INTERIM DESIGN REVIEW THERMAL STORAGE DEVICE

GROUP 17

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VERDICORP

- Organic Rankine Cycle Power systems
- Builds Modular Vapor Power cycles
- Runs from waste or low temperature heat sources
- Uses environmentally friendly fluids (R245a)

Figure 1. Image of Verdicorp ORC System

NEED & SOLUTION

Depending on waste or renewable heat sources causes:

1. unreliable power output
2. Limits running time to that of the fuel source
3. Decreases system efficiency

Solved by inclusion of Thermal Energy Storage

Goal: To produce a commercially viable thermal storage solution for Verdicorp's Rankine Cycle utilizing environmentally friendly materials.

THERMAL ENERGY STORAGE

Forms of storage:

- Sensible
- Latent

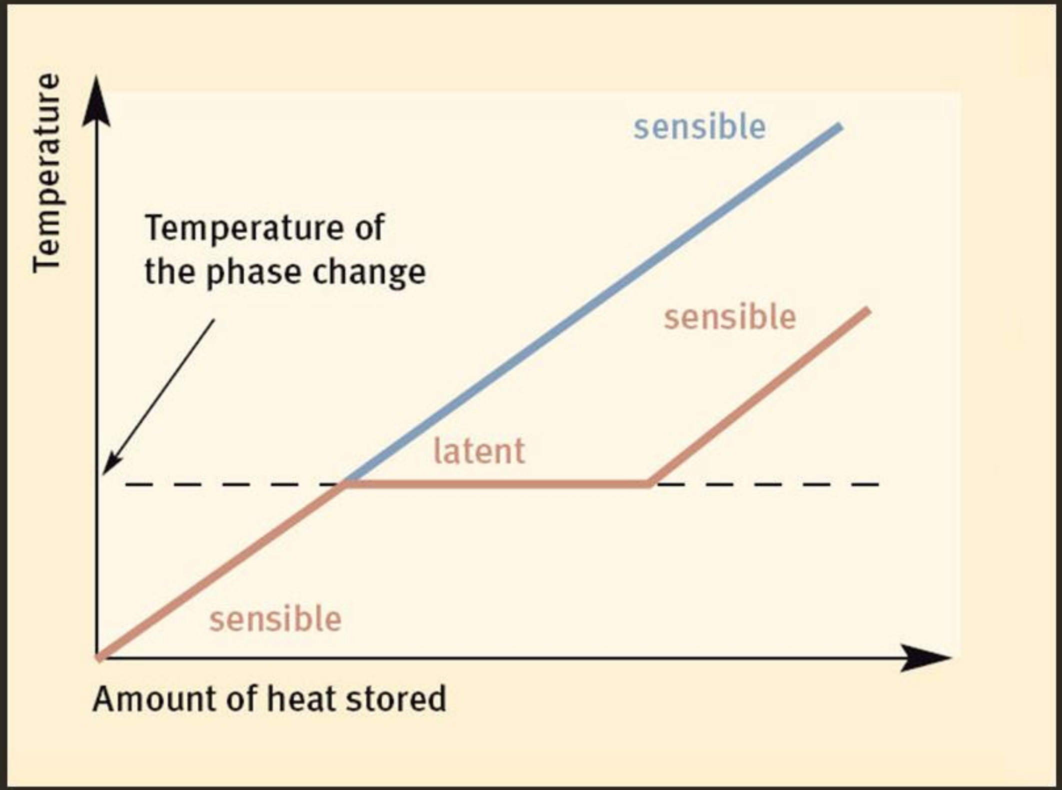


Figure 2. Heat Storage Forms

LATENT HEAT STORAGE

- Based on Shell-and-tube heat exchanger
- Tubes are 12 inch long Schedule 10
- Transfer fluid transfers heat to/from phase change material
- Full size: 37.8GJ Model: 8.8MJ
- Energy Scale: 1/4000th
- Capsule Length Scale: 1/20th

