Solar Air Heater Final Presentation

Jacob Apodaca – Test Engineer
Brendan Frazier – Project and Logistics Manager
Tyler Hedgecock – CAD Engineer
Joseph Meza – Financial Manager
Calvin Schenkenberger – Manufacturing Engineer

Northern Arizona University

Flagstaff, AZ 86001

PROJECT DESCRIPTION

- **Problem Statement:** Design a solar air heating system for installation into the Renewable Energy Lab. This will replace currently non-renewable methods. Batteries stored in the building must remain at 40°F. This project aims to reduce the building heat load required to maintain an adequate temperature.

- **Sponsor/Supplier:** Home Depot

- **Client & Advisor:** Dr. Carson Pete

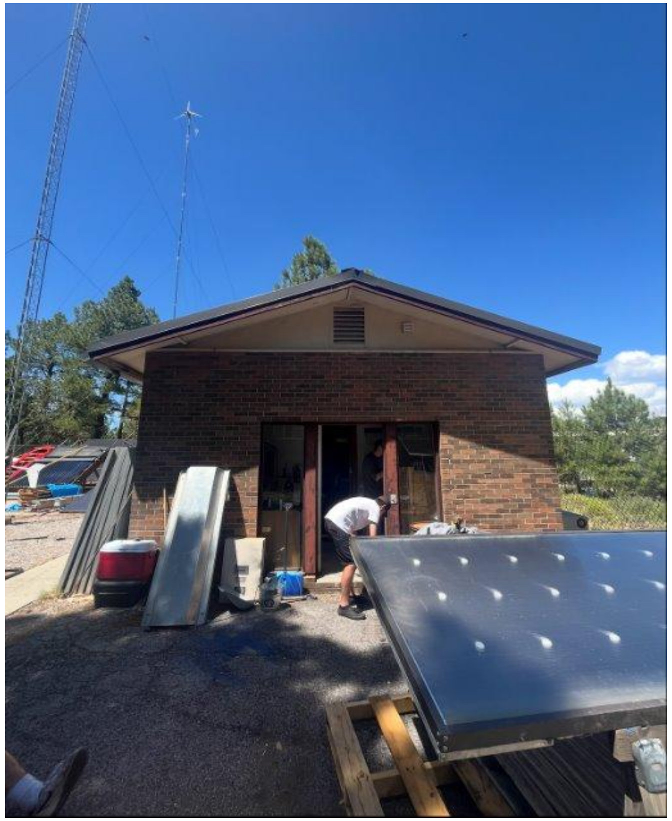


Figure 1: Renewable Energy Building

FUNCTIONAL DECOMPOSITION

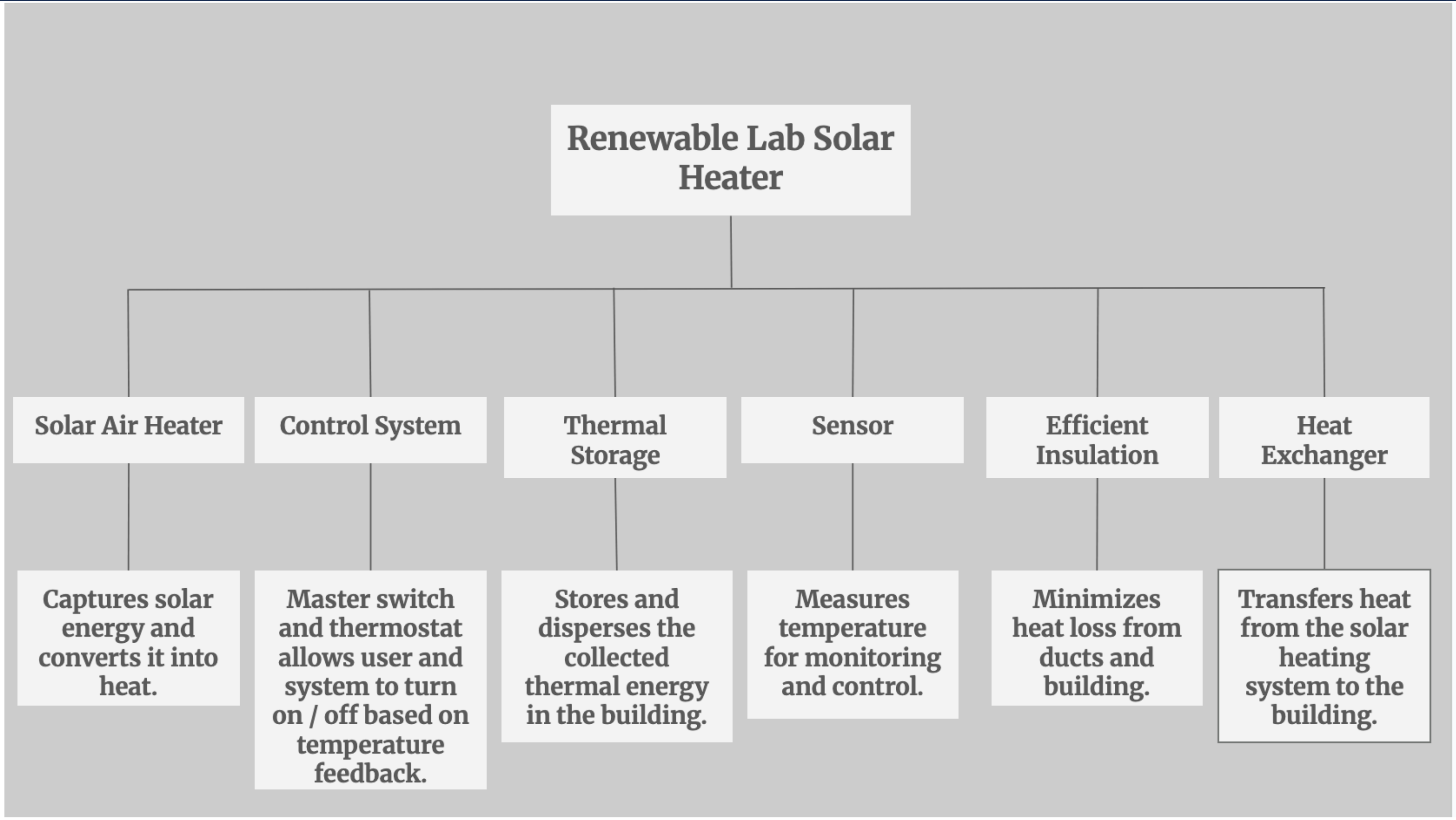


Figure 2: Functional Decomposition

PROJECT DELIVERABLES

Table 1: ME476C - ME486C Project Deliverables

Deliverable	Description
3 Project Design Presentations	Present all efforts in the design process. Includes functional decomposition, concept generation, and selection.
Prototyping Results and Presentations	Record of prototyping completed. Proof of concept and results of prototype testing.
3 Hardware Status Updates	Record of work completed on manufacturing and installation / assembly of the project.
4 Website Checks	Grading of the current state of the project website.
Occasional Individual Homework	Assignments including self-learning and individual analysis.
3 Reports on Project Status	Initial design, conceptual design, and final design reports.

BENCHMARKING

Vacuum Tube Solar Collector Kit [33]

- Solar hot water heating system
- Mounting system provided
- 92% coating absorbance
- Tilt angle up to 75˚ Degrees
- Expected lifetime ≈25-30 years
- Typically, able to offset 40-80% of home heating needs with a less than 8-year payback period
- $2,159.94

Applications

- Domestic and residential hot water
- Radiant floor heating
- Pool and spa heating
- Commercial hot water

Figure 3: 30 Tube Evacuated Solar Collector

Artica 4000 Series Solar Air Heater [54]

- 11,800 BTUh Max Heating Capacity
- Rated for 500 sqft room
- 150 – 160 cfm
- 4" ducting
- Optional thermostat / fan / PV panel kit (+$180.00)
- $1599.00
- Estimated $376 in savings per year
- 5 year payback period

Applications

- Residential space heating

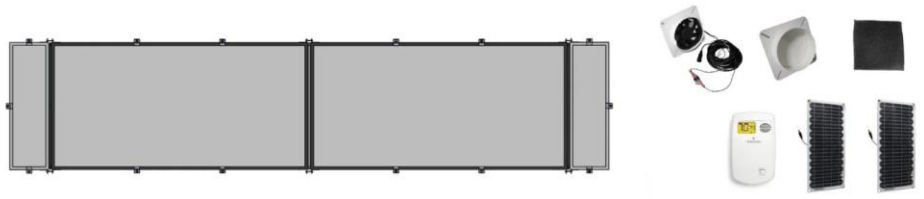


Figure 4: Artica Solar Air Heater

EG4 12k BTU Hybrid Solar Mini-Split AC/DC R32 [58]

- Hybrid Solar heating system
- Runs on solar DC power (90-380DVC)
- Accepts solar power from 1,100 Watts to 2,200 Watts
- Has smart energy management, limits how much energy can be used from built-in AC power limiter.
- Runs entirely on solar power when necessary
- Has a warranty up to five years
- Max solar current is 12 Amperes

Applications

- Meets strict guidelines for maximum energy savings
- Eliminates costs of solar inverters
- Designed for maximum efficiency and energy independence
- can use both solar and AC power

