Red Feather Thermal Energy for Homes

Capstone Team 4:

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Project Description

Client: Mark Hall, the Executive Director of the Red Feather non-profit organization [1].

Mark's scope for this project is to conduct a cost analysis on alternatives to coal as a fuel and to determine the most affordable and safe way to improve heating in the Hopi and Navajo reservation homes for winter.

The ideal cost for this purpose would range from $1200 to $1500.

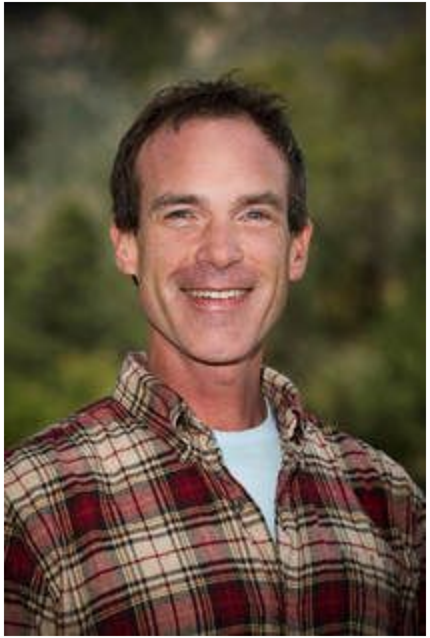


Figure 1: Mark Hall [1]

Project Description

- Currently, coal stoves serve as the main source of home heating
  - Inefficient
  - Causes pollution inside and outside homes
  -
- Navajo Generating Station (NGS) and Kayenta Coal Mine are in the process of closing
  - Free coal no longer available for reservation
  - This problem is time dependent and will need to be addressed sooner than later.

Figure 2: Peabody Kayenta Coal Mine [2]

Project Description

- Red Feather Development Group
  - Non Profit in Flagstaff provides assistance to residents of the Reservations in improving and retrofitting homes [3]

- Constraints
  - Families don’t have disposable income
  - No grid access
  - Isolated regions: little access to fuel and resources

Figure 3: Red Feather Development Group Logo [3]