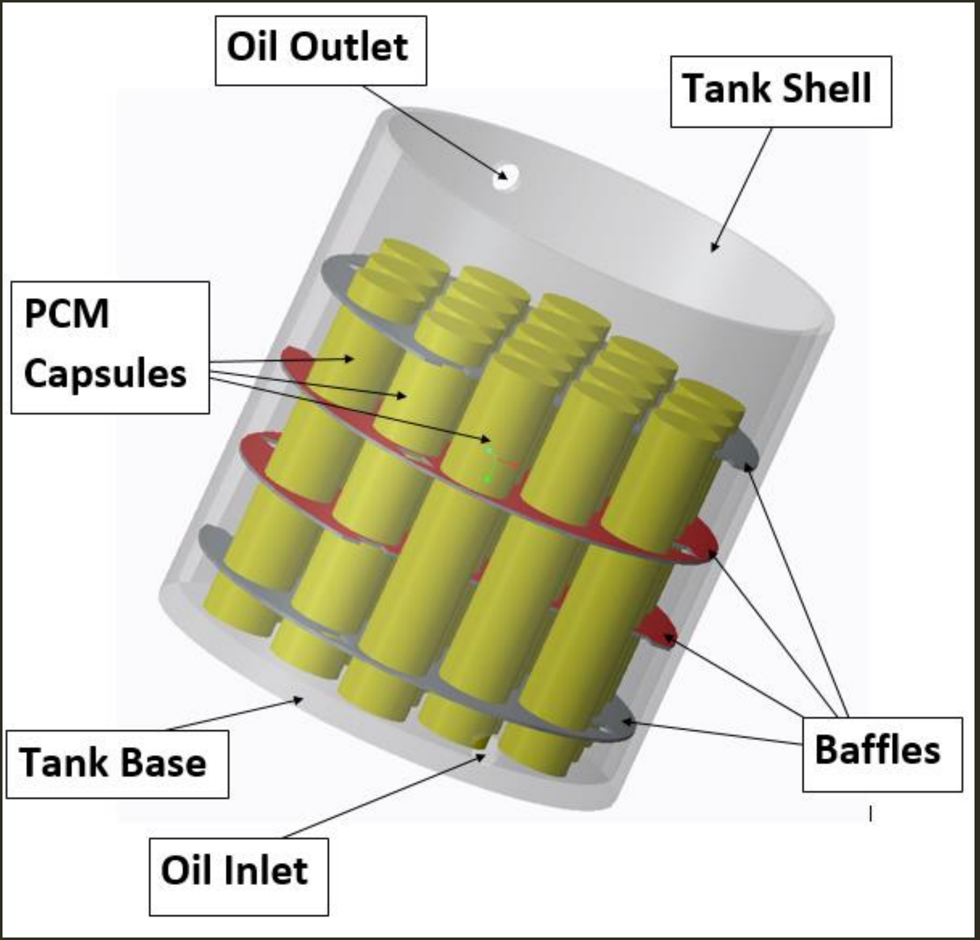


Figure 3. Model of Latent Heat Storage Device

SYSTEM OVERVIEW

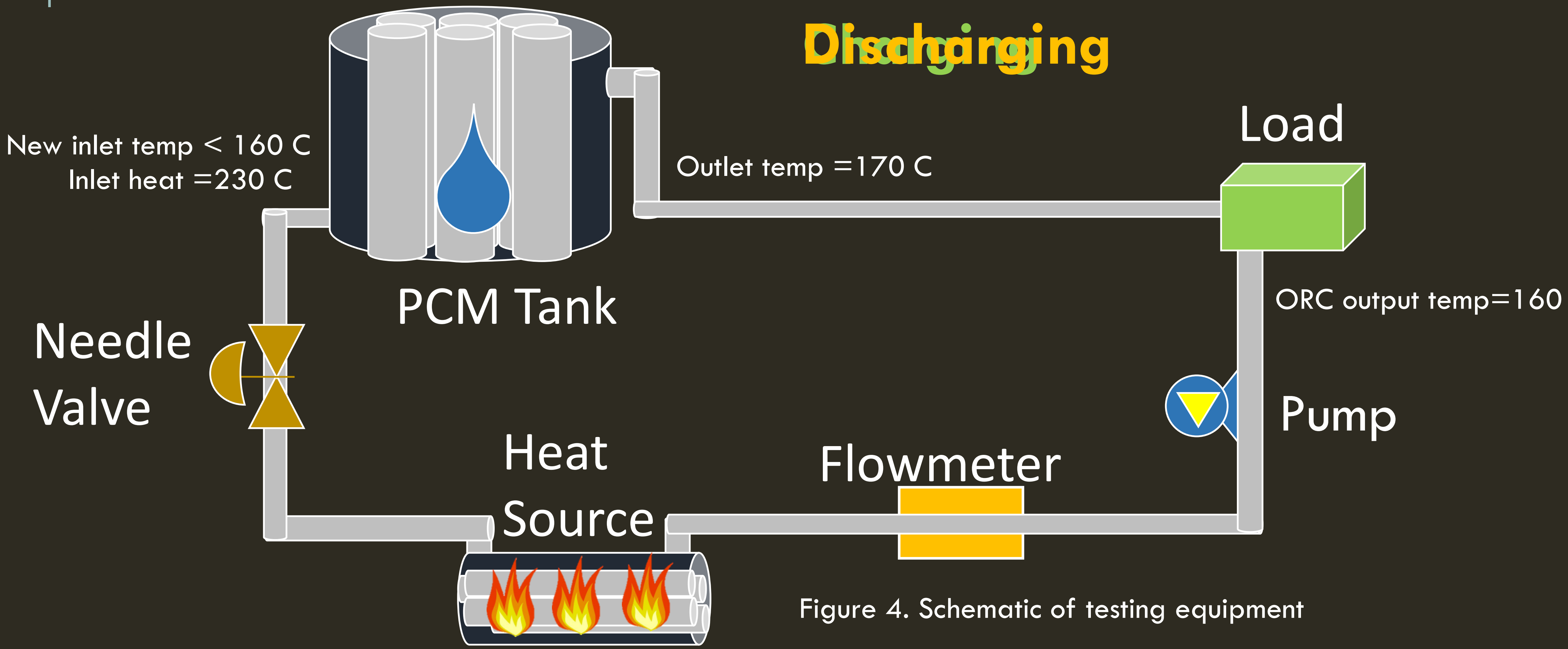


Figure 4. Schematic of testing equipment

FLUID FLOW: SINGLE SEGMENTAL

- Fluid flow is dictated by baffles
- Baffle cuts are 30% of tank inside diameter
- Spacing is 1/5 the tank inside diameter
  - 3.05 in apart
- Tube Pitch is the center-to-center distance of each tube
  - 1.25 times outside diameter of tube

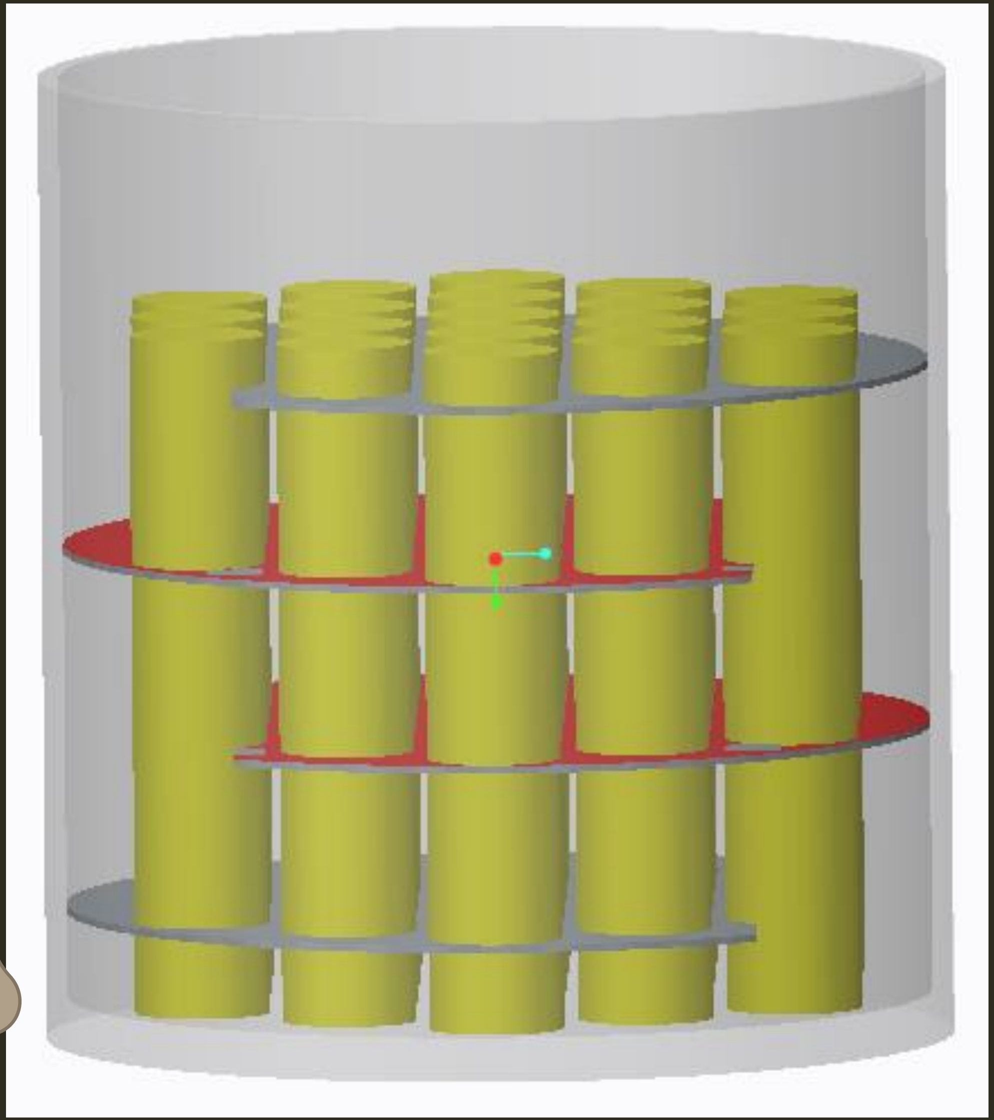
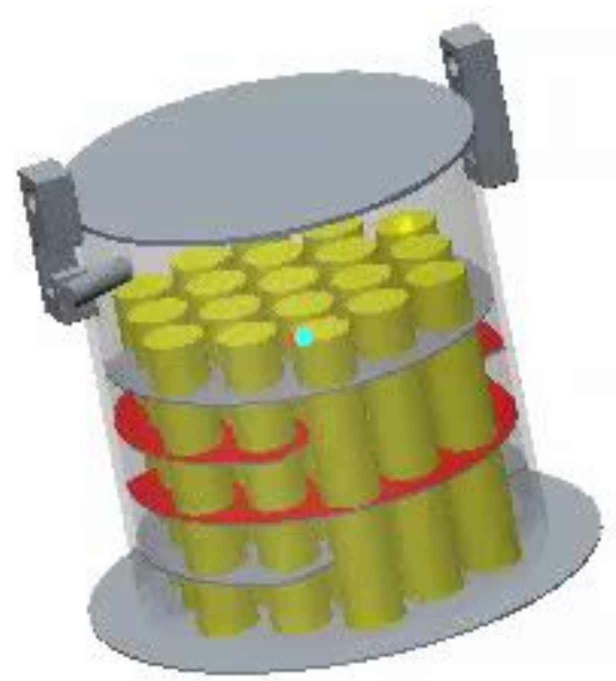