Figure 5: Hybrid Solar Mini Split System

LITERATURE REVIEW

FLUID SELECTION

Figure 6: Open Loop Solar Air Heater

Air Based Solar Thermal System

Pros

- Lower maintenance and cost
- Optimized for direct space heating

Cons

- Low heat capacity
- Lower overall efficiency

Figure 7: Closed Loop Solar Water Heater

Water Based Solar Thermal System

Pros

- Allows thermal storage for overnight use
- Higher efficiency

Cons

- Requires major building modifications
- Freeze risk in Flagstaff

CIRCUIT DIAGRAM

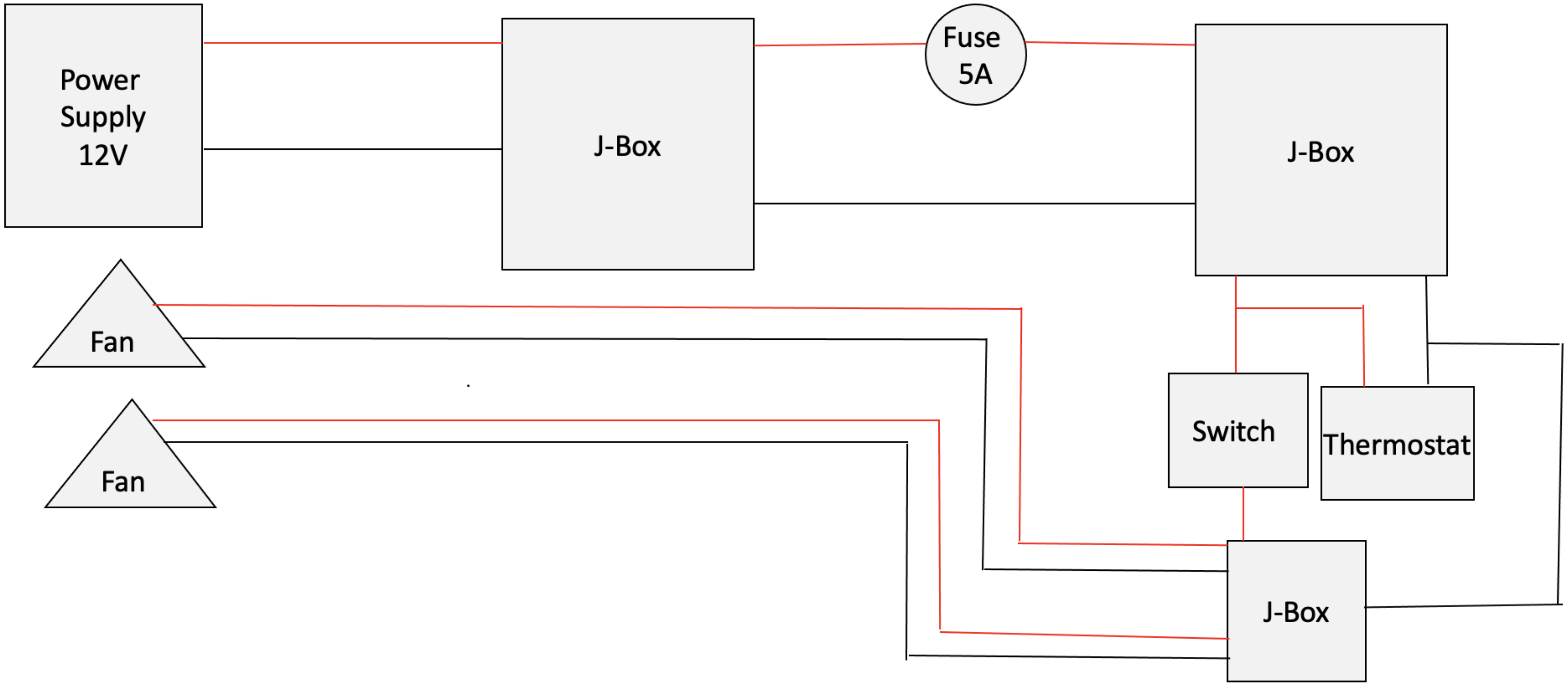


Figure 8: Circuit Diagram for Solar Air System

DUCT FLOW DIAGRAM

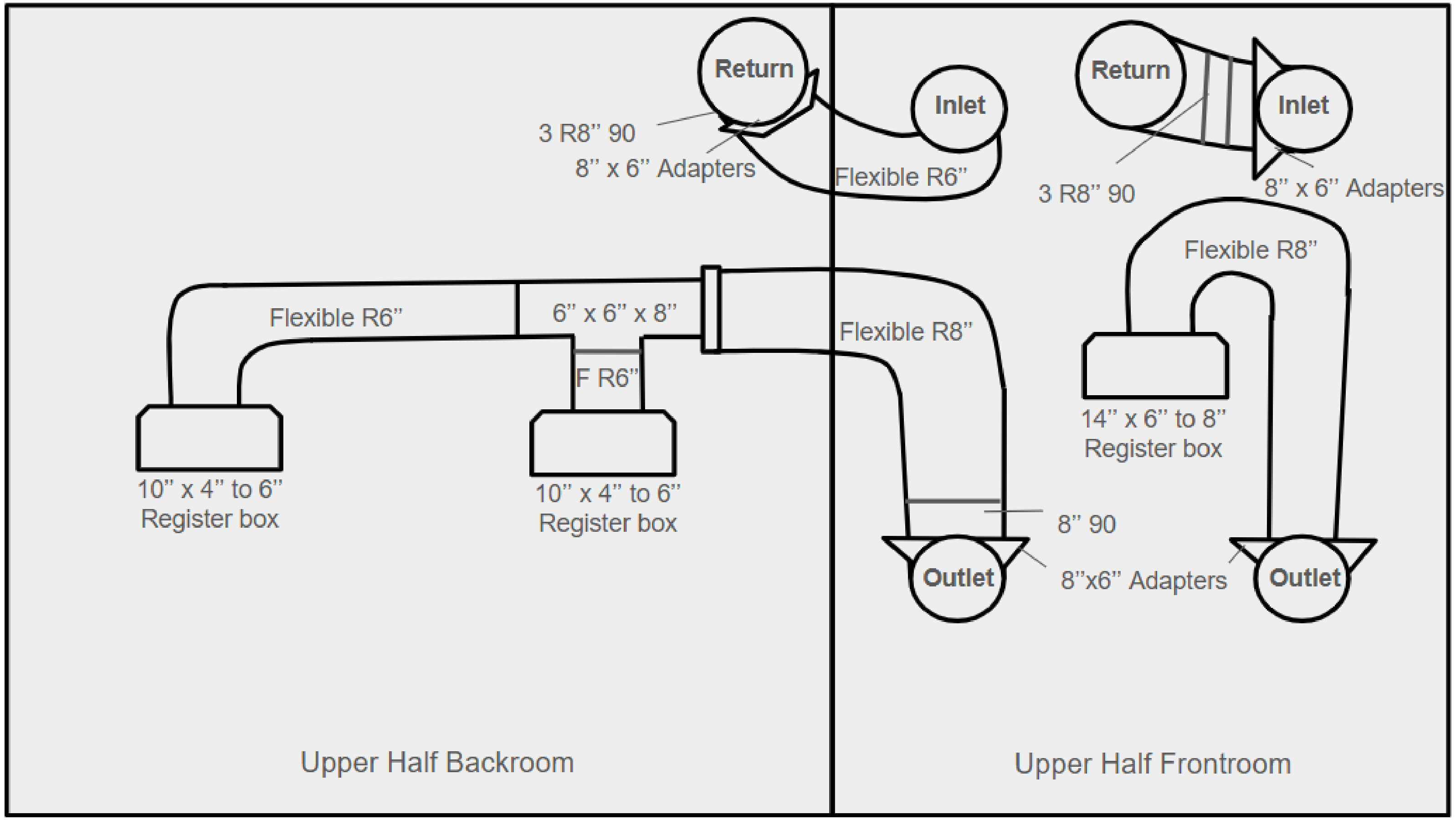
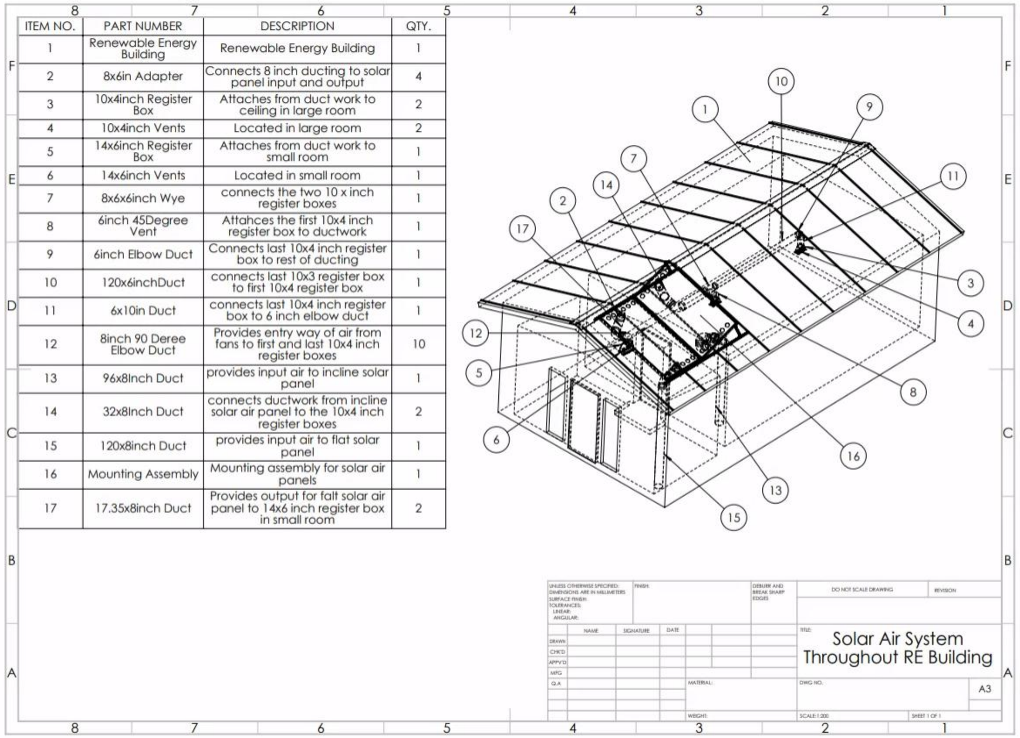