Functional Decomposition

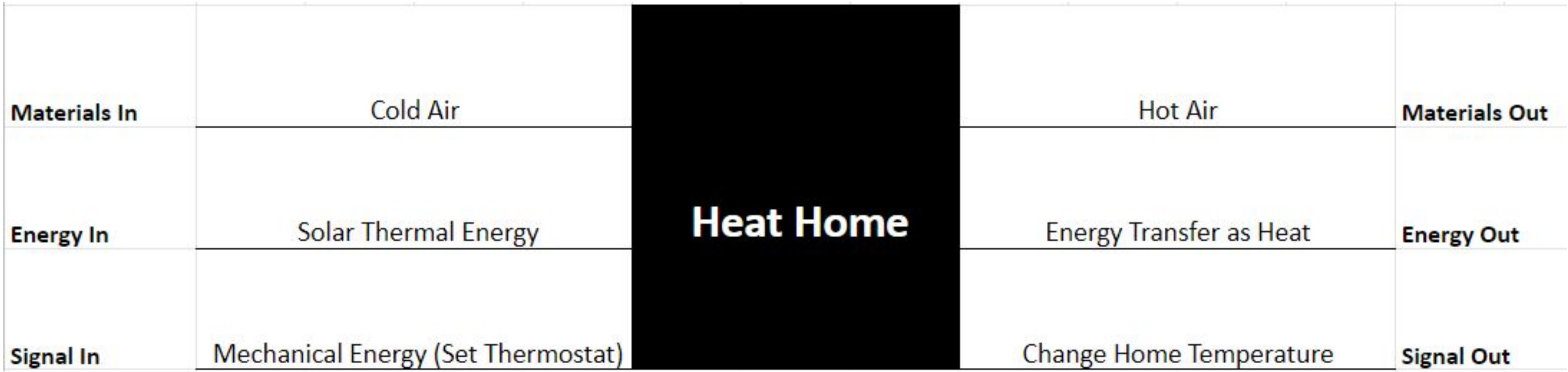


Figure 4: Black Box Model

Functional Decomposition

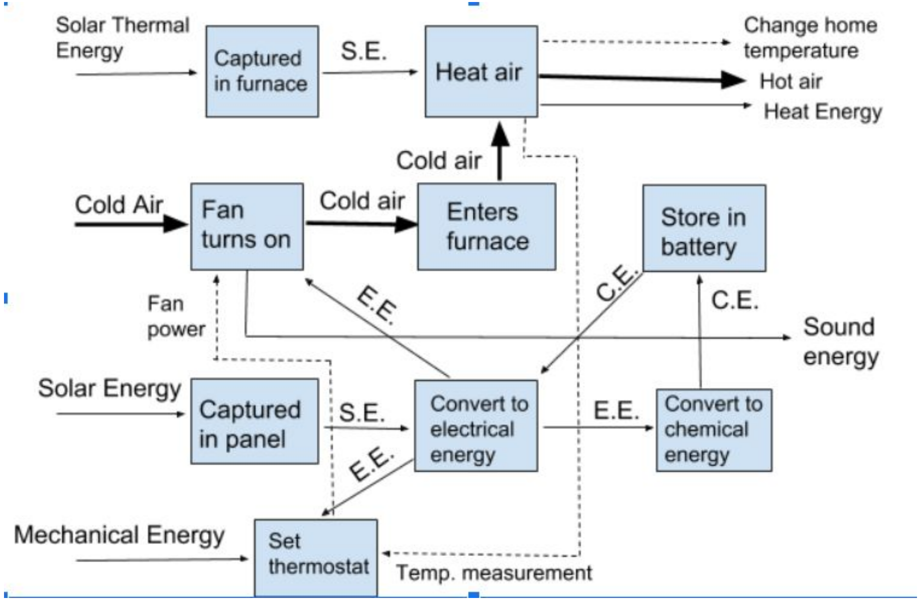


Figure 5: Initial Functional Decomposition

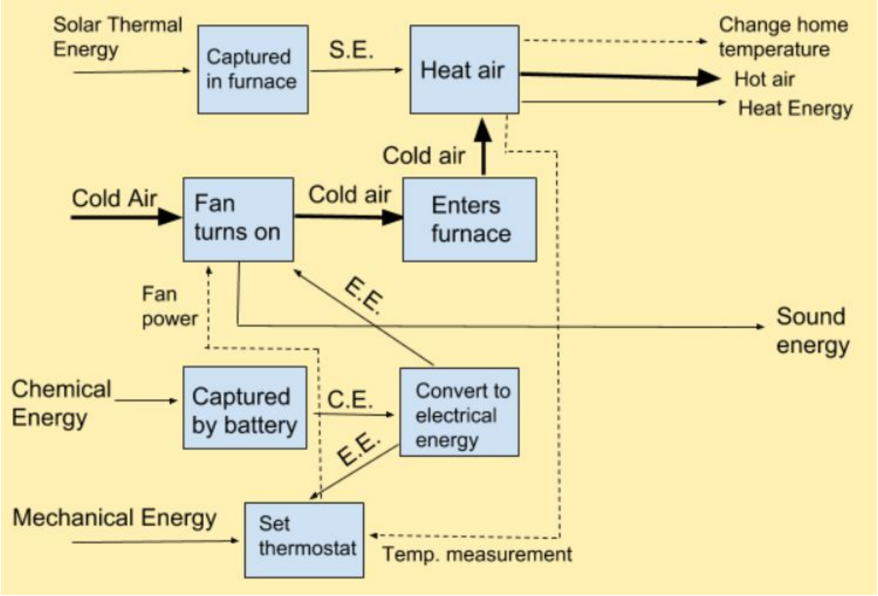


Figure 6: Current Functional Decomposition

Concept Generation

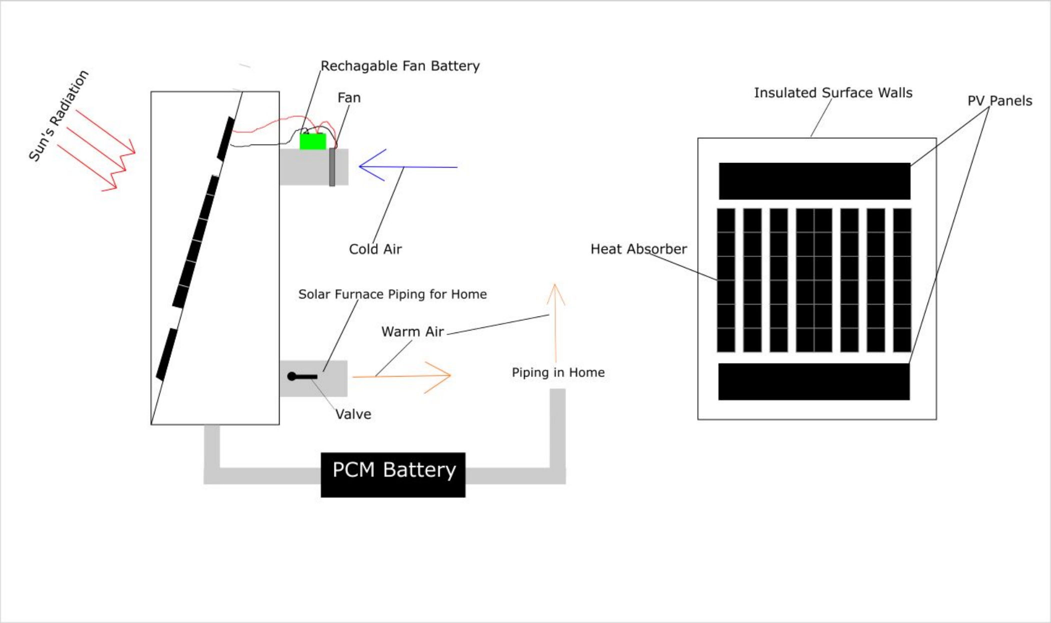


Figure 7: Base Concept Generated for Modeling

Current Design

- Analytical Project
- Main focus: Economics
- Energy Modeling to find operational costs
- Consider up front costs vs. lifetime costs, while considering health and safety benefits
- Regional needs determine viability
- Assume 500 square foot red masonry home - common construction on reservation

Figure 9: Common Navajo Reservation Home [4]

Software Concepts

- Important to select energy software that is able to model concept designs
- EnergyPlus (Trimble SketchUp with OpenStudio plugin)
  - Able to model phase change materials through SketchUp
  - Limited availability due to lack of plugin support
- EQuest
  - No direct PCM modeling capability but it is possible through workarounds
  - Support available through NAU

Energy Modeling

- Selection: EQuest
- Energy model includes specifications of structure
- Outputs fuel/energy consumption meters