Figure 5. Animation of Fluid Flow in Shell

SINGLE SEGMENTAL CONFIGURATION



FLUID FLOW:
DISK AND DOUGHNUT

Annular area between disk and shell is same as area of ring

Spacing is 1/5 the tank inside diameter

- 3.05 in apart

Tube Pitch is the center-to-center distance of each tube

- 1.25 times outside diameter of tube

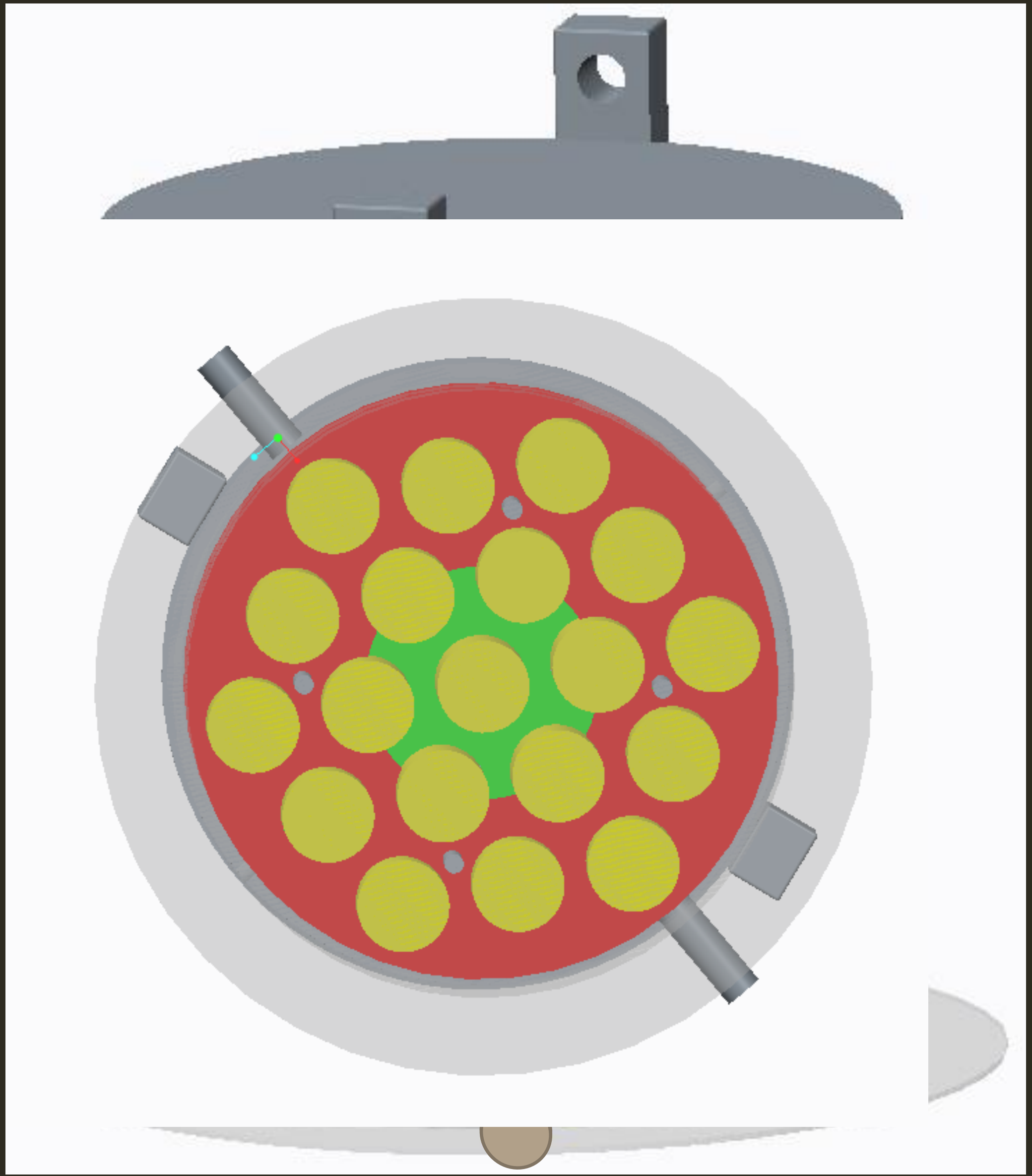
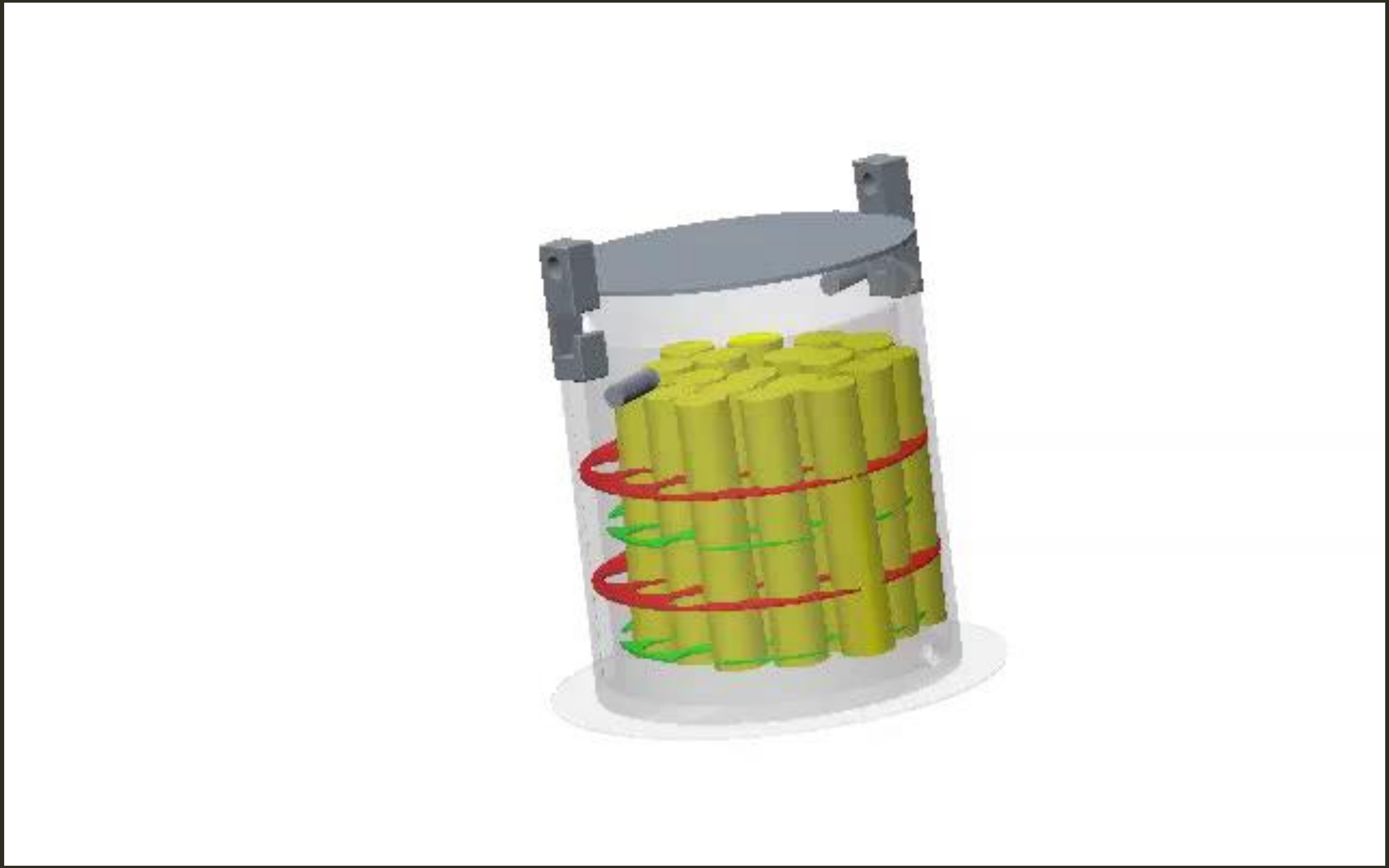


Figure 6. Animation of Fluid Flow in Shell

DISK AND DOUGHNUT CONFIGURATION



WHICH DO WE CHOOSE?

Table 1- Pros and cons of the two configurations

Single Segmental Configuration		Disk and Doughnut Configuration	
Pros	**Cons**	**Pros**	**Cons**
Easy to manufacture	Higher pressure drop	Lower pressure drop	Harder to assemble
Proven and used extensively	Not ideal in high vibration situations	Better symmetrical flow	Heat transfer suffers due to less cross flow
Great heat transfer	Likely to produce dead zones if not careful resulting in increased fouling	Great for high vibration	Fouling is a greater concern for this type

STORAGE MEDIUM & TRANSFER FLUID

Dynalene MS-1 (Phase Change Material)

- Molten Salt with minimal corrosion to stainless steel
- Stable thermal properties throughout operation temperature range
- 3% expansion allows for higher power density per capsule
- Melting Point of 225°C

Duratherm HF (Heat Transfer Fluid)

- Petroleum based
- High oxidation resistance
- Low viscosity
- Available at the price of synthetic car oil
- Flash point of 275°C
- Compatible with steels and aluminum

TABLE OF MATERIAL PROPERTIES

Table 2- Properties for tank materials including oil and salt

Property	Dynalene, MS-1	Duratherm HF	304 Stainless Steel
Specific Heat kJ/kg*K	$C_{PD} = 1.4$	$C_{PL} = 2.587$	-
Thermal Conductivity W/m*K	$k_D = 0.5$ (200)	$k_L = 0.225$ (260)	$k_S = 16.2$
Density kg/m^3	$\rho_D = 1900$	$\rho_L = 700$	-
Viscosity m^2/s	-	$10.45*10^{-6}$	-

HEAT TRANSFER

Transfer to and from Storage defined as Q

$$Q = \frac{\Delta T}{R_{total}} = \frac{T_{inf} - T_{origin}}{R_{Dynalene} + R_{304\ Steel} + R_{convection}},\ T_{inf} = 240°\text{C inlet temperature}$$

- Define T_{origin} as average temperature in the center of the PCM capsules

Assumptions

- Dynalene and 304 Steel resistance can be modeled as conduction
- Convective heat transfer from Duratherm to capsule walls
- Radiative resistance is negligible

What's the total Resistance?

