
Jan: 21.1% of monthly requirement covered
    Building Heatload: 2594.4 kWh, Energy Supplied: 547.3 kWh
Feb: 21.8% of monthly requirement covered
    Building Heatload: 2332.8 kWh, Energy Supplied: 507.6 kWh
Mar: 28.2% of monthly requirement covered
    Building Heatload: 1984.0 kWh, Energy Supplied: 558.7 kWh
Apr: 47.6% of monthly requirement covered
    Building Heatload: 1128.3 kWh, Energy Supplied: 537.6 kWh
May: 100.0% of monthly requirement covered
    Building Heatload: 545.1 kWh, Energy Supplied: 545.2 kWh
Jun: 100.0% of monthly requirement covered
    Building Heatload: 52.8 kWh, Energy Supplied: 522.9 kWh
Jul: 100.0% of monthly requirement covered
    Building Heatload: 0.0 kWh, Energy Supplied: 514.8 kWh
Aug: 100.0% of monthly requirement covered
    Building Heatload: 0.0 kWh, Energy Supplied: 512.1 kWh
Sep: 100.0% of monthly requirement covered
    Building Heatload: 26.4 kWh, Energy Supplied: 516.1 kWh
Oct: 98.4% of monthly requirement covered
    Building Heatload: 539.3 kWh, Energy Supplied: 530.5 kWh
Nov: 35.5% of monthly requirement covered
    Building Heatload: 1465.4 kWh, Energy Supplied: 520.7 kWh
Dec: 20.9% of monthly requirement covered
    Building Heatload: 2570.2 kWh, Energy Supplied: 537.0 kWh

Total Annual Heatload Coverage: 33.0%
```

Figure 19: Monthly and Annual Heat Load Coverage

MATLAB Simulation (Energy)

- Lowest building heat load coverage in December (20.9%) and January (21.1%)
- Further Improvements
    - Use of NREL solar irradiation data based on location and time of day
    - Instead of dynamic angle input real world historical data

Specification Sheet CRS

Table 2: Customer Requirements Specification Sheet

Customer Requirement	CR Met? (Yes or No)	Client Acceptable (Yes or No)
1) Reduce Load by 30%	Yes by EX1 and EX2, Pending by EX8	No
2) Function in Winter	Yes by EX1, Pending by EX8	Yes
3) Use Renewable Energy	Yes by design	Yes
4) No Significant Mods	Yes by design	Yes
5) Must be Safe	Yes by EX3 and EX4	Yes
6) Minimal Maintenance	Yes by EX6	Yes
7) 10 Year Payback	Pending by EX8	No
8) Visual Indicator of Status	Yes by EX1 and EX8	Yes
9) Monitoring System		No
10) No Overheating	Yes by EX1, EX4 and EX8	Yes

Joseph Meza

Specification Sheet ERS

Table 3: Engineering Requirements Specification Sheet

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met? (Yes or No)	Client Acceptable (Yes or No)
ER1 – Energy Stored	30kWh	+/- 5	TBD	TBD	TBD
ER2 – Insulation	10R	+/- 2	8R	Yes	Yes
ER3 – Thermostat Control	~70F	+/- 3	40-75F	Yes	Yes
ER4 – Flow Rate	190CFM	+/- 10	157CFM	No	Yes
ER5 – Life Expectancy	10 Years	+/- 2	10-15 Years	Yes	Yes
ER6 - Cost	$3000	+ 0	$2527.84	Yes	Yes
ER7 – Mounting Weight	20kg	+/- 5	11.4kg	Yes	Yes

Brendan Frazier

Thank You

Questions?