- Input parameters include building materials, insulation type and amount, and occupancy

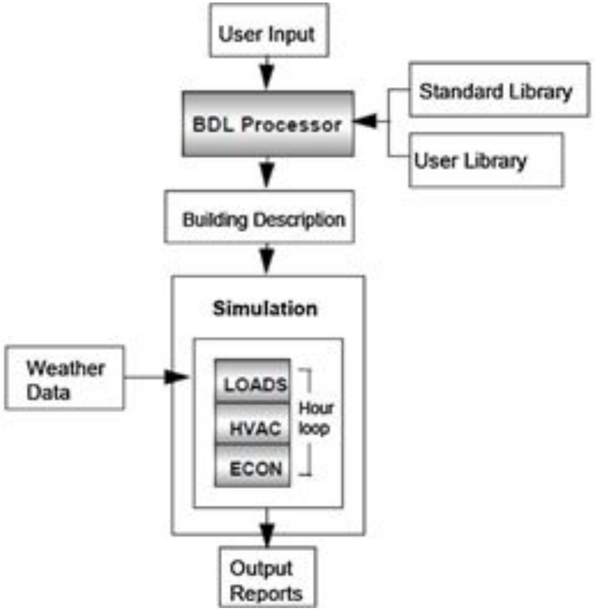


Figure 8: EQuest Flow Chart [5]

Energy Modeling

- Some Scenarios Considered:
  - Coal Furnace
  - Solar Furnace
  - Insulation Amount and Location
  - Phase Change Material (PCM) Thermal Battery
  - Other Building Characteristics (Window Types, Building Materials)

Layers: EWall Cons Layers

Inside Film Resistance (R-val): 0.680

Material Layers (ordered from outside to inside):

	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	Face Brick 4in (BK05)	0.333	0.7576	130.00	0.220	n/a
2	Conc HW 140lb 4in (CC03)	0.333	0.7576	140.00	0.200	n/a
3	EWall Cons Mat 2 (10.19)	n/a	n/a	n/a	n/a	10.190
4	GypBd 1/2in (GP01)	0.042	0.0926	50.00	0.200	n/a
5		n/a				
6		n/a		n/a	n/a	
7		n/a		n/a	n/a	n/a
8		n/a	n/a	n/a	n/a	
9		n/a	n/a		n/a	n/a
10	n/a	n/a				n/a

Figure 10: EQuest Wall Layers

Energy Modeling

- Consider output of different models
  - Which models are even viable based on price?
  - Which models present the best return on their installation cost?
  - Any models excluded based on health/safety constraints?

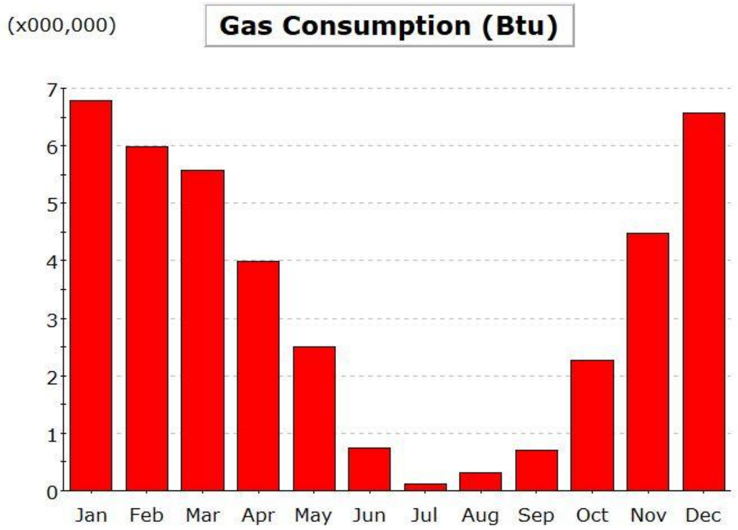


Figure 11: EQuest Consumption Model

Energy Modeling

Figure 20: 2-D View of EQUEST model home.