THERMAL RESISTANCE COMPONENTS

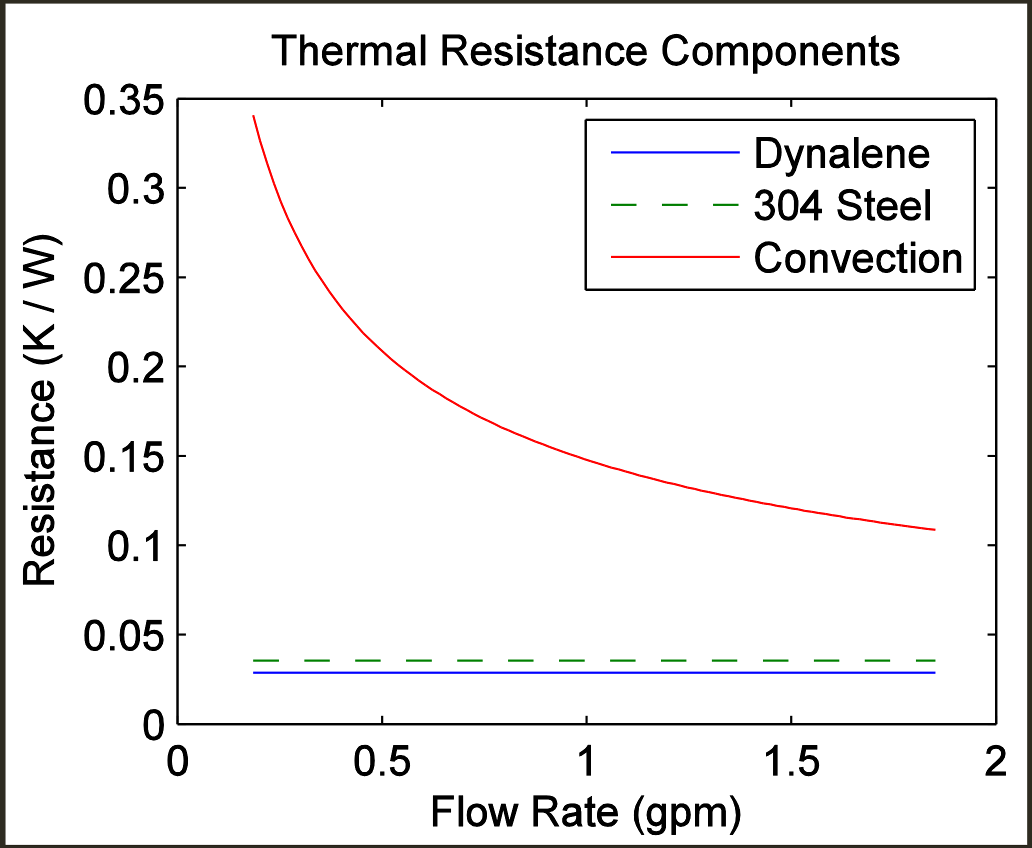


Figure 9. Thermal resistance estimation based on model

EFFICIENCY

Taken as the ratio of energy stored to energy available for storage

$Q_{available} = \dot{m}C_{PL}(240°\text{C} - 170°\text{C})$, energy available to be stored

$Q_{stored} = \frac{\Delta T}{R_{total}}$, Energy transferred or stored in PCM capsules

$$\eta = \frac{Q_{stored}}{Q_{available}} * 100$$

OPERATION POINT

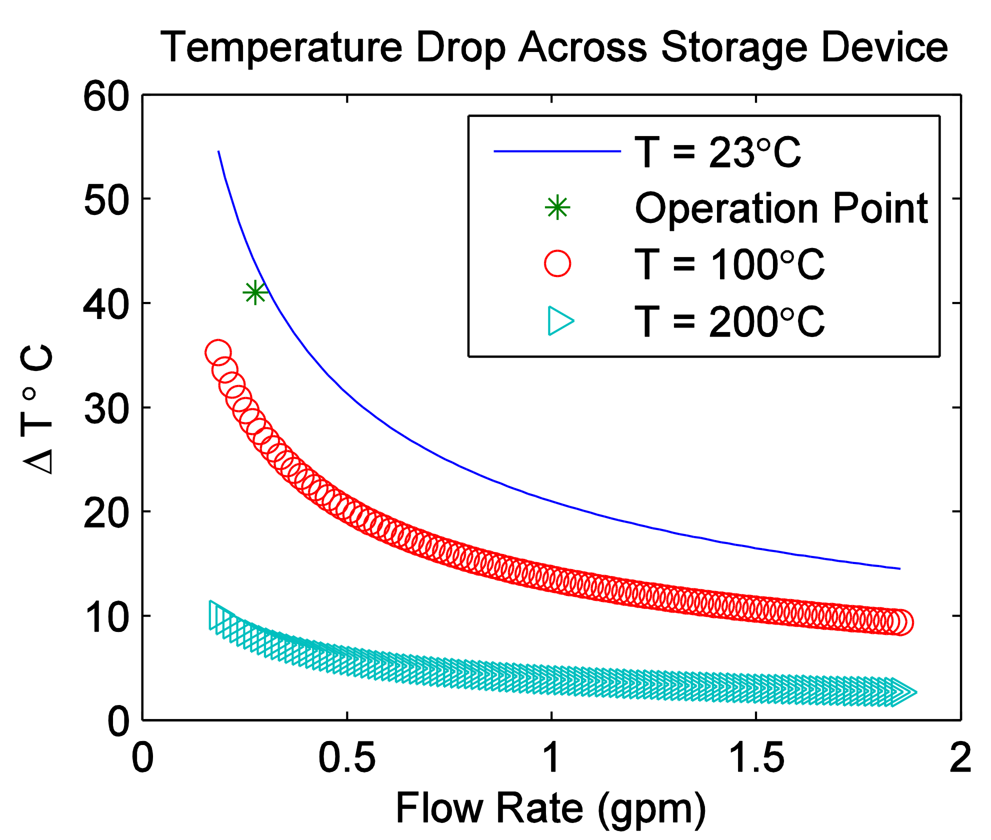


Figure 10. Temperature drop estimation

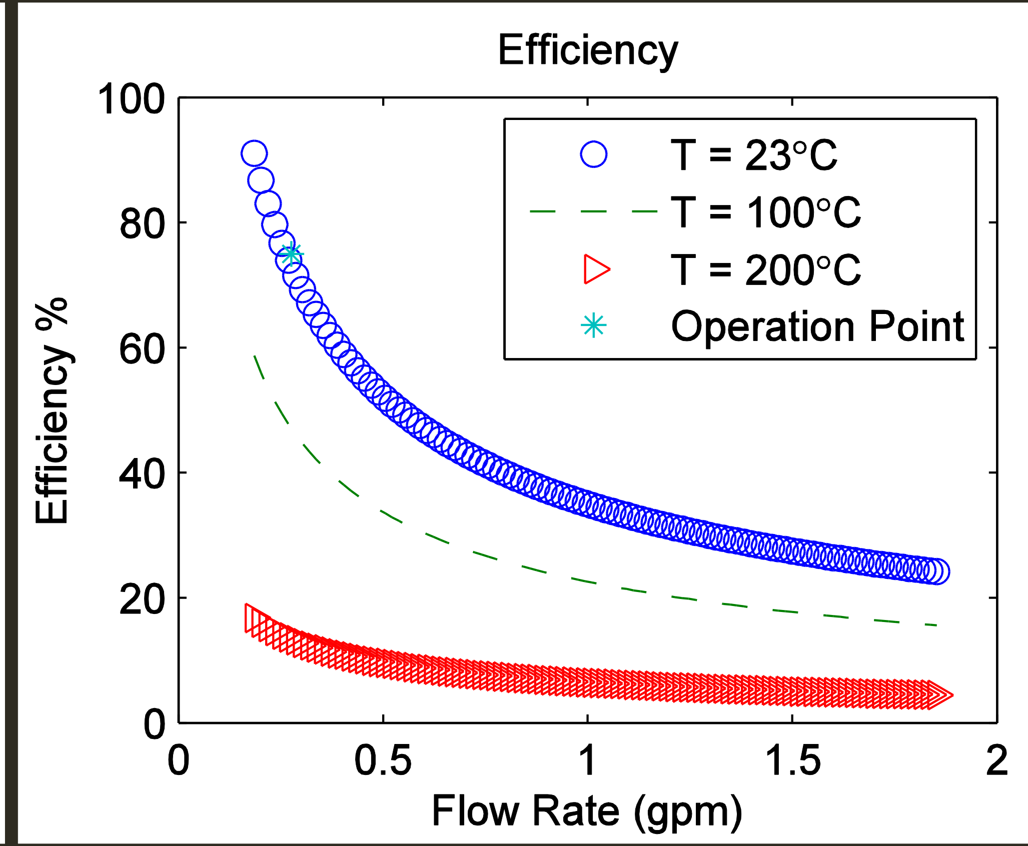


Figure 11. Efficiency estimation of system

SIMULATION METHOD

Methodology

1. Take the inlet temp. and calculate the heat lost per level
2. Record energy stored per level
3. Recalculate the Duratherm temp. and use as T_{inf} for adjacent level
4. Record total energy stored
5. Repeat over 15min intervals

Assumptions

- Flow rate of 0.27gpm
- Ambient temperature for each level is constant
- Initial Duratherm Inlet temperature of 240°C
- losses of 205W based on tank held at 240°C in room temp. conditions

