On-Orbit Xenon Refueling Loading Times and Transient Analysis

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Background

- The Power and Propulsion Element (PPE) of the Lunar Orbital Platform-Gateway will demonstrate the first on-orbit refueling of xenon propellant for a solar electric propulsion system.
- Due to xenon's non-ideal behavior, loading xenon into a pressurized tank causes large thermal property changes and makes optimizing tank parameters difficult.

Presentation Overview

- Purpose: Provide summary of transient loading analyses assuming gas conduction only to assess the effects of xenon refueling duration for PPE based on the following parameters:
  - Xenon Mass: 2000, 2100 and 2500 kg
  - Xenon Tank Pressures: 1000 - 3000 PSIA
  - Xenon Tank Diameters: 29” and 46”
  - Xenon Flow Rates: Basic 10.8 kg/hr and various other flow rates
  - PPE Spacecraft Bus Temperatures: -15, 0 and 20°C
  - Residual Xenon Mass in the tank at the start of refueling: 2% and 20%
  - Comparison of gas conduction and convection models at variable gravitational constants

Nomenclature

c	specific heat
c_p	specific heat at constant pressure
c_v	specific heat at constant volume
C_t	Thermal capacitance
Δ()	incremental change
D	diameter
E	blackbody emissivity (σT^4)
ε	emissivity
ε*	MLI effective insulation emissivity
F	view factor
g_c	Gravitational constant
h	Enthalpy
J	radiosity
k	Thermal conductivity
L	Length of cylinder
m	mass
$\dot{m}$	mass flow rate
Q	heat transfer rate
$\dot{q}$	rate of energy generation per unit volume
ρ	density, reflectivity
r	radius
R	Thermal resistance
t	time
T	temperature
u	internal energy
V	volume

Subscripts

bus	spacecraft shell structure
g	gas
i	inside
w	wall
r	radiation
t	thermal
0	stagnation
∞	outside

Superscripts

p	indicates which time step, t=pΔt

Key Assumptions

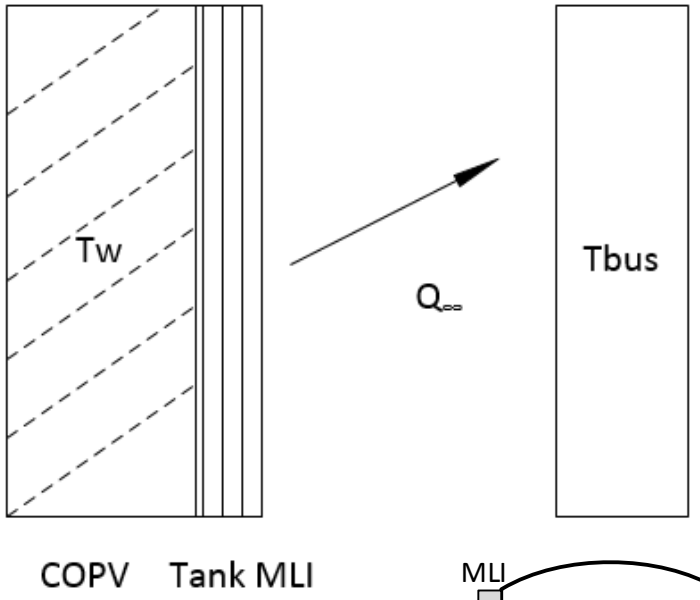
- PPE Spacecraft Bus Temperatures: -15, 0 and 20°C
- Inlet Xenon Temperature: 20°C
- Propellant Utilization Efficiencies (PUE): 98% and 80%
- Constant Tank Diameters: 29” and 46”
  - Small dimension from previous ARRM analysis
  - Large dimension from PPE Commercially Derived Vehicle study
- If gas temperature exceeds 50 ^{0}C in the loading model, mass flow stops and the gas is allowed to cool to a set lower value (22 ^{0}C) before resuming loading
  - Upper gas temperature limit for flow shutoff results in cycling xenon flow on/off during refuel.
- Thermal Control System on PPE assumed to radiate internally generated heat from Xenon tank COPV surface during refueling