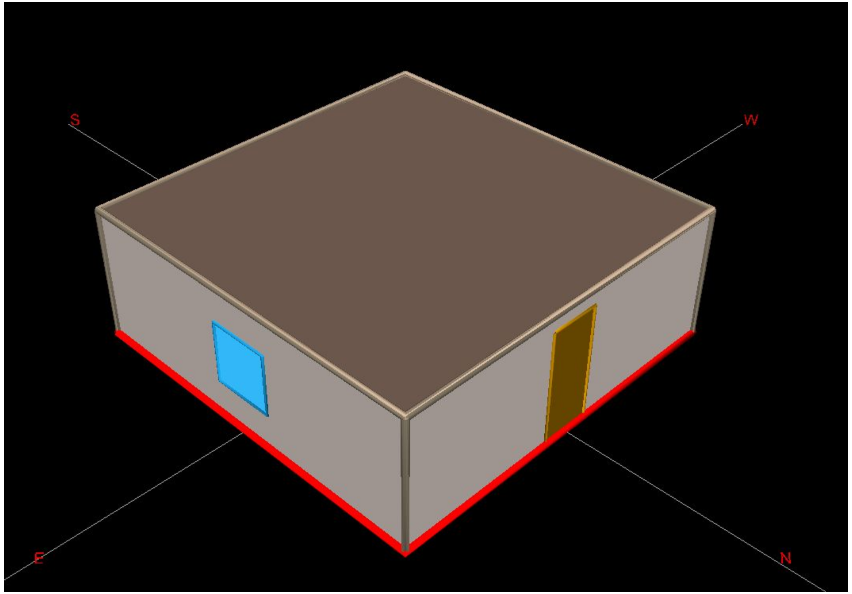


Figure 21: 3-D View of EQUEST model home.

Analyses Summary (Will Legrand)

- Geometry of Thermal Battery components affects the rate of heat transfer in and out of the battery.
- Forced convection is the major source of heat transfer as the battery is exposed to a duct
- Conduction also plays a role depending on the design

$$T_{air,out} - T_{air,in} = \frac{q'' A_s}{\dot{m} C_{p,fluid}}$$

$$Re = \frac{4\dot{m}}{\pi D \mu} \qquad h = Nu \frac{K}{L}$$

$$q = h(A_s - N_{fins} A_{c,fin})(T_s - T_\infty) + N_{fins} hP K_{fin} A_{c,fin} (T_s - T_\infty) \tanh\,[\text{sqrt} \sqrt{\left(\frac{hP}{K_{fin} A_{c,fin}}\right)} L]$$

Figure 12: Internal Convection Equations [6]

Analyses Summary (Will Legrand)

- Convection
- Opportunities for increasing heat transfer in and out of battery include extended surfaces and increasing the exposed surface area
- For phase change materials, the most effective means of increasing heat transfer is use of a metal foam with embedded PCM - large surface area increase

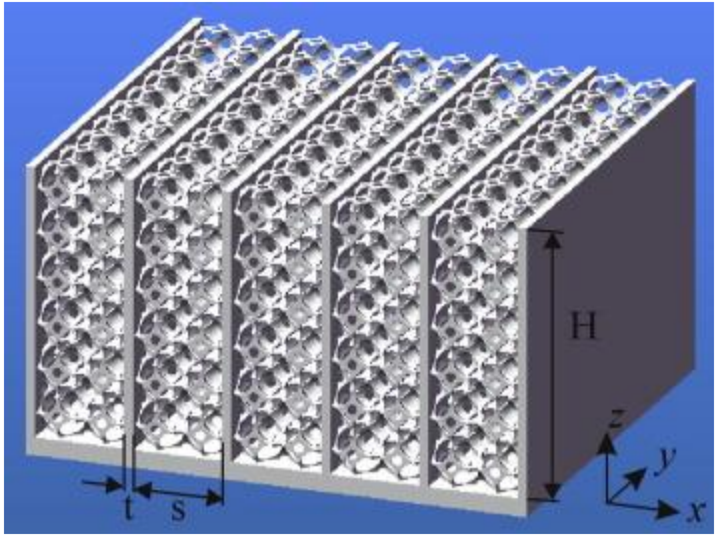


Figure 13: PCM with Metal Foam [7]