CHARGING TIME - SIMULATION RESULTS

Charging time of 2.25hrs

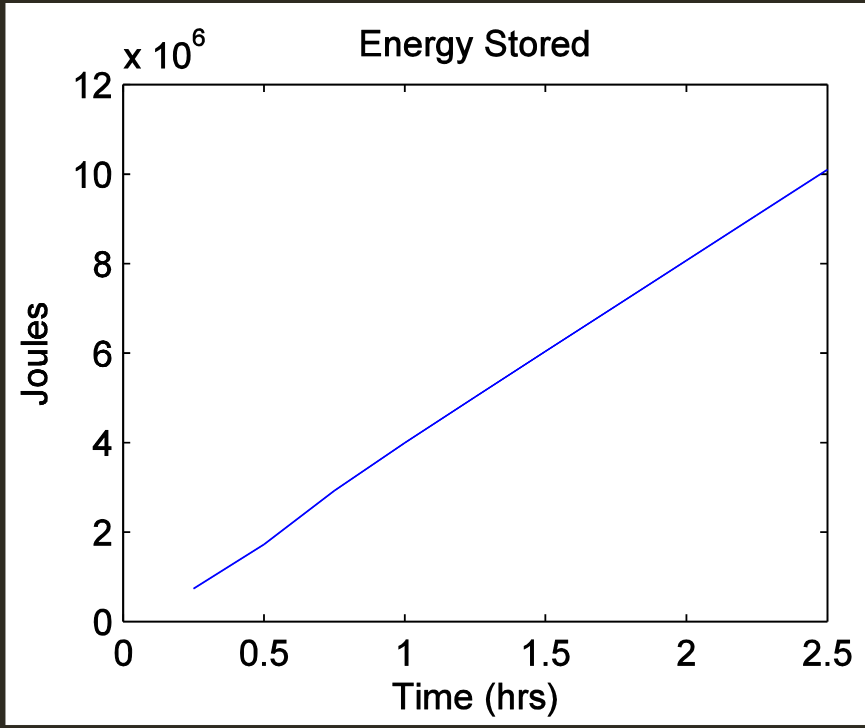


Figure 12. Energy stored vs. Time

Temperature Output

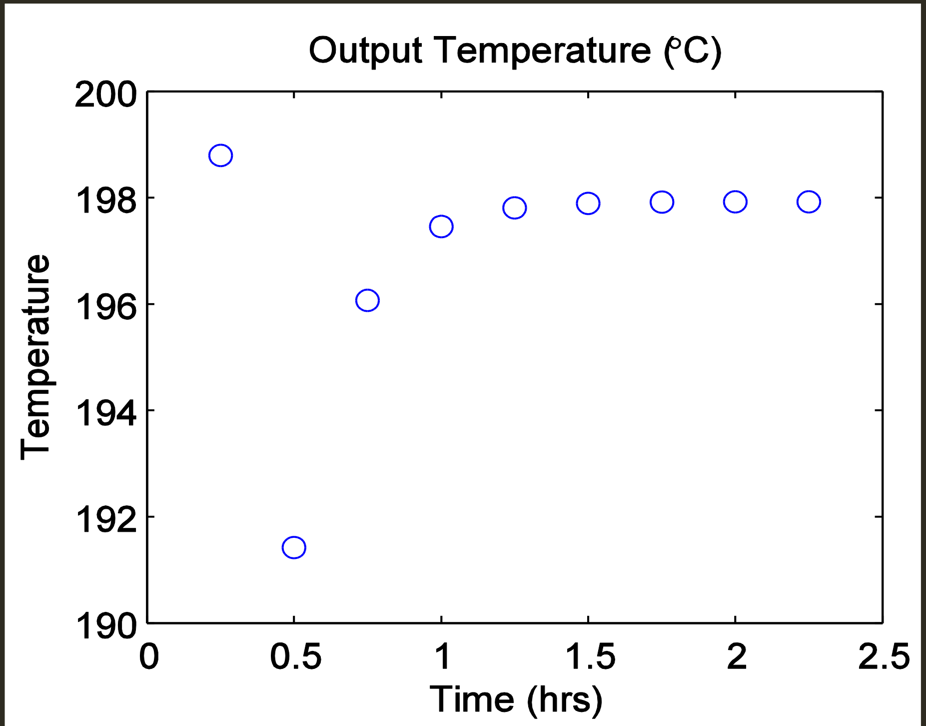


Figure 13. Temperature vs. Time

CHARGING TIME CONT. – SIMULATION RESULTS

Efficiency

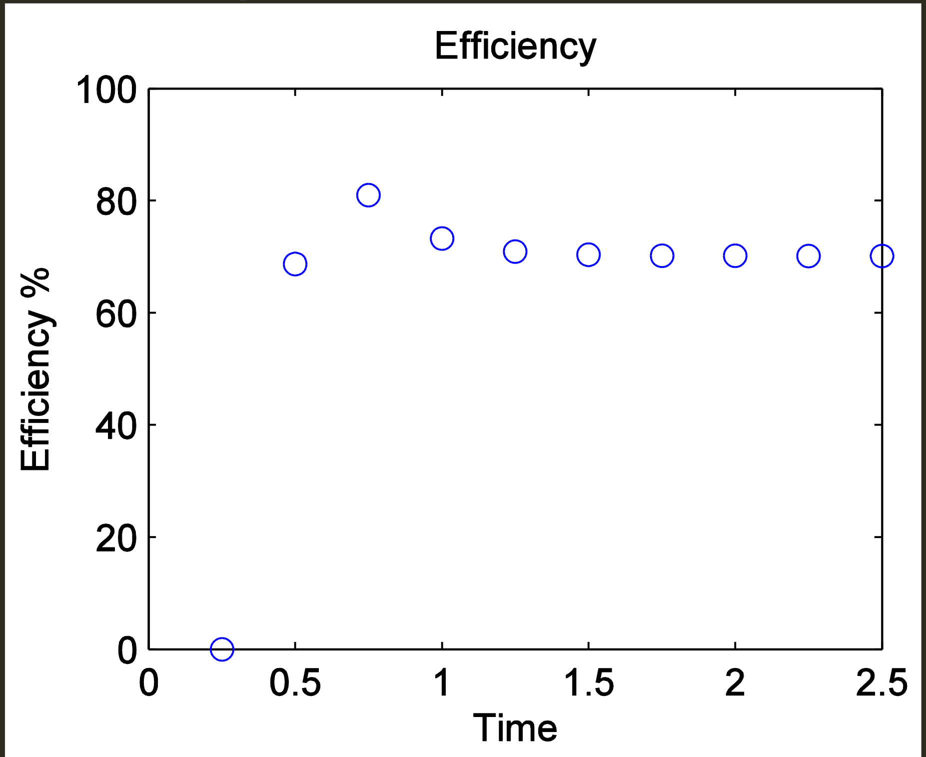


Figure 14. Efficiency vs. Time

Analysis summary

- ✓Charges in 2.25 hours
- ✓Output temperature is stabilizes at 200°C
- ✓Operates at an efficiency of 70%
- ✓7Pa pressure drop

OPERATION TIME - SIMULATION RESULTS

At the end of charging:

- Energy stored is 8.8MJ
- However the useful Stored above 170°C is 4.9MJ
- 44% of the energy stored can not be used to produce electricity
- 34mins On full load, 2274W (70°C drop at 0.27gpm)

- Found by using the energy balance equation below:

$$Energy_{useful} = time * (load + losses)$$

MANUFACTURING SCHEDULE / BUDGET BAR

Table 3- Manufacturing progress

What needs to be done?	When will it be done by?
Tank	Finished
Baffles	Finished
PCM Capsules	Finished
Heat Source	Awaiting 4" pipe
Assembly	Awaiting remaining parts