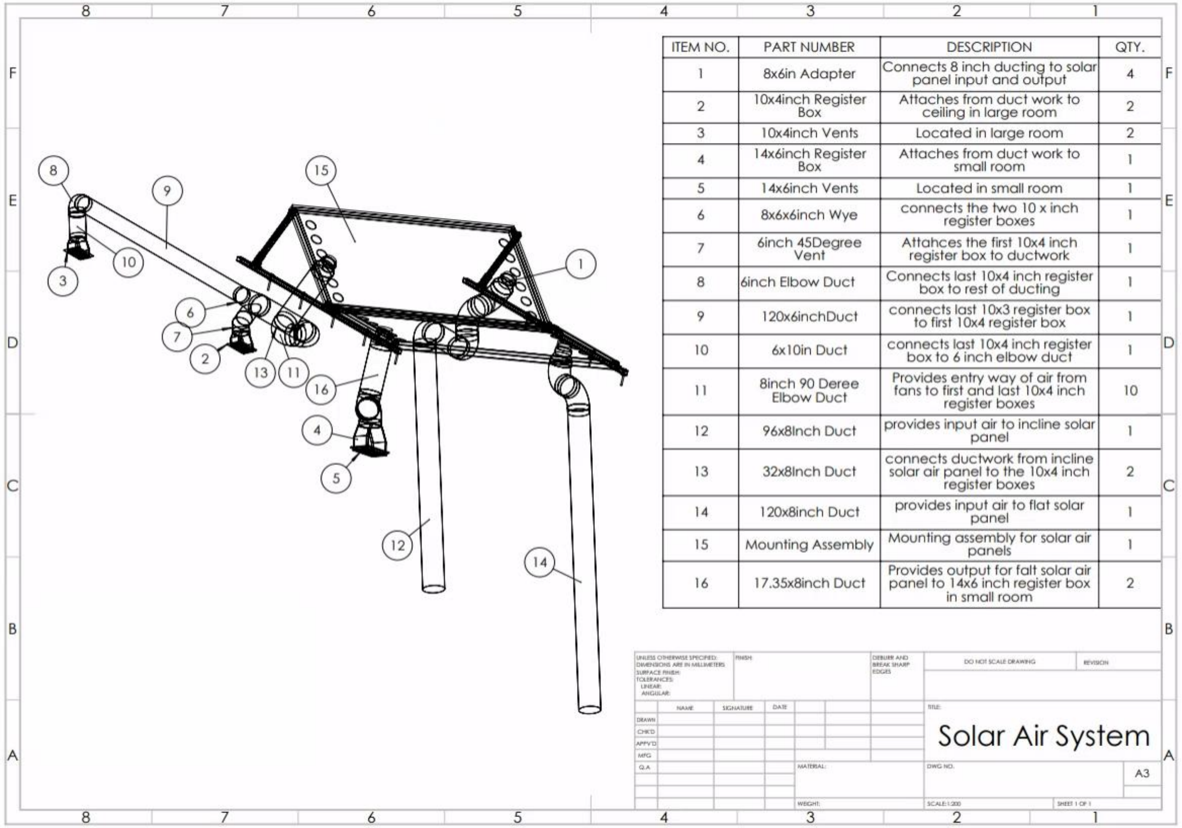
Figure 9: Duct Flow Diagram for Solar Air System

FINAL DESIGN



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Renewable Energy Building	Renewable Energy Building	1
2	8x6in Adapter	Connects 8 inch ducting to solar panel input and output	4
3	10x4inch Register Box	Attaches from duct work to ceiling in large room	2
4	10x4inch Vents	Located in large room	2
5	14x6inch Register Box	Attaches from duct work to small room	1
6	14x6inch Vents	Located in small room	1
7	8x6x6inch Wye	connects the two 10 x inch register boxes	1
8	6inch 45Degree Vent	Attahces the first 10x4 inch register box to ductwork	1
9	6inch Elbow Duct	Connects last 10x4 inch register box to rest of ducting	1
10	120x6inchDuct	connects last 10x3 register box to first 10x4 register box	1
11	6x10in Duct	connects last 10x4 inch register box to 6 inch elbow duct	1
12	8inch 90 Deree Elbow Duct	Provides entry way of air from fans to first and last 10x4 inch register boxes	10
13	96x8Inch Duct	provides input air to incline solar panel	1
14	32x8Inch Duct	connects ductwork from incline solar air panel to the 10x4 inch register boxes	2
15	120x8inch Duct	provides input air to flat solar panel	1
16	Mounting Assembly	Mounting assembly for solar air panels	1
17	17.35x8inch Duct	Provides output for falt solar air panel to 14x6 inch register box in small room	2

Figure 10: Solar Air System Throughout RE Building



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	8x6in Adapter	Connects 8 inch ducting to solar panel input and output	4
2	10x4inch Register Box	Attaches from duct work to ceiling in large room	2
3	10x4inch Vents	Located in large room	2
4	14x6inch Register Box	Attaches from duct work to small room	1
5	14x6inch Vents	Located in small room	1
6	8x6x6inch Wye	connects the two 10 x inch register boxes	1
7	6inch 45Degree Vent	Attahces the first 10x4 inch register box to ductwork	1
8	6inch Elbow Duct	Connects last 10x4 inch register box to rest of ducting	1
9	120x6inchDuct	connects last 10x3 register box to first 10x4 register box	1
10	6x10in Duct	connects last 10x4 inch register box to 6 inch elbow duct	1
11	8inch 90 Deree Elbow Duct	Provides entry way of air from fans to first and last 10x4 inch register boxes	10
12	96x8Inch Duct	provides input air to incline solar panel	1
13	32x8Inch Duct	connects ductwork from incline solar air panel to the 10x4 inch register boxes	2
14	120x8inch Duct	provides input air to flat solar panel	1
15	Mounting Assembly	Mounting assembly for solar air panels	1
16	17.35x8inch Duct	Provides output for falt solar air panel to 14x6 inch register box in small room	2

Figure 11: Solar Air System with Ducts

HEAT LOAD SIMULATION

Assumptions:
- Gas Heating (Most similar option available)
- Building needs to be heated 24/7
- Materials and R Values (R-13 walls, R-30 attic)

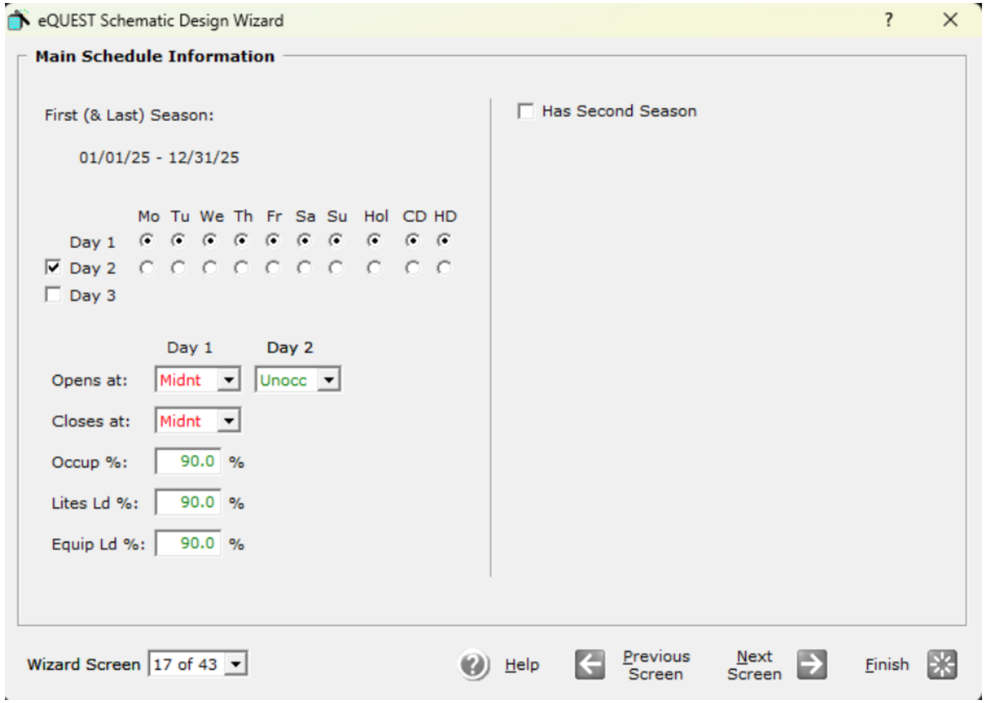


Figure 12: Example eQUEST Dialogue Window

Figure 13: RE Lab

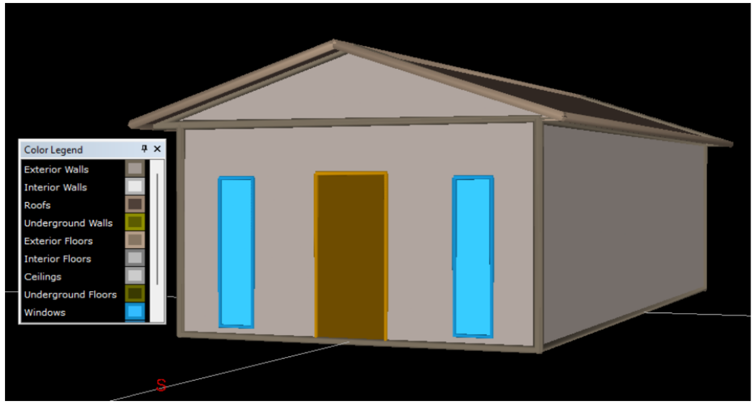


Figure 14: Resulting 3D Model of RE Lab

Sensible Heat Formula:

Q = 1.08 * CFM * (Ts – Tr)

Where:

Q = Heat [Btu/hr]

CFM = Volumetric Flowrate [cfm]

Ts = Supply Temperature [°F]

Tr = Room Temperature [°F]

Given Values:

CFM = 380 [cfm]

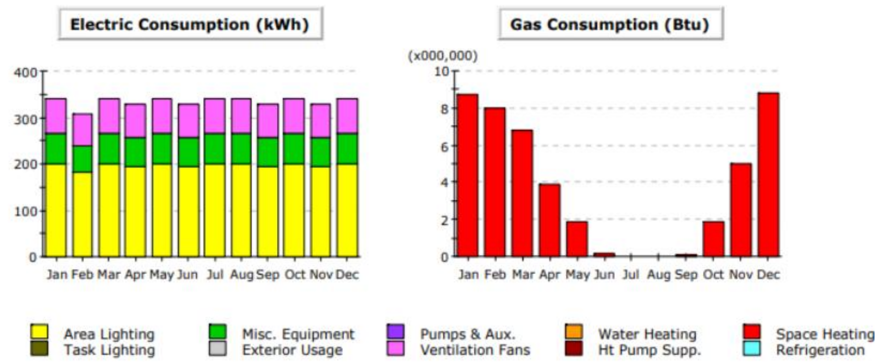
Ts = 92.3 [°F]

Tr = 55.0 [°F]

Solved:

Q = 15,307 [Btu/hr]

HEAT LOAD SIMULATION



Electric Consumption (kWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	73.6	66.5	73.6	71.2	73.6	71.2	73.6	73.6	71.2	73.6	71.2	73.6	866.7
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	65.0	58.7	65.0	62.9	65.0	62.9	65.0	65.0	62.9	65.0	62.9	65.0	765.3
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	200.8	181.4	200.8	194.3	200.8	194.3	200.8	200.8	194.3	200.8	194.3	200.8	2,364.4
Total	339.4	306.6	339.4	328.5	339.4	328.5	339.4	339.4	328.5	339.4	328.5	339.4	3,996.4