Analyses Summary (Jeff Macauley)

Temperature inputs

Ambient Temperature	T =	65	F
	T =	291.3833	K
PCM Temperature	T_s =	100	F
	T_s =	310.8278	K

Dimensions of Rectangular ducting

Width	W =	0.1016	m
height	H =	0.127	m
Length	L =	1.2	m
wetted perimeter	P =	0.4572	m
Cross sectional area	A =	0.012903	m^2
Hydraulic Diameter	D_h =	0.112889	m

Figure 14: Geometric properties and temperature inputs

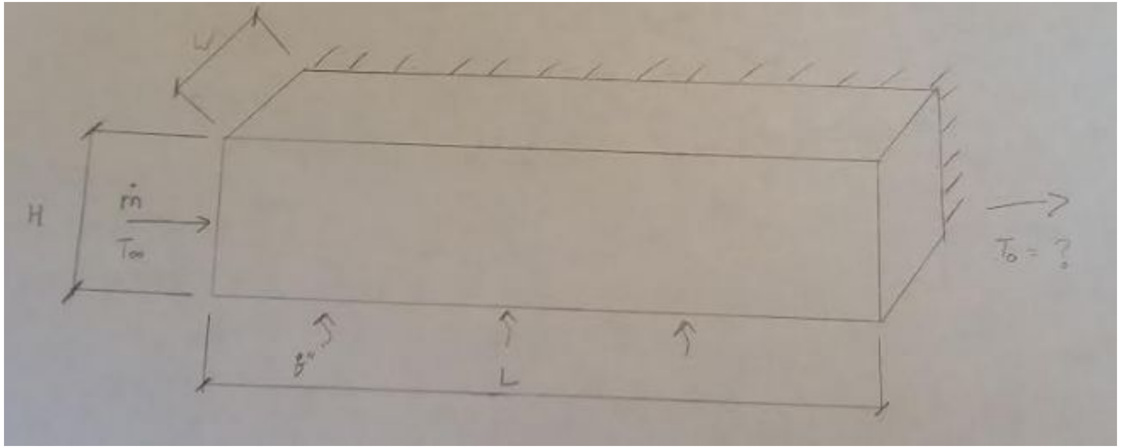


Figure 15: Representation of Experimental Model

Analyses Summary (Jeff Macauley)

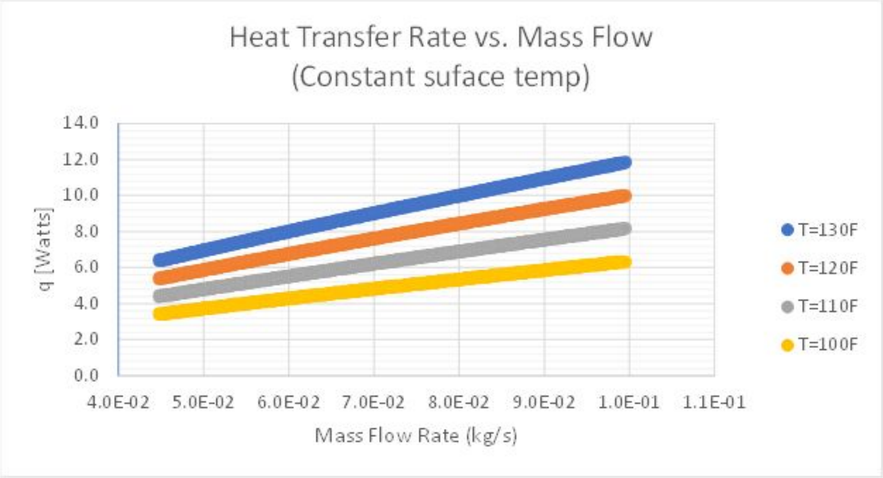


Figure 16: Heat Transfer Rate

$$f = (0.790 \ln Re_D - 1.64)^{-2}$$

$$Nu_D = \frac{(f/8)(Re_D - 1000)\,Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

$$\bar{h} = \overline{Nu}_D \frac{k}{D}$$

$$q_{conv} = \bar{h} A_s \Delta T_{lm}$$

Figure 17: Equations [6]

Approximately two lbs of paraffin wax will take half an hour to solidify

Analyses Summary (Jeff Macauley)

$$\frac{T_s - T_m(x)}{T_s - T_{m,i}} = \exp\left(\frac{-Px\bar{h}}{\dot{m}c_p}\right)$$

Figure 18: Equations [6]