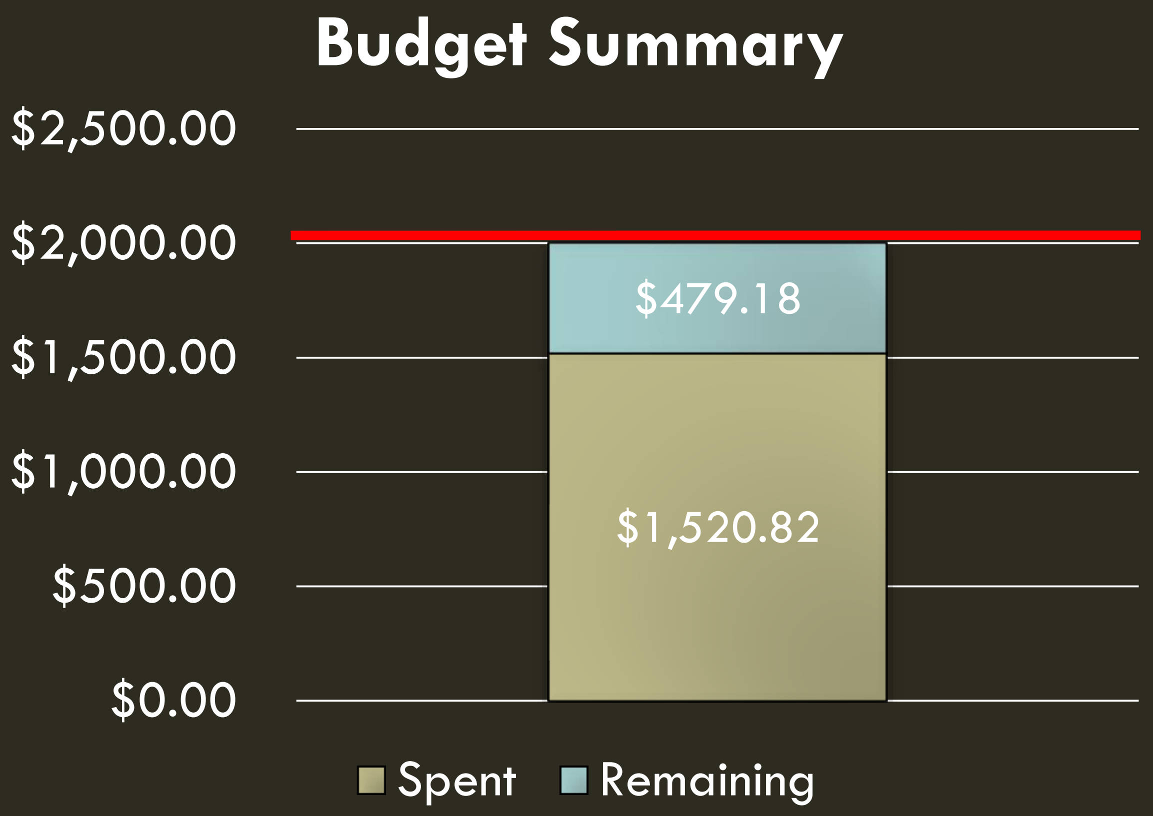


Figure 15. Current budget

MANUFACTURING PROGRESS

- Base
  - Diameter: 18”
  - Height: ¼”
- Tank
  - Outer Diameter: 16”
  - Inner Diameter: 15-1/4”
  - Height: 17”
- Top
  - Diameter: 16-1/4”
  - Overall Height: 2-1/4”

Figure 16. Final tank assembly

MANUFACTURING PROGRESS CONT.


Figure 17. Tank caps

- Water tight welds were used to secure the base to the bottom of the tank
- A 1/4" tall ring with a diameter of 15" was welded to the top to prevent it from slipping off
- A handle was then welded to the top for easier mobility
- The inlet and outlet holes were drilled in the tank at the desired locations and caps were added

MANUFACTURING PROGRESS CONT.

Figure 18. Baffles

Baffles

- Fabricated at the college of engineering in the machine shop using the water jet
- Fourth baffle had small defect but will be fixed by the end of the day today
- Next step is to build baffle frame with threaded rod and insert into the tank
- Excess threaded rod will be used to lock frame of baffles in place to prevent movement caused by the oil flow

MANUFACTURING PROGRESS CONT.

Left to be done

- Revisit latching and lifting system
- Tank assembly
  - Includes: baffle frame, weld threadolets, weld lifting latches, and painting
- Assemble rest of system
  - Includes: Attach components such as piping, heat exchanger (fan), flow meter, needle valve, pump, and heat source

Testing

- Insert the 19 PCM capsules
- Fill system with 6.9 gallons of oil to the 14.5" mark in storage tank
- Once heat is added the oil will expand to 8.48 gallons and reach the 16.5" mark inside the tank
- Simple thermocouples will determine the inlet and outlet temperatures of the oil in the storage tank

Gantt Chart

	Task Name	Duration	Start	Finish
1	**Purchases**	**20 days**	**Mon 1/5/15**	**Fri 1/30/15**
14	**Simulation & Modeling**	**26 days**	**Mon 1/5/15**	**Mon 2/9/15**
19	**Building**	**15 days**	**Mon 2/16/15**	**Fri 3/6/15**
20	Create Capsules	14 days	Mon 2/16/15	Thu 3/5/15
21	Create Heat Exchanger	14 days	Mon 2/16/15	Thu 3/5/15
22	Weld bottom to tank	1 day	Mon 2/16/15	Mon 2/16/15
23	Cut Baffels	1 day	Mon 2/16/15	Mon 2/16/15
24	Frame for baffels	3 days	Mon 2/16/15	Wed 2/18/15
25	Connect pipes	1 day	Thu 3/5/15	Thu 3/5/15
26	Place capsules/oil in tank	1 day	Thu 3/5/15	Thu 3/5/15
27	Screw top on tank	1 day	Thu 3/5/15	Thu 3/5/15
28	**Testing**	**21 days**	**Mon 3/9/15**	**Mon 4/6/15**
29	**First configuration**	**10 days**	**Mon 3/9/15**	**Fri 3/20/15**
30	Test 1	2 days	Mon 3/9/15	Tue 3/10/15
31	Test 2	2 days	Fri 3/13/15	Mon 3/16/15
32	Test 3	2 days	Mon 3/16/15	Tue 3/17/15
33	**Second configuration**	**10 days**	**Mon 3/23/15**	**Fri 4/3/15**
37	**Evaluation on tests**	**7 days**	**Wed 4/1/15**	**Thu 4/9/15**
40	**Future Suggestions**	**7 days**	**Sat 4/11/15**	**Mon 4/20/15**
43	**Presentation Prep**	**5 days**	**Mon 4/20/15**	**Fri 4/24/15**

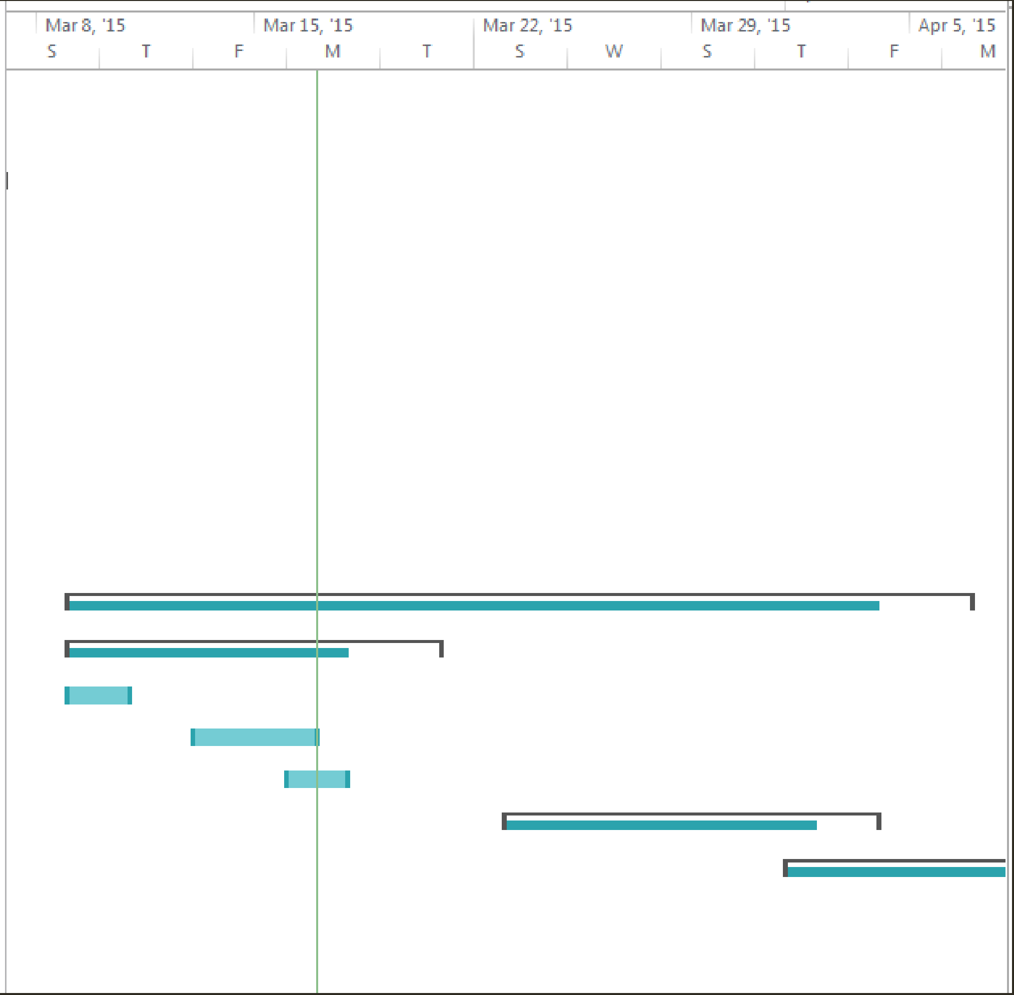


Figure 19. Gantt Chart

RESOURCES

Hasnain, S.M., “Review on Sustainable Thermal Energy Storage Technologies, Part 1: Heat Storage Materials And Techniques,” Energy Conversion Mgmt., Vol. 39 No. 11 pp1127-1138, 1997.

Sharma, Atul, Tyagi, V.V., Chen, C.R., Buddhi, D., “Review on Thermal Energy Storage with Phase Change materials and applications,” Renewable and Sustainable Energy Reviews 13, pp318-345, 2009.