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	8.75	7.96	6.77	3.85	1.86	0.18	-	-	0.09	1.84	5.00	8.77	45.08
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	8.75	7.96	6.77	3.85	1.86	0.18	-	-	0.09	1.84	5.00	8.77	45.08

Figure 15: Building Energy Consumption

Results:

Greatest Heat Load by Month:
December (8.77 MBtu)

December Hourly Heat Load:
11.8 KBtu/h

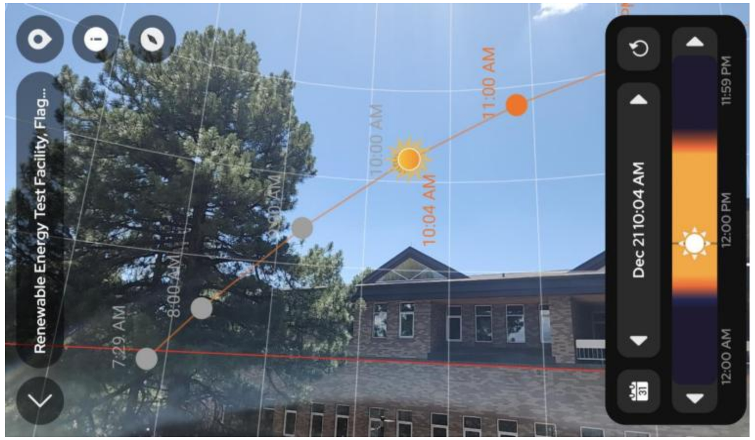


Figure 16: AR Simulation of Sun's Path

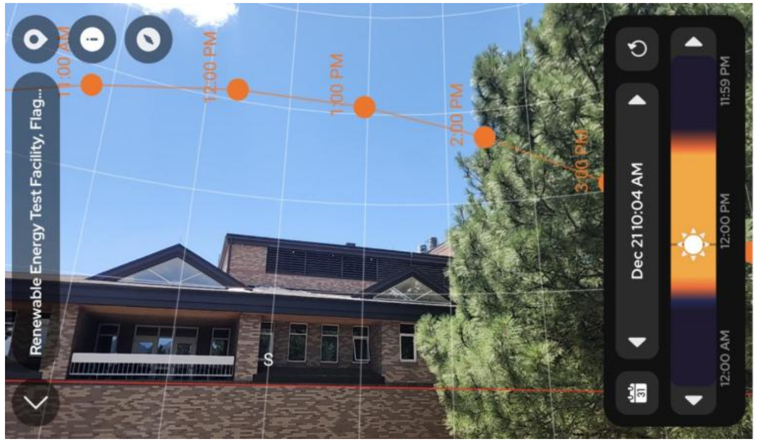


Figure 17: AR Simulation of Sun's Path

ENERGY SUPPLY MODEL

Assumptions

- Building Temperature 55 Fahrenheit
- ASHRAE Solar Irradiation Data
- Incident Radiation Angle from 0 to 71.25 degrees
- Inlet Temperature same as building temperature

Energy Equations

$$q_{in} = \dot{m} * c_p * (T_{air} - T_{building})$$

Fundamental Heat Transfer Equations

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

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

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

Temperature Equations

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

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

ENERGY SUPPLY MODEL

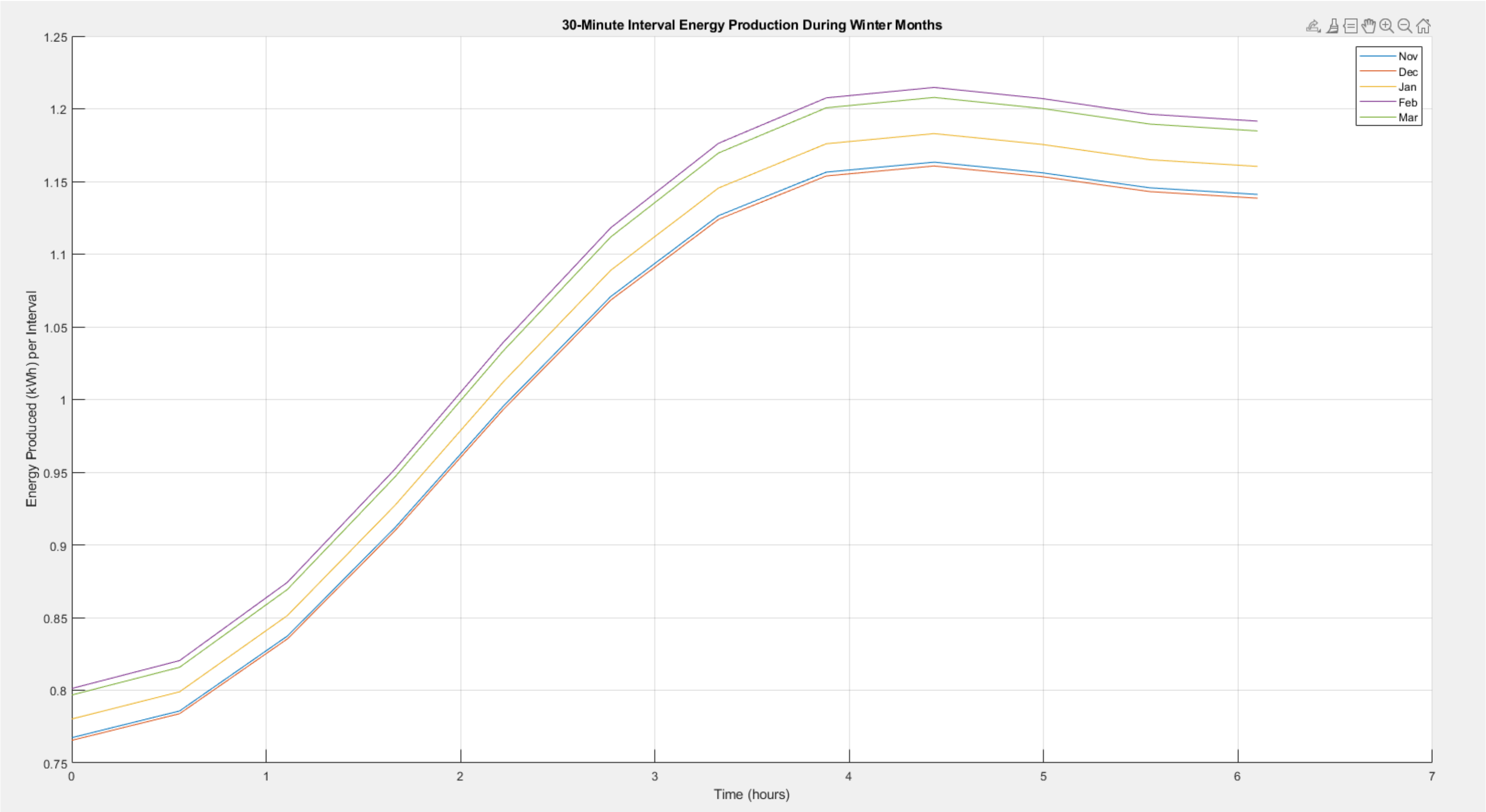


Figure 19: Dynamic Angle Energy Output

ENERGY PERFORMANCE TEST

```
===== Building Heat Load Coverage with 2 Panels =====
Jan: 11.9% covered | Load: 2594.4 kWh | Potential 307.7 kWh
Feb: 15.8% covered | Load: 2332.8 kWh | Potential 369.6 kWh
Mar: 27.7% covered | Load: 1984.0 kWh | Potential 549.1 kWh
Apr: 60.5% covered | Load: 1128.3 kWh | Potential 683.0 kWh
May: 100.0% covered | Load: 545.1 kWh | Potential 791.5 kWh
Jun: 100.0% covered | Load: 52.8 kWh | Potential 907.2 kWh
Jul: 100.0% covered | Load: 0.0 kWh | Potential 392.1 kWh
Aug: 100.0% covered | Load: 0.0 kWh | Potential 385.7 kWh
Sep: 100.0% covered | Load: 26.4 kWh | Potential 467.7 kWh
Oct: 90.1% covered | Load: 539.3 kWh | Potential 485.7 kWh
Nov: 25.1% covered | Load: 1465.4 kWh | Potential 367.4 kWh
Dec: 10.3% covered | Load: 2570.2 kWh | Potential 264.4 kWh

================== ANNUAL TOTALS ==================
Total Annual Building Heat Load:      13238.7 kWh
Total Annual Solar Heat Supplied:     3651.2 kWh
Overall Percent Covered:              27.6%
```