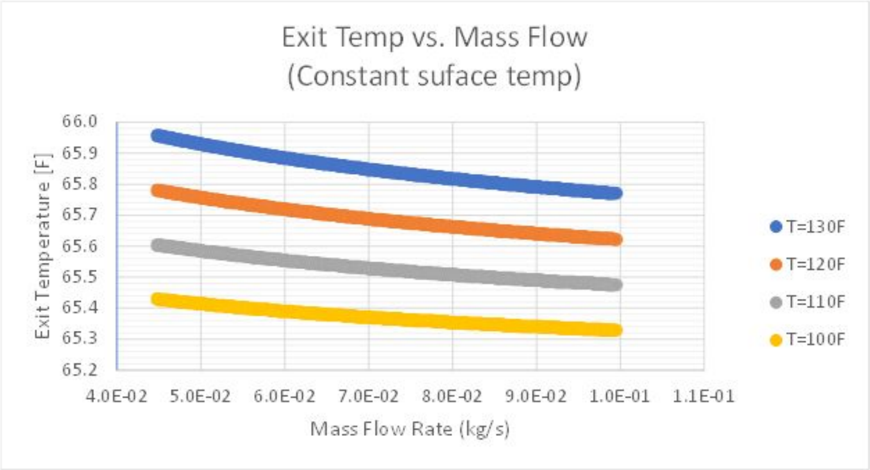


Figure 19: Duct Exit Temperature

Velocity range: 3 - 6.7 m/s

Some Model Assumptions

The model home is a 500 square foot 1 story home made with red masonry brick. It has 3 single paned windows and a door. The home has minimal access to electricity, and all electrical systems were removed in subsequent models. All models are operating with a coal furnace which produces 10,000-30,000 Btu/hr and has an efficiency of 77% [8]. The models created and their assumptions are the following:

Model 1: Coal Furnace with No Insulation in Walls or Ceiling and Minimal Electrical Systems

- Thermostat and fan are the only electrical systems to our knowledge being read.
- 5 people inhabit the home and produce 450 Btu/hr-person
- No ground floor finish

Model 2: Coal Furnace with No Insulation, people or Electrical Systems

Model 3: Coal Furnace with Insulation and Minimal Electrical Systems

- Thermostat and fan are the only electrical systems to our knowledge being read.
- 5 people inhabit the home and produce 450 Btu/hr-person
- R-13 Insulation in Walls (Fiberglass 3 5/8 in is an option)
- Vinyl floor finish on the ground base and ceiling insulation
- R-3(Mineral Wool of about an inch)

Some Model Assumptions

Model 4: Coal Furnace with Insulation and no people or Electrical Systems.

Model 5: Coal Furnace with Insulation, PCM heated airflow, and no people or electrical systems.

- Thermostat and fan are the only electrical systems to our knowledge being read.
- 6 people inhabit the home and produce 2500 Btu/hr-person (THis is done to model the PCM)
- R-13 Insulation in Walls (Fiberglass 3 5/8 is an option)
- Vinyl floor finish on the ground base and ceiling insulation
- R-3(Mineral Wool of about an inch)

$$\sqrt{X * \frac{0.429923\frac{BTU}{lb}}{1\frac{kJ}{kg}} * \frac{160lb}{1\,person} * \frac{350BTU}{hr*person}} = \frac{155.1634*\sqrt{X*\frac{kg}{kJ}}*BTU}{hr*person}$$

Figure 22: Equation to model Btu/hr-person given a heat Storage Capacity(X) in kJ/kg [9]

Analyses Summary (Edwin Beraud)

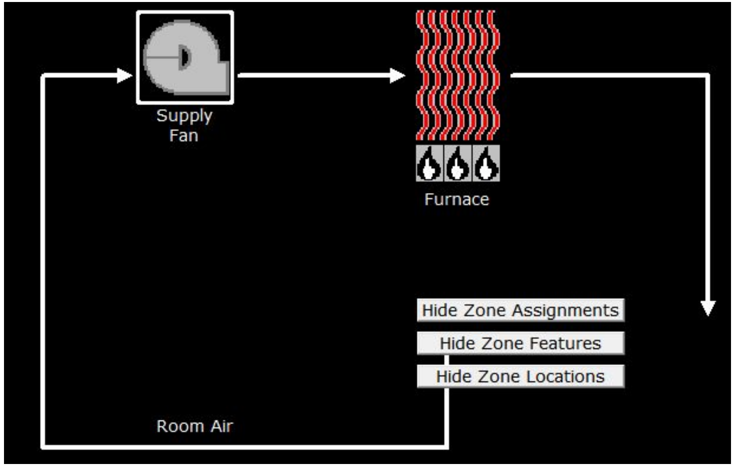


Figure 23: Coal Furnace Model

Material			BTU/hr	Cost ($)
Coal	2000	lb	19460000	33.72
	1	lb	9730	

Coal needed for 15000 BTU/hr	Units	Cost ($)	24hr Cost ($)
2.374100719	lb	0.040027	0.960656115