Cengel, Yunus, and Cimbala, John M., and Turner, Robert, *Fundamentals of Thermal Fluid Sciences*, 4th ed., New York, New York, 2011

Mukherjee, R , (2014, December 20) *Effectively Design Shell-and-Tube Heat Exchangers. (1st ed.)* [Online] Available: http://www.mie.uth.gr/ekp_yliko/CEP_Shell_and_Tube_HX.pdf

Appendix Follows

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CONVECTION COEFFICIENT CONFIGURATION 1

Determining h, the convective heat transfer coefficient

$h = \frac{Nu * K_L}{D}$, where D (2.375in) diameter of the capsule

Nusselt's Number, Nu, for flow across a cylinder defined as:

$$Nu = 0.3 + \frac{0.62 * Re^{0.5} * Pr^{\frac{1}{3}} * \left(1 + \frac{Re}{282000}^{\frac{5}{8}}\right)\verb|^|\left(\frac{4}{5}\right)}{(1+(0.4/Pr)^{2/3})^{1/4}}$$

Prandtl's Number, Pr = $(viscosity * \rho_L * C_{PL})/k_L$

Reynold's Number, Re = $(v * D_h)/viscosity$

Figure 7. Example of external flow around a cylinder

CONVECTION COEFFICIENT CONFIGURATION 2

Determining h, the convective heat transfer coefficient

$h = \frac{Nu * K_L}{D}$, where D (2.375in) diameter of the capsule

Nusselt's Number, Nu, for flow in a rectangular pipe:

$Nu = 0.664 * Re_L^{0.5} * Pr^{1/3}$

Prandtl's Number remains the same

Reynold's Number, Re = $(v * D_h)/viscosity$ = 21.4

Changing hydraulic diameter to

$D_h = 4 * \mathrm{Area_{UA}}/(\mathrm{pi} * r_o)$

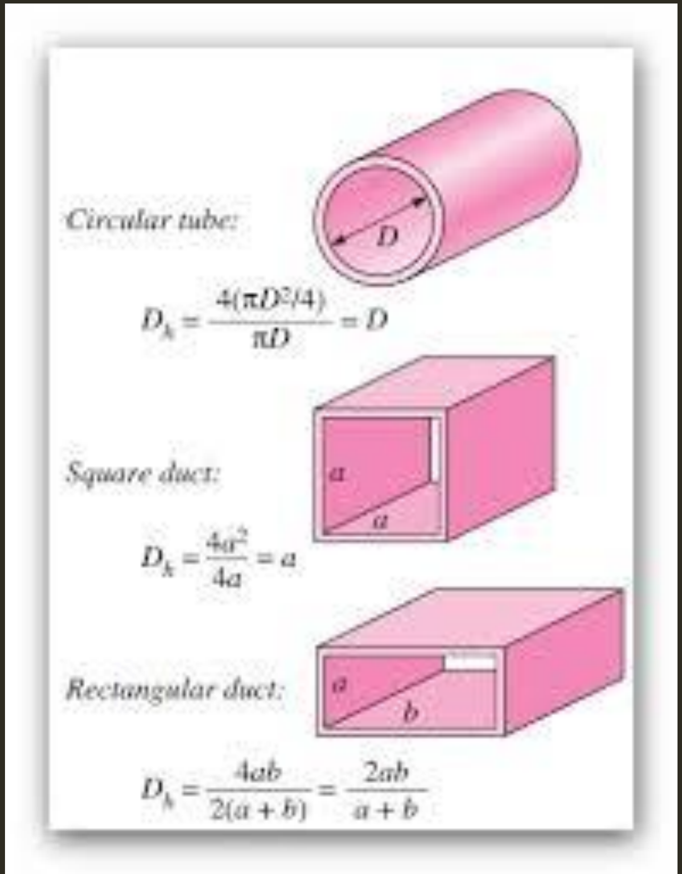

Figure 6. Characteristic diameter of various shapes

TRANSIENT HEAT CONDUCTION, T_{ORIGIN}

Need Origin temperature to find the heat added to storage per cycle

$$\frac{\partial^2 y}{\partial^2 x} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad | \quad \frac{\partial^2 \theta}{\partial X^2} = \frac{\partial \theta}{\partial \tau}$$

Taking the boundary & initial conditions to be:

1. $\theta(X, 0) = 1$
2. $\frac{\partial \theta(0,\tau)}{\partial X} = 0$
3. $\frac{\partial \theta(1,\tau)}{\partial X} = -Bi\theta(1, \tau), \quad Bi = \frac{h * r_o}{k_D}$

A numerical solution for simple geometries can be found and the origin Temperature can be determined

TRANSIENT HEAT CONDUCTION, T_{ORIGIN} CONT.

Our problem specific geometry is a short cylinder

Introduces multidimensional heat conduction radially and vertically

Solution: $\theta_{short\ cylinder} = \frac{T(r,x,t)-T_\infty}{T_i - T_\infty} = \theta_{plane\ Wall} * \theta_{long\ cylinder}$, T_i = 23°C

$\theta_{plane\ Wall} = A_w e^{-\lambda^2 \tau} * \cos(\frac{\lambda x}{L})$, L = height of cylinder and x is vertical displacement

$\theta_{long\ Cylinder} = A_{cyl} e^{-\lambda_{cyl}^2 \tau} * J_0(\frac{\lambda_{cyl} * r}{r_0})$, r_0 = 2.375in

Making a mesh of temperature points within the capsule (1.55x 1.21cm cells) the average temperature at the origin was found

CAPSULE THERMAL RESISTANCE ANALYSIS

Convection

Varies with average flow velocity, v

- $R_{convection} = \frac{1}{2*\pi*r_{outer}*Height*h}$

- h depends on the Nusselt # specific to the flow velocity

- Assume a Hydraulic Diameter:

$$D_h = \frac{4 * tubepitch * baffleSpacing}{2 * (tubepitch + baffleSpacing)}$$

Conduction

- Thermal properties remain constant
- Outer/Inner Diameters for schedule 10 pipe (2.375in)/(2.157in)
- Height of 12in

- $R_{304\ Steel} = \frac{ln(r_{outer}/r_{inner})}{2*\pi*Height*k_s}$
- $R_{Dynalene} = \frac{r_{inner}}{2*\pi*Height*k_D}$

PRESSURE DROP

$$\Delta P = \Delta P_{tank} + f * \frac{L*\rho}{D*2} * v^2 + 8 * K_L * v^2 + 2 * K_r * v^2$$

Assuming

- L =15ft of D= 0.5inch pipe
- K_L = 1.1 90 degree turn minor loss coefficient (8)
- K_r = 0.1 for reduction fittings (2)
- V = 0.0149m/s for mass flow rate of 0.0123kg/s or lower

HEAT EXCHANGER LOAD

Hayden #1260 Liquid to air heat Exchanger

- Provided by Verdicorp
- Coupled with 2 300cfm fans
- Rated at 2000W
- Produces a Temperature drop of 70°C