Figure 37: Total Potential Energy Supply and Coverage

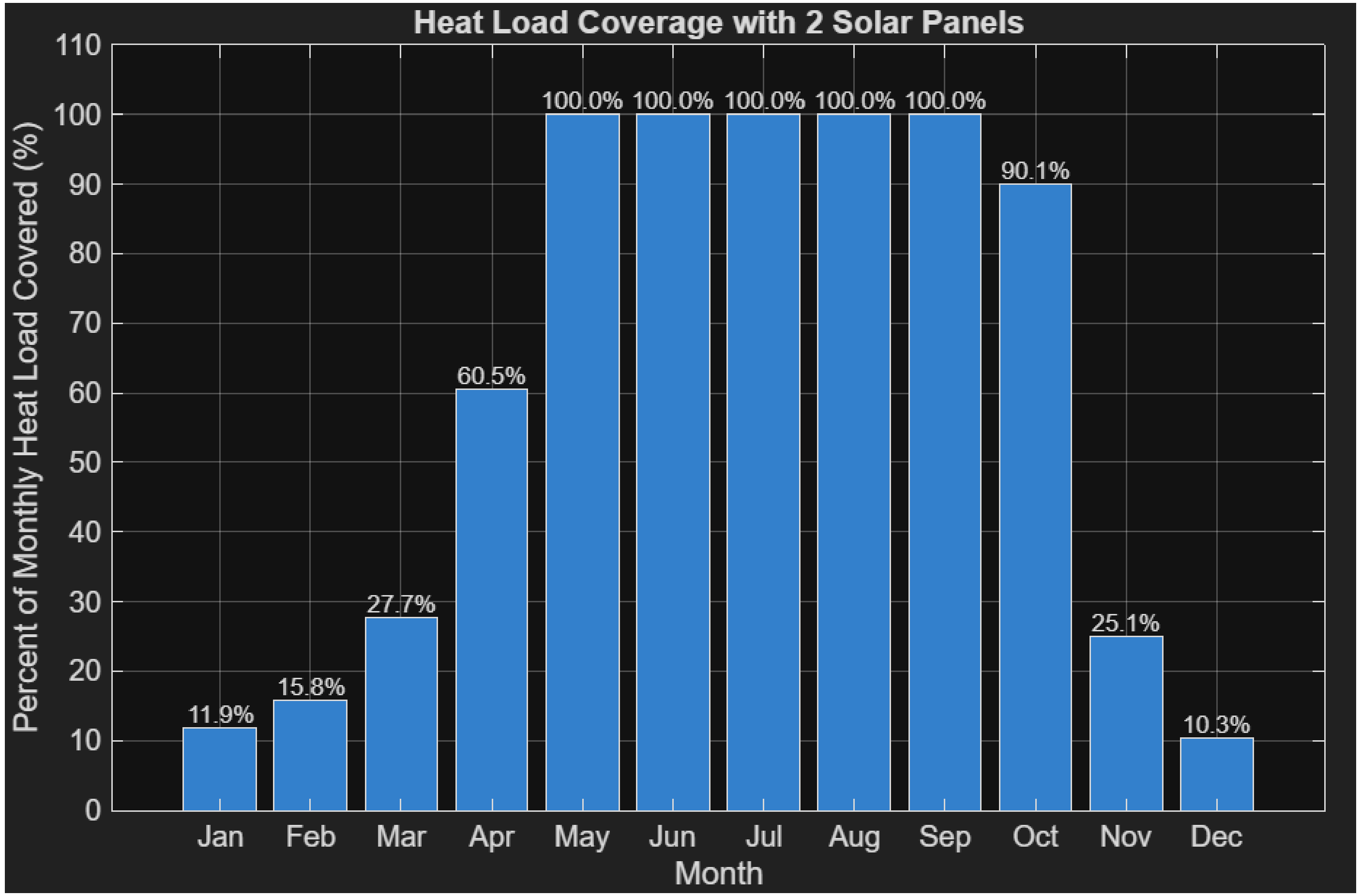


Figure 37: Percent Coverage from MATLAB Model

SCHEDULE

RE LAB Solar Heater

NAU Capstone Project FALL 2025

Project start: **Mon, 8/25/2025**

Display week: **2**

Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			8/25/25	12/12/25
Project Management 486C Final Draft	Everyone	100%	8/25/25	9/2/25
Hardware Status Update (33% Build)	Everyone	100%	8/25/25	9/22/25
>PVT Solar Panel Removall (Roofing)	Everyone	100%	8/30/25	9/22/25
>Refurbishing one solar air collector	Brendan Frazier	100%	9/14/25	9/22/25
>Mounting Assembly prototype	Jacob Apodaca	100%	9/14/25	9/22/25
>New roof BOM	Calvin Schenkenberger	100%	9/14/25	9/22/25
Engineering Calculations Summary	Everyone	100%	8/25/25	9/8/25
Self Learning / Individual Analysis	Everyone	100%	8/31/25	9/8/25
Peer Evaluation 1	Everyone	100%	8/25/25	9/22/25
Website Check #1	Joseph Meza	100%	9/15/25	10/6/25
Hardware Status Update (66% Build)	Everyone	100%	9/15/25	10/13/25
>Purchashed BOM	Calvin Schenkenberger	100%	9/21/25	10/6/25
>Both Solar Panels fully refurbished	Jacob and Brendan	100%	9/22/25	10/13/25
>Building / roof modifications installed (Drip edge)	Everyone	100%	9/28/25	10/13/25
>Install New Roof	Everyone	100%	9/28/25	10/13/25
>Circuit Diagram (Electrical Components)	Calvin and Brendan	100%	10/5/25	10/13/25
Peer Evaluation 2	Everyone	100%	10/1/25	10/20/25
UGRADS Registration	Everyone	100%	10/1/25	10/20/25
Draft of Poster	Everyone	100%	10/1/25	10/27/25
Finalized Testing Plan	Everyone	100%	10/14/25	10/27/25

Figure 21: Gantt Chart

SCHEDULE

RE LAB Solar Heater

NAU Capstone Project FALL 2025

Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			8/25/25	12/12/25
Hardware Status Update (100% Build)	Everyone	100%	10/6/25	11/3/25
>Electrical Installation (Circuitry)	Jacob Apodaca	100%	10/13/25	10/30/25
>Soldering Connections (Wire nuts / lever nuts)	Jacob Apodaca	100%	10/14/25	10/30/25
>Fuse work	Jacob Apodaca	100%	10/14/25	10/30/25
> Mounting Conduit	Tyler Hedgecock	100%	10/14/25	10/30/25
>Install Pipe Halo Flashing	Calvin Schenkenberger	100%	10/14/25	10/21/25
>Install unistrut guides cut and attach supporting unistrut	Calvin Schenkenberger	100%	10/14/25	10/26/25
>Install solar panels to mounting assembly	Brendan Frazier	100%	10/14/25	10/26/25
>Ductwork Installation	Joseph Meza	100%	10/14/25	10/26/25
Peer Evaluation 3	Everyone	100%	10/31/25	11/10/25
Initial Testing Results	Jacob Apodaca	100%	11/1/25	11/17/25
>Output temp	Jacob Apodaca	100%	11/10/25	11/17/25
>Output flow rate	Jacob Apodaca	100%	11/10/25	11/17/25
>Wind loading	Calvin Schenkenberger	100%	11/10/25	11/17/25
>Voltage drop	Jacob Apodaca	100%	11/10/25	11/17/25
>Air leakage test	Joe Meza	100%	11/10/25	11/17/25
>Water leakage test	Brendan Frazier	100%	11/10/25	11/17/25
>Data collection	Tyler Hedgecock	100%	11/10/25	11/17/25
>Performance test	Everyone	100%	11/10/25	11/17/25
>Thermostat Controller test	Jacob Apodaca	100%	11/10/25	11/17/25

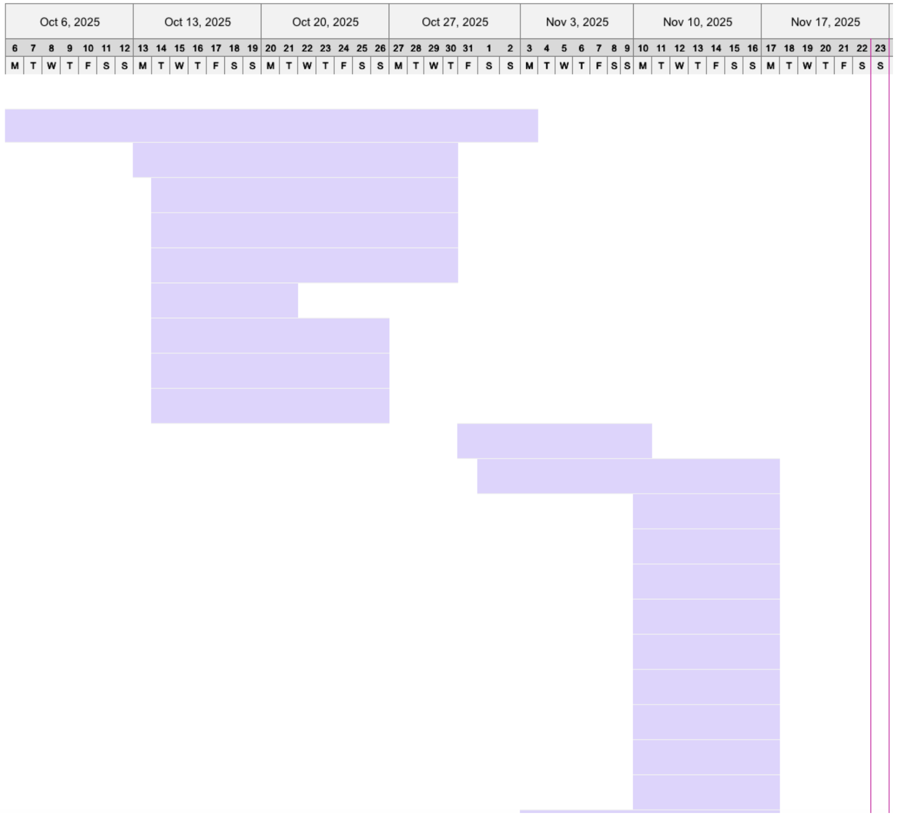


Figure 22: Gantt Chart

NORTHERN ARIZONA UNIVERSITY

Jacob Apodaca

SCHEDULE

RE LAB Solar Heater

NAU Capstone Project FALL 2025

Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			8/25/25	12/12/25
Final CAD Packet	Tyler Hedgecock	100%	11/3/25	11/17/25
Final Poster & PPT	Brendan Frazier	100%	11/4/25	11/17/25
Final Testing Results	Jacob Apodaca	100%	11/10/25	11/24/25
Operation / Assembly Manual	Calvin Schenkenberger	0%	11/20/25	12/1/25
Final Report	Brendan Frazier	0%	11/20/25	12/1/25
Final Website Check	Joseph Meza	0%	11/15/25	12/3/25
Expo PPT and Poster Presentation Results	Everyone	0%	11/23/25	12/5/25
Peer Evaluation 4	Everyone	0%	11/28/25	12/11/25
Client Handoff	Everyone	0%	11/30/25	12/8/25