Material			BTU	Cost ($)
Propane	8.35552	lb	91547	2
Pound	1	lb	10956.4695	

Propane needed for 15000 BTU/hr		Cost ($)	24hr Cost ($)
2.108343386	lb	0.504659	12.11181142

Figure 24: Coal vs Propane Price Comparison [10],[11],[12]

Mount of PCM with Heat Capacity 260kJ/kg needed to produce 15000 Btu per hour							
Heating Hours	1	2	3	4	5	6	7
Weights(kg)	60.5109816	121.022	181.5329	242.0439	302.5549	363.0659	423.5769
Price $	328.57463	657.1493	985.7239	1314.299	1642.873	1971.448	2300.022

Figure 25: PCM Price Comparison under optimal heat release in bulk configuration [13]

Analyses Summary

PCM Model Biot Number Calculation

Paraffin Properties	Values
Operational Temperature(T)	300 K
Density(ρ)	900 kg/m^3
Thermal Conductivity (k)	0.240 W/mK
Specific Heat (Cp)	2890 J/kgK

Figure 26: Paraffin Properties[6]

$$Bi = \frac{L_c h}{k_f}$$

$$Re = \frac{\rho_{air} * u * L}{\mu}$$

$$Nu = 0.664 Re^{0.5} Pr^{\frac{1}{3}}$$

$$h = \frac{Nu * k_p}{L_c}$$

Figure 27: Eqns. used to find Biot Number [6]

Air Properties @ Film Temperature		
Viscosity (Ns/m^2) -µ	Density(kg/m^2)-ρ	Prandtl Number (Pr)
0.00001971	1.073	0.703

Parameter	Magnitude	Units
Initial Temperature (Ti)	27.0	C
Fluid Temperature (To)	80.0	C
Film Temperature (Tf)	53.5	C
Plate Length(L)	0.1035	m
Characteristic Length of Plate (Lc):	0.05175	-
Airflow Speed(u)	3.0	m/s
Thermal Conductivity of Air(kf)	0.02826	W/mK
Thermal Conductivity of Paraffin	0.24	W/mK
Reynolds Number	16903.42466	Laminar Flow
Nusselt Number	76.76098497	
Thermal Coefficient of Air (h)	41.91817266	W/m^2K
Paraffin Plate's Biot Number	9.03860598	-

Figure 28: Parameters calculated and Biot Number [6]

Model Results(Btus needed to heat up the home over he months)

Model 1	**Coal Model w/ People and Electricity(Minimal)**												Total Btus of Months of interest
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Btux10^6	8.81	7.95	7.4	4.98	2.77	0.61	0.03	0.13	0.64	2.85	6.66	8.93	25.69
Model 1	**Coal Model w/ no People or Electricity**												
Btux10^6	9.27	8.41	8.33	6.19	3.97	1.14	0.21	0.55	1.32	4.03	7.83	9.47	27.15
Model 2	**Coal/Insulation Model w/ People and Electricity(Minimal)**												Total Btus of Months of interest
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Btux10^6	5.54	4.84	4.29	2.75	1.39	0.25	0	0.01	0.13	1.2	3.19	5.32	15.7
Model 2	**Coal/Insulation Model w/ no People or Electricity**												
Btux10^6	7.21	6.37	6.02	4.44	2.96	1.01	0.27	0.58	1.03	2.71	4.93	6.99	20.57
Model 3	**Coal/Insulation/PCM Model w/ no People or Electricity**												Total Btus of Months of interest
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Btux10^6	6.56	5.77	5.33	3.74	2.27	0.64	0.09	0.24	0.55	2.02	4.25	6.35	18.68
(blue)	**Compare Values for models under similar conditions**												
(yellow)	**Months of interest**												

Analyses Summary (Jake Shaw)

- Solar furnace selection process using specification sheets from the Solar Rating and Certification Corporation [14]
- Best type of solar furnace for this home: Glazed Flat Plate Collector
- The most solar radiation is obtained from a south-facing panel at 50.13° from horizontal [15]
- Required average heat output: 120,000 BTUs/day
- Solar furnaces compared based on heat output, size, and number of panels required
- Heat output of the panels was determined for the coldest months of the year, assuming below average solar radiation

Analyses Summary Cont. (Jake Shaw)

- Selected solar furnace: Fresco Glazed Flat Plate manufactured by Trigo Energies Inc. [16]
- Energy Output: 33029.53 BTUs/panel/day [16]
- To meet required heat output, there would need to be four of these panels
- At a gross area of 5.25 m²/panel, this would take about 21 m²
- Covers about half of the roofing for a 500 sq. ft. home

Figure 27: Similar collectors developed by Trigo Energies [17]