Figure 9. Heat Exchanger

HEAT SOURCE

Cartridge Heater

Provided by Verdicorp

Rated at 1000W each Only 1 is Needed at steady state

Using Q = $\dot{m}C_p(230^{\circ}\text{C}) \approx 6{,}000W$

Need up to 6 cartridges to have speedy start up time

Figure 10. Generic Cartridge Heaters

HEAT SOURCE

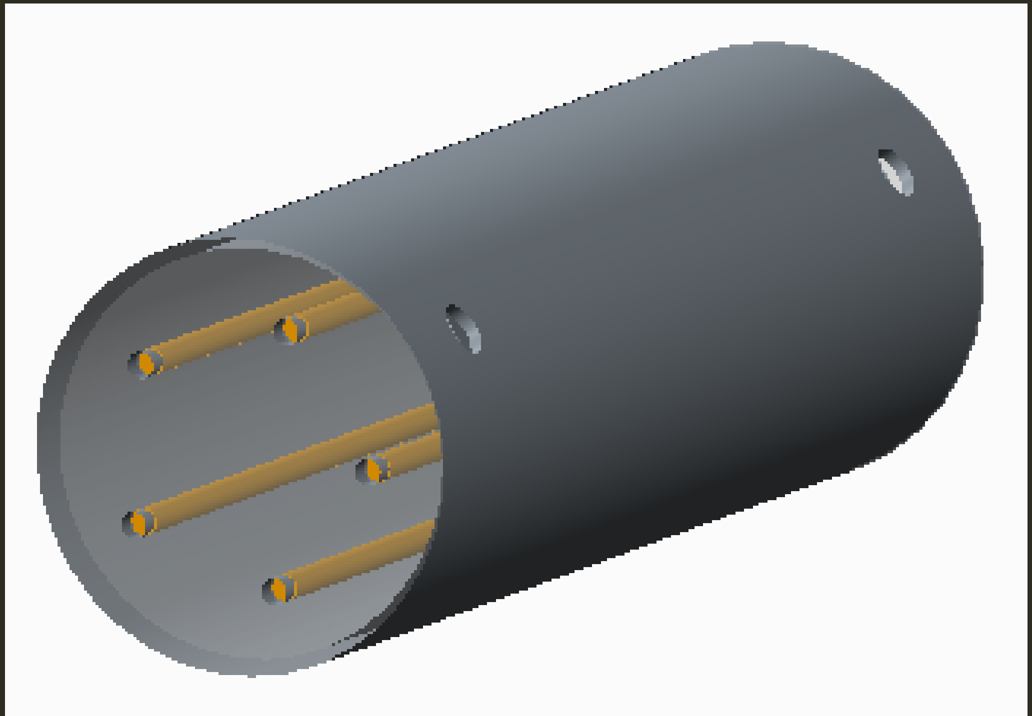

Figure 11. Generic Cartridge Heaters

TWIST-ON LID DESIGN

Latch design allows for easy removal of lid

When lifted the welded pegs will lock into place

Reduces manufacturing time

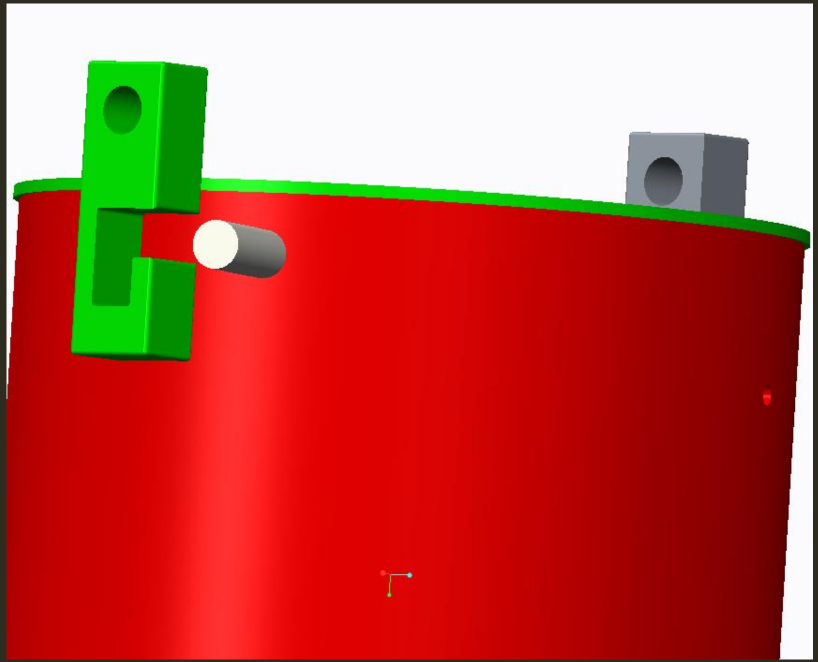

Figure 7. Proposed Lid Design

LATCH STRESS ANALYSIS

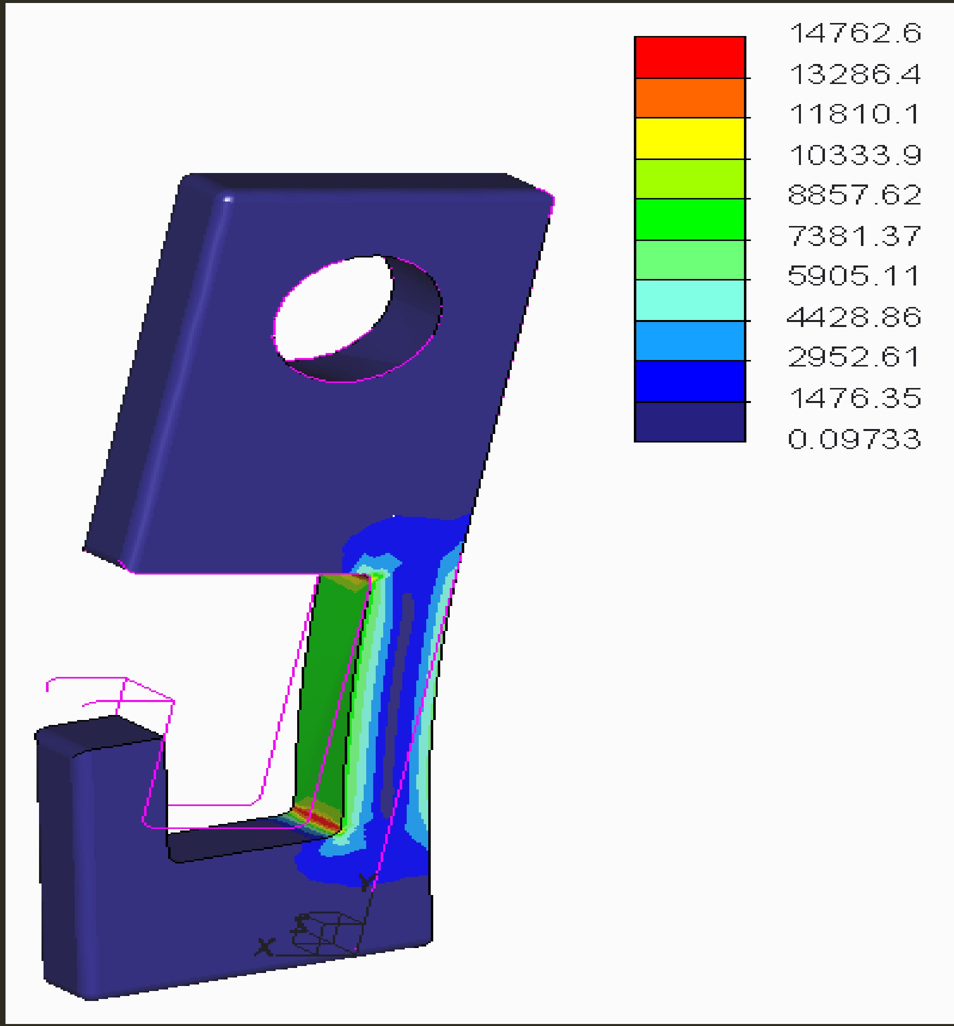

Figure 8. von Mises' Stress (psi)

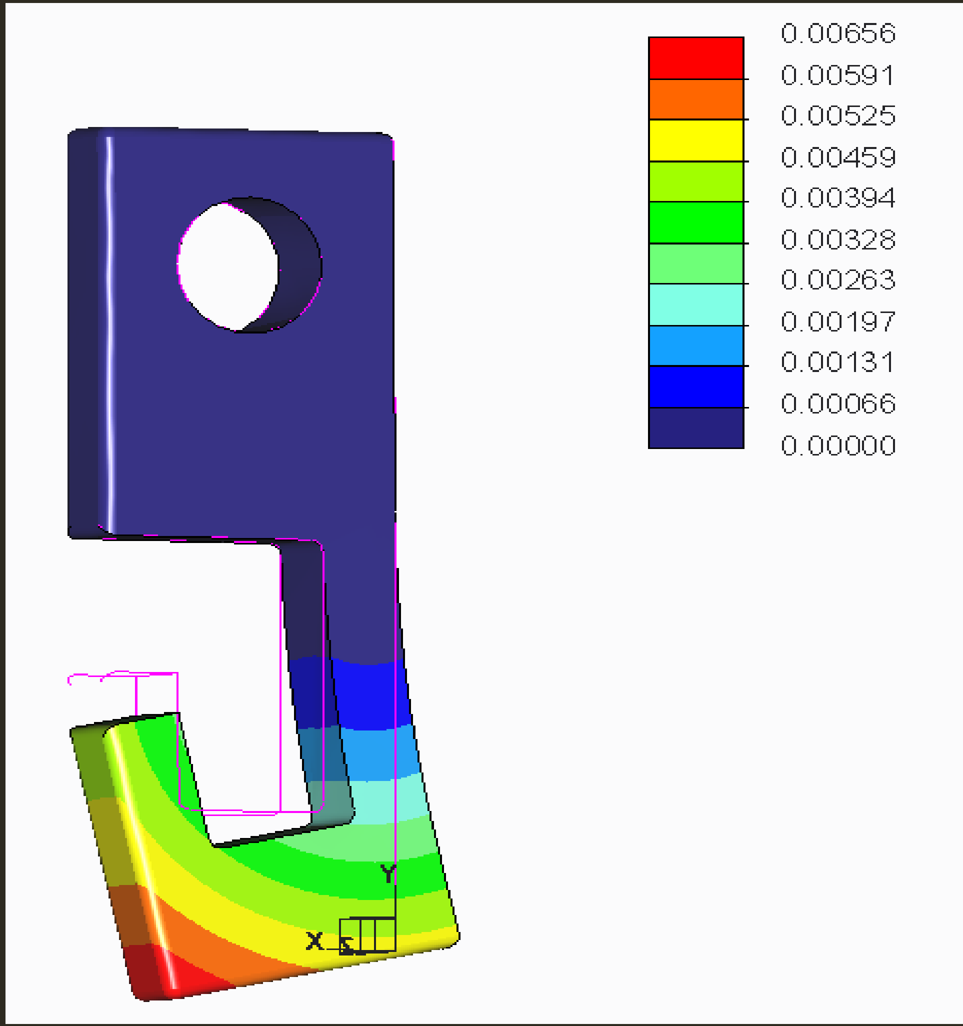

Figure 9. Displacement (in)