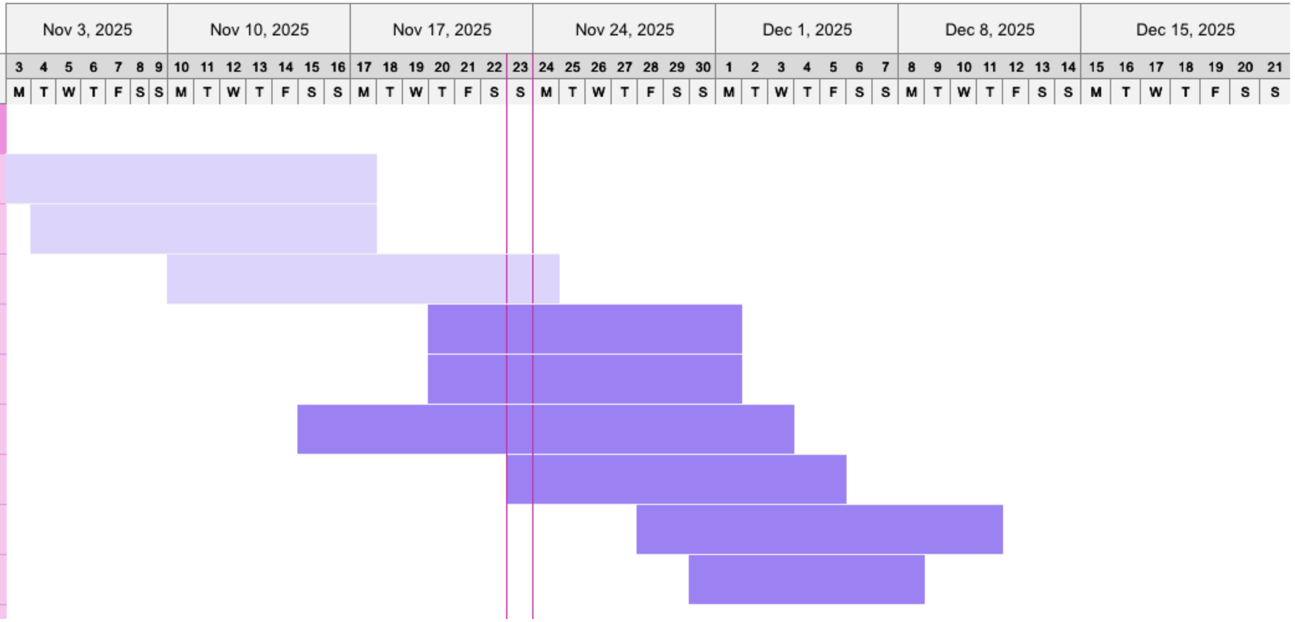


Figure 23: Gantt Chart

BILL OF MATERIALS

Bill of Materials					
Item	Category	Description	Unit Cost	Quant	Cost
14 Gauge Unistrut	Materials: Mounting	10ft section for mounting frame	$41.00	3	$123.00
1/2" by 5" Lag Screws	Materials: Mounting	Mounting unistrut to roof	$1.76	10	$17.60
Gold Galv Sqr Washer	Materials: Mounting	Mounting unistrut to roof	$2.12	18	$38.16
Gold Galv 2-hole L Bracket	Materials: Mounting	Mounting panels to unistrut	$3.44	8	$27.52
1/2" Nylon Cone Nuts	Materials: Mounting	Connecting unistrut or L brackets	$1.31	24	$31.44
1/2" Locking Washer	Materials: Mounting	Safety measure for mounting	$0.47	30	$14.10
1/2" Washer	Materials: Mounting	Spacers and securing	$0.45	30	$13.50
1/2" x 5/16" galv bolt	Materials: Mounting	Mounting L bracket to unistrut	$0.62	8	$4.96
1/2 x 1-1/2 galv bolt	Materials: Mounting	Mounting panel to L bracket	$1.01	8	$8.08
1/2 x 13 tpi galv bolt	Materials: Mounting	Matched to bolt size and tpi	$0.52	8	$4.16
Pivoting Strut Brkt	Materials: Mounting	For angling rear panel	$55.97	2	$111.94
GAF Roll Roofing	Materials: Roofing	New roof material	$133.40	9	$1,200.60
Drip Edge Flashsing	Materials: Roofing	Prevent water leakage at roof edge	$8.73	2	$17.46
Roofing Nails	Materials: Roofing	Secure DE flashing (50 pk)	$6.10	1	$6.10
SKYSHALO Pipe Flashing	Materials: Roofing	Sealing location of ducts	$39.87	4	$159.48
Henry 900	Materials: Roofing	Waterproofing screws and flashing	$12.01	2	$24.02
Sunon 12V DC Fan	Materials: Electrical	Fans used to transport heated air	$79.51	2	$159.02
Weewooday Thermostat	Materials: Electrical	Engage or disengage the system	$6.99	1	$6.99
Flexible Conduit	Materials: Electrical	Route wiring in attic	$27.00	1	$27.00
EMT Conduit	Materials: Electrical	Route wiring in main room	$6.83	1	$6.83
Junction Box	Materials: Electrical	Storage for electrical components	$3.73	2	$7.46
10 AWG PV Wire	Materials: Electrical	Wires exposed to outdoors	$0.60	30	$18.00
16 AWG Wire	Materials: Electrical	Wires internal of the building	$17.98	1	$17.98
5A Fuse	Materials: Electrical	Over current protection	$1.40	1	$1.40
Fuse Housing	Materials: Electrical	Holds fuse in circuit	$5.99	1	$5.99
Single Pole Togle Switch	Materials: Electrical	Used as master switch for system	$4.40	1	$4.40

Figure 24: BOM

Bill of Materials					
Item	Category	Description	Unit Cost	Quant	Cost
8"x6"x6" Wye	Materials: Ducting	Splits air for main room	$17.98	1	$17.98
8" 90	Materials: Ducting	Used at inlets ducts	$9.98	10	$99.80
6 inch 90	Materials: Ducting	Used at angled panel to direct ducts	$8.68	2	$17.36
8 x 6 adapter	Materials: Ducting	All transitions for attaching to panel	$14.28	4	$57.12
6 inch duct	Materials: Ducting	Routes air to main room	$59.68	1	$59.68
8 inch duct	Materials: Ducting	Routes air to front room	$67.98	1	$67.98
Duct Insulation	Materials: Ducting	Additional insulation energy retention	$27.98	1	$27.98
10 x 4 to 6 register box	Materials: Ducting	For vents in main and front room	$12.49	3	$37.47
10 x 4 vent	Materials: Ducting	General purpose vents for dispersion	$13.98	3	$41.94
Duct Tape	Materials: Ducting	Duct connections and sealing	$13.98	1	$13.98
4 x 8 White Polywall Panel	Materials: Panels	Replacing backing on panels	$28.42	2	$56.84
1 x 4 x 8 R-6	Materials: Panels	1 inch thick insulation for panels	$36.02	3	$108.06
Nashua 324A Premium Foil	Materials: Panels	For reassembling panel interiors	$26.22	1	$26.22
1/2 In 4 x 8 Polystyrene	Materials: Panels	1/2 inch thick insulation for panels	$13.09	1	$13.09
			Total Budget		$3,000
			Total Cost		$2,484.50
			Remaining Budget		$515.50

Figure 25: BOM

Joseph Meza

DESIGN VALIDATION AND PROTOTYPING

Data Recording Setup

- Set at 16 Degrees
- 190 CFM volumetric flow rate
- RTD temperature measurement device
- Data recorded every 5 seconds

Figure 26: Solar Panel Setup

Figure 27: RTD Setup

PROTOTYPE DATA

Variable Voltage

- Voltage supplied from photovoltaic panel is dependent on irradiation

Transient Output Temperature

- 12V steady state at 60 °C
  - Q = 190 CFM
- 10V steady state at 79 °C
  - Q < 190 CFM
- Fan Design Temperature
  - Tmax = 70 °C

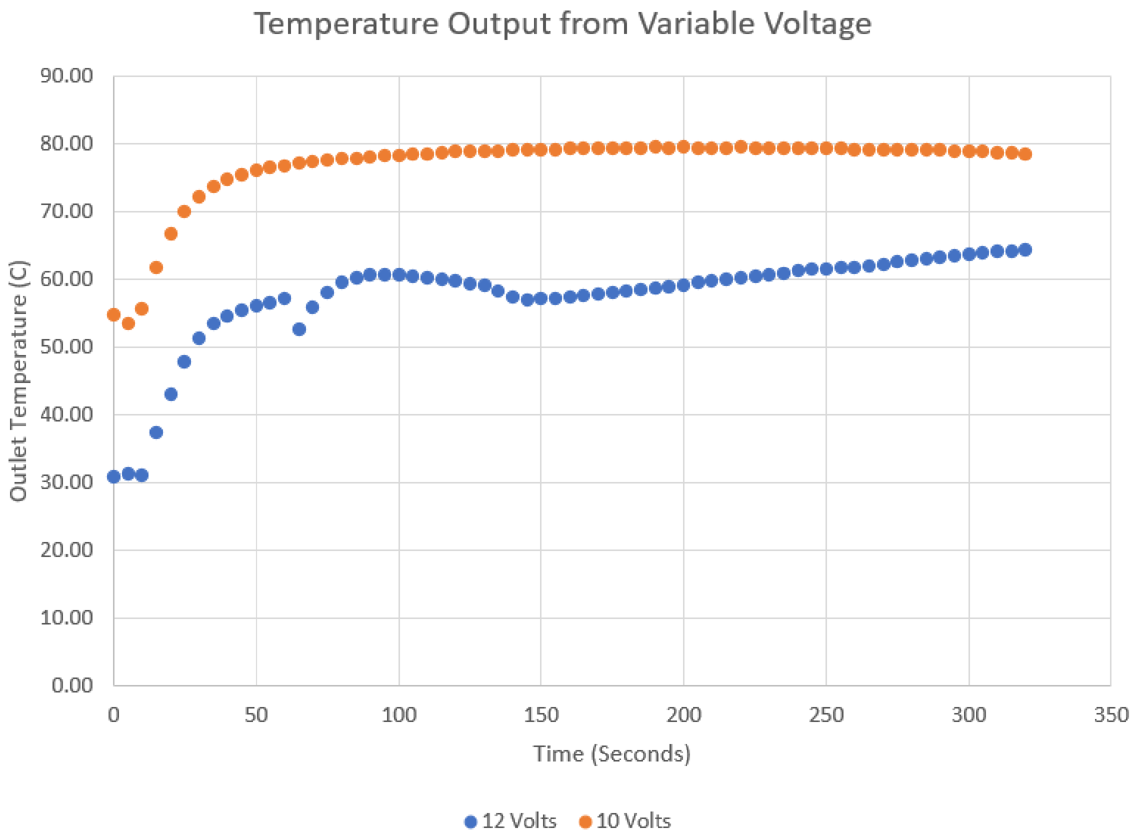


Figure 28: Measured Steady State at Variable Voltage

Joseph Meza

FINAL HARDWARE: MOUNTING

Mounting Hardware

- 14-gauge Unistrut
- Nylon Unistrut Cone Nuts
- 5-inch Lag Screws
- Unistrut Pivot Bracket
- 1.5-inch Square Washers
- 0.5-inch Locking Washers

Figure 29: Solar Panel Mounting

Figure 30: Solar Panel Setup

Calvin Schenkenberger

FINAL HARDWARE: ELECTRICAL

Figure 34: Load Box

Figure 35: Master Switch and Thermostat

Figure 36: Conduit Through Attic

Jacob Apodaca

FINAL HARDWARE: DUCTING

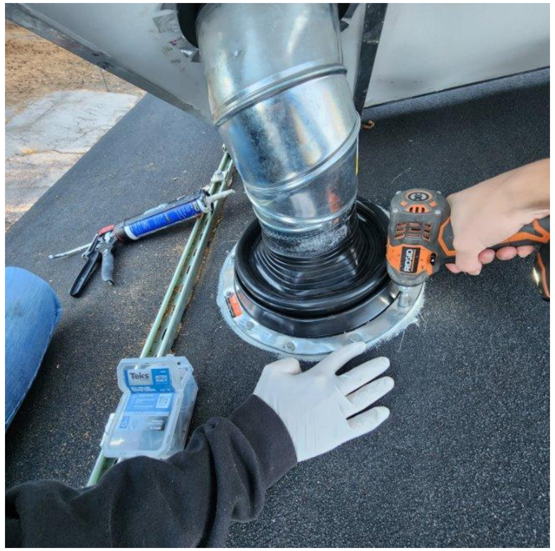


Figure 31: Angled Fan Ducting

Figure 32: Ducts Leading to Main Room

Duct Work Setup:

- Fans are connected to the solar air panels
- Fans provide heated air through the ducts
- Duct work provides heated air throughout the RE building

Figure 33: Input Duct for Front Room

Inlet Ducting Setup:

- Located in both the smaller and larger rooms
- Solar air panels take the air in the building, heats it, and lets the fans distribute the heated air in the small and large room.

Joseph Meza

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

Brendan Frazier

DETAILED TESTING PLAN

- EXP1: Test temperature input and output
  - Measure input temperatures and output temperatures from vents using hot wire anemometer.
- EXP2: Test flowrate input and output
  - Measure velocity of air in feet per minute at inputs and outputs and multiply by the cross-sectional area to get volumetric flowrate and compare against specification sheet for the fans vol. flow rate CFM (cubic feet per minute)
- EXP3: Test maximum wind loads from past 30 years on air heaters using data from Flagstaff Pulliam Airport.
  - Collect wind data from weather station capstone team at RE Lab to calculate wind loads to validate mounting system.
- EXP4: Test voltage drop
  - Measure voltage using multimeter at different points along electrical path to determine voltage drop which should be around ≈2%.
- EXP5: Test for air leaks
  - Using fog machine block vents and run fog through inputs to find any leaks in ducting and seal afterwards.
- EXP6: Test for water leaks
  - Look for water leakage and seal after rainy day.
- EXP7: Test for annual weather changes through data collection
  - Find annual weather data for flagstaff and determine how this affects our solar air systems output parameters.
- EXP8: Test performance for energy input
  - Calculate energy input from the measured temperature due to solar irradiance.

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TESTING SUMMARY

Table 3: Testing 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

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ENERGY PERFORMANCE TEST

Procedure

- Take temperature measurements at each vent every 30 minutes
- Record building temperature every 30 minutes

Results

- Total Energy Supply: 11.37kWh

Testing Conditions

- Partly / Mostly Cloudy
- Limited Solar Window (4 Hours)

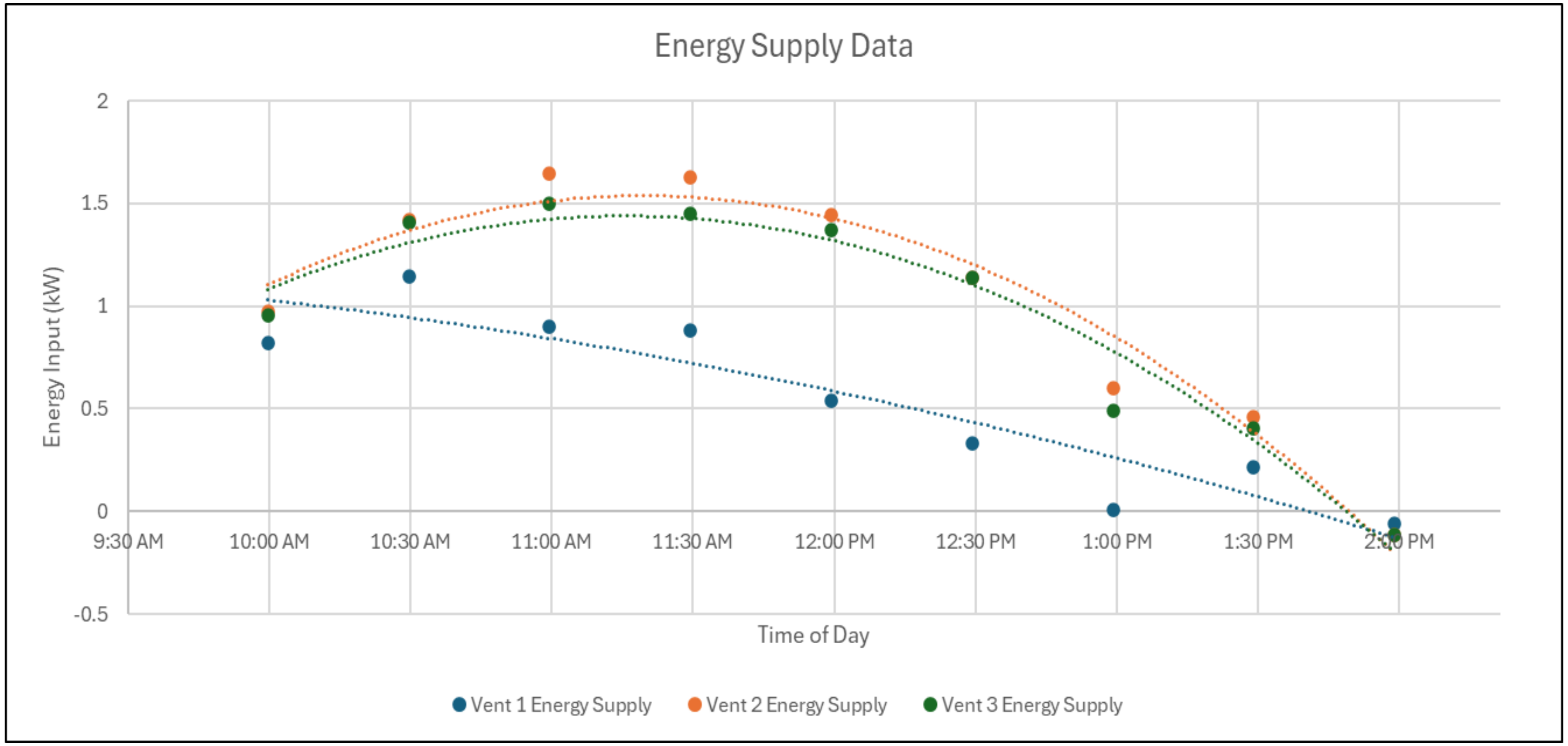

Figure 37: Thermal Performance Plot

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AIR LEAKAGE TEST

Procedure

- Connect smoke machine to the main inlet duct
- Inspect ducts
- Record any visible smoke escaping the system
- Re-seal

Results

- 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 38: Fog to Input Duct

Figure 39: Fog to output Duct

Figure 40: Air Duct Sealant

FLOW RATE TEST

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 41: Vent 1 output flow rate test

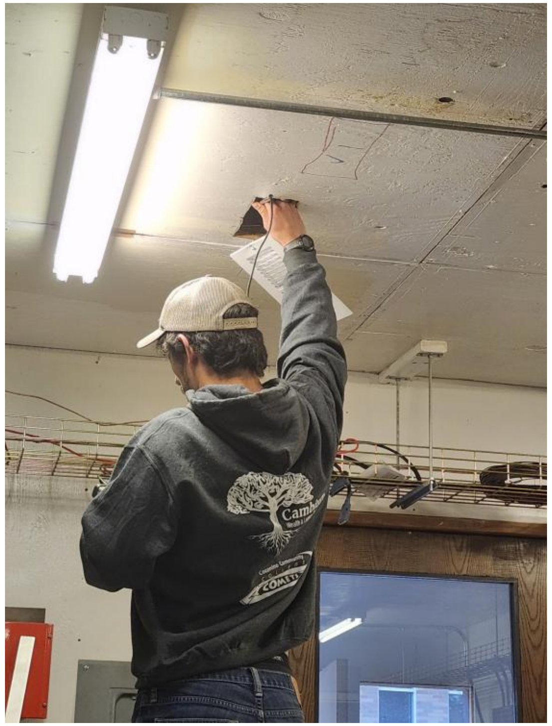

Figure 42: Vent 2 output flow rate test

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VOLTAGE DROP TEST

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 43: Multimeter Voltage Test at First J-Box

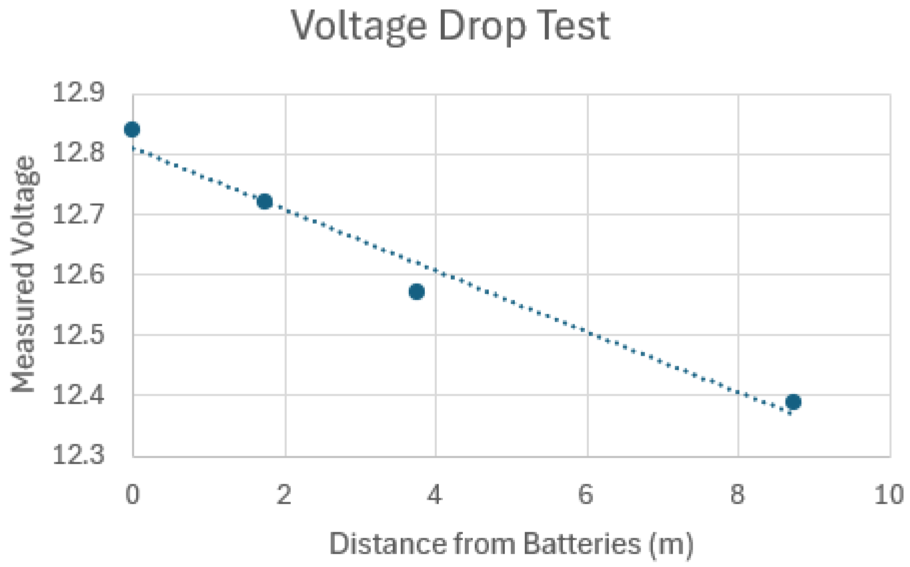

Figure 44: Voltage Drop Plot

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QFD AND DESIGN REQUIREMENTS

Quality Function Deployment

Project title: RE Lab Solar Heater
Project leader: Brendan Frazier
Date: 6/10/2025

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

5	3	1	0
Strong	Moderate	Weak	None

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	-

Competitive evaluation (1: low, 5: high)

	Customer importance rating (1: low, 5: high)	Desired direction of improvement (↑,0,↓) / 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	↑	↑	↓	[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	$1,000	20 kg						
		Priorities rank	1	5	7	[redacted]	3	4	8	9	6						

Figure 45: QFD

Specification Sheet CRS

Table 4: Customer Requirements Specification Sheet

Customer Requirement	CR Met? (✓ or ✗)	Client Acceptable (✓ or ✗)
1) Reduce Load by 30%	✗	✓
2) Function in Winter	✓	✓
3) Use Renewable Energy	✓	✓
4) No Significant Mods	✓	✓
5) Must be Safe	✓	✓
6) Minimal Maintenance	✓	✓
7) 10 Year Payback	✓	✓
8) Visual Indicator of Status	✓	✓
9) Monitoring System	✓	✓
10) No Overheating	✓	✓

Tyler Hedgecock

Specification Sheet ERS

Table 5: Engineering Requirements Specification Sheet

Engineering Requirement	Target	Tolerance	Measured/Calculated Value	ER Met? (✓ or ✗)	Client Acceptable (✓ or ✗)
ER1 – Energy Stored	30 kWh	+/- 5	7.6 kWh	✗	✗
ER2 – Insulation	10 R	+/- 2	8 R	✓	✓
ER3 – Thermostat Control	n/a	n/a	n/a	✓	✓
ER4 – Flow Rate	190 CFM	+/- 10	157 CFM	✗	✓
ER5 – Life Expectancy	10 Years	n/a	10-15 Years	✓	✓
ER6 - Cost	$3000	< $3000	$2527.84	✓	✓
ER7 – Mounting Weight	20 kg	+/- 5	11.4 kg	✓	✓

FUTURE WORK

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Thank You
Questions?

Appendix

Appendix A: LITERATURE REVIEW

- Books / Chapters
  - Shigley's Mechanical Engineering Design 10th edition [3]
    - Reference textbook for fundamental concepts and equations.
  - Fundamentals of Heat and Mass Transfer 8th edition (Chapter 6) [1]
    - Reference textbook for fundamental concepts and equations.
  - Introduction to Fluid Mechanics 10th Edition [2]
    - Reference textbook for fundamental concepts and equations.
- Papers
  - Review on solar air heating system with and without thermal energy storage system [4]
    - Research on phase change materials used for latent heat storage vs sensible heat storage and solar air heater applications and performance.
  - Estimation of the heating time of small-scale buildings using dynamic models [59]
    - Estimates time taken for a certain temperature increase to find optimal time to turn on heating system.
  - R. S. Subramanian, Pipe flow calculations [60]
    - Examples and figures of pipe flow calculations with assumptions, constants, and equations used.
- Online Resources
  - Wind and weather statistic Flagstaff Pulliam Airport [13]
    - Weather data in flagstaff Az that was used for calculations.
  - Numerical Simulation Study on Transpired Solar Air Collector [11]
    - A published study with simulation results of their solar air collector's performance.
  - Active Solar Heating [37]
    - A .gov website detailing how active solar heating systems work.
  - What You Can Do in SolidWorks Flow Simulation [6]
    - SolidWorks tutorial and help with using the flow simulation model.
  - Solar Air Heater – DIY [9]
    - Online website forum where people talk about how they designed or built their own solar air heaters.
  - DIY Solar Air Heater Part #1 [10]
    - A YouTube series where the person shares their DIY approach and steps to building an at home solar air heater.

Appendix B: LITERATURE REVIEW

- Books / Chapters
  - Fundamentals of Heat and Mass Transfer 8th edition (Chapter 3) [1]
    - Reference textbook for absorber plate efficiency with examples and equations.
- Papers
  - Wind Loads on Flat Plate Photovoltaic Array Fields[38]
    - Equations and tables on wind load calculations for flat and variably angled solar panels.
  - Thermal Performance Improvement Method for Air-Based Solar Heating Systems [15]
    - Equations based on volume of space and direction of panel angle to optimize efficiency
  - Calculation of Optimal Thermal Load of Intermittently Heated Buildings [16]
    - Reference for calculating building heat load requirements as part of validation for heat load simulation
- Online Resources
  - Building Thermal Performance Analysis by Using MATLAB/SIMULINK [14]
    - Reference website for using MATLAB in developing energy model / mathematical simulation
  - National Weather Service: Flagstaff Pulliam Airport [19]
    - Provides weather data needed during testing processes and design process based on historical data
  - How Does Central Heating and Cooling Work? [17]
    - Documentation on optimization of building heating including pump/fan requirements and distribution of heat
  - Research on Heating Performance of Heating Radiator at Low Temperature [34]
    - Used in design selection process for preliminary analysis on water based solar thermal system
  - National Weather Service: Weather Conditions for Flagstaff [19]
    - Used in data collection for calculating losses in solar panels based on outside temperature, irradiation, and precipitation that are recorded hourly

Appendix C: LITERATURE REVIEW

- Books / Chapters
  - Fundamentals of Heat and Mass Transfer 8th edition (Chapter 13, PDF) [1]
    - Serves as a reference to perform radiation analysis and calculate the energy input of the solar air panels.
  - Fundamentals of Engineering Thermodynamics 8th edition (PDF) [26]
    - Specific for fans and heat pumps, to decide which one to utilize for the heating system.
- Papers
  - Design and Implementation of Peltier Based Solar Powered Air Conditioning and Water Heating System [27]
    - Discusses the possibility of replacing HVAC systems with a peltier prototype to mitigate the issue of greenhouse gases and obtaining air conditioning and water heating applications from a single source.
  - Experimental Analysis of Artificial Equilateral Triangle Solar Air Heater Using Zig-zag Channel [23]
    - Analyzes the use of a flat plate, triangular plate with one passage, and a triangular plate with zig-zag air flow for dark and light passes regarding energy and thermal efficiencies.
  - Energy Saving of Air Conditioning System by Oscillating Heat Pipe Heat Recovery Using Binary Fluid [28]
    - Examines oscillating heat exchangers to improve energy savings and thermal efficiency in heat pipes.
- Online Resources
  - Everything You Should Know About Inverter Heat Pumps [29]
    - Explores how an inverter heat pump works and its efficiency when supplying air condition to homes.
  - Solar Panel Cost [31]
    - Shows the trends of solar panel costs over the years and how it decreased over time.
  - What Wavelength Do Solar Panels Use? [30]
    - Discusses the wavelengths of different solar panel types and helped aid the team in designing the solar air heating system to understand the wavelengths they can absorb.
  - Absorbed Solar radiation [24]
    - Provides information about the absorptivity of a surface due to color and material.
  - Solar Energy and solar power in Flagstaff, AZ [32]
    - Provides data for the solar irradiation in Flagstaff, AZ. By using this information, it aided in calculations to accurately determine the amount of solar energy the solar panels will be absorbing in the winter.

Appendix D: LITERATURE REVIEW

- Books / Chapters
  - Fundamentals of Heat and Mass Transfer 8th edition (Chapter 7) [1]
    - Reference textbook for which is the movement of fluid (like wind) over a surface

- Online Resources
  - A complete guide to home ductwork design – Stack Heating [36]
    - Homeowner-focused guide on duct design and HVAC layout; useful for understanding airflow routing relevant to your solar air system.
  - Solar Air Heating – Arctica Solar [37]
    - Overview of solar air heating technology and operational principles; helpful for describing how your system works.
  - Active Solar Heating – Energy.gov [38]
    - Federal reference explaining types of active solar heating systems, performance factors, and system components.
  - CFM Calculator – Omni Calculator [39]
    - Tool for calculating airflow (CFM), used for blower sizing and duct sizing in your capstone project.
  - HVAC Duct Calculator (Duct Size) – ServiceTitan [40]
    - Online calculator for determining duct dimensions based on inputs like CFM and friction loss.
  - How to Install Solar Panels on a Roof – This Old House [41]
    - Reference for panel mounting procedures, roof integration, and installation steps.
  - How to Calculate CFM for HVAC – Housecall Pro [42]
    - Explains HVAC CFM calculation methods & formulas, useful for airflow testing and fog-leak testing.
  - Solar Air Heater – Instructables [43]
    - DIY reference on solar air heater construction and design principles similar to your recycled collector

Appendix E: LITERATURE REVIEW

Books / Chapters

- Fundamentals of Heat and Mass Transfer, 8th Edition, Chapter 12: Radiation [44]
  - Equations for calculating performance of solar air and solar water heaters
- Theory And Design for Mechanical Measurements, Chapter 8: Temperature Measurements [45]
  - What thermocouples to use in each scenario and how to calibrate them
- ASHRAE Handbook & Product Directory, 1980 Systems [53]
  - Manual J method of calculating heat loads

Papers

- On-Grid Flat Plate Solar Water Heater Collector Application for Electrical Energy Saving Contribution [46]
  - Informs design decision on whether storage tanks are necessary for solar water heater
- Study of the enhancement in the performance of a hybrid flat plate solar collector using water and air as working fluids [47]
  - Study of the increased cost and efficiency of hybrid (water and air) solar collectors
- Efficient design of converged ducts in solar air heaters for higher performance [48]
  - How to maximize efficiency of solar air panels using duct placement

Online Resources

- ThermoPowerTM 30 Tube Evacuated Tube Solar Collector [43]
  - Performance of solar water heaters in varying environments
- Solar PV Analysis of Flagstaff, United States
  - Electrical output of solar panels in Flagstaff
- ASHRAE Standards and Guidelines [50]
  - Building codes
- Rocks: The Unexpected Powerhouse of Sustainable Solar Energy Storage – SolarPACES [51]
  - Potential medium for thermal batteries if solar air heater is used
- Solar Energy and Solar Power in Flagstaff, AZ [52]
  - Seasonal solar data in Flagstaff
- 4000 Series Solar Air Heater [54]
  - State of the art solar air heater
- How Heat Load Calculation Works – Phononic [55]
  - Introduction to heat load calculations and related equations
- Cooling and Heating Equations – Engineering Toolbox [57]
  - Sensible heat formula uses temperature and flowrate to calculate energy