Design Requirements

- Improve current heating solution
- Maintain comfortable temperature in winter
- Must account for heat loss from home
- System must be reliable with temperature fluctuations
- Cannot pose unacceptable health or safety risks to the home occupants or neighbors

Schedule

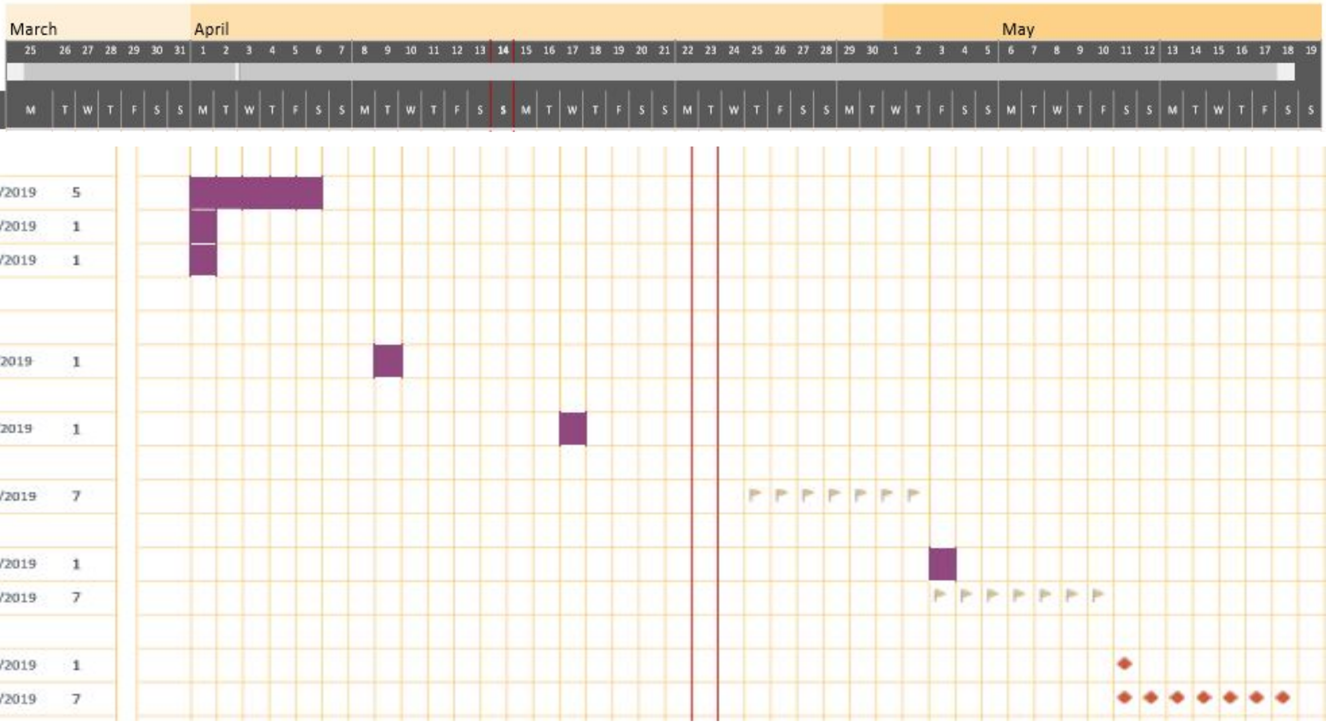
PROJECT TITLE **Red Feather**

Project number 4
Project Lead Jake S.

Project Start Date: 1/22/2019
Scrolling Increment: 62

Legend: On Track | Low Risk | Med Risk | High Risk | Unassigned

Milestone Description	Category	Assigned To	Progress	Start	No. Days
Week 9					
Furnace Software	Med Risk	TBD	100%	3/26/2019	5
Staff Meeting 4	Med Risk	TBD	100%	3/26/2019	1
Website Check 2	Med Risk	TBD	100%	3/26/2019	1
Week 10					
Staff Meeting 5	Med Risk	TBD	100%	4/2/2019	1
Week 11					
Staff Meeting 6	Med Risk	TBD	100%	4/9/2019	1
Week 12					
Presentation 3	Milestone	TBD	100%	4/16/2019	7
Week 13					
Staff Meeting 7	Med Risk	TBD	0%	4/23/2019	1
Final Report	Milestone	TBD	25%	4/23/2019	7
Week 14					
Website 3	Goal	TBD	30%	4/30/2019	1
BOM/CAD	Goal	TBD	25%	4/30/2019	7



Budget

- No expenses to date
- No anticipated expenses
- Theoretical price for the system is between $1200 and $1500
- Theoretical anticipated expenses include price of insulation, solar collectors, and possibly a ventilation system

Questions?

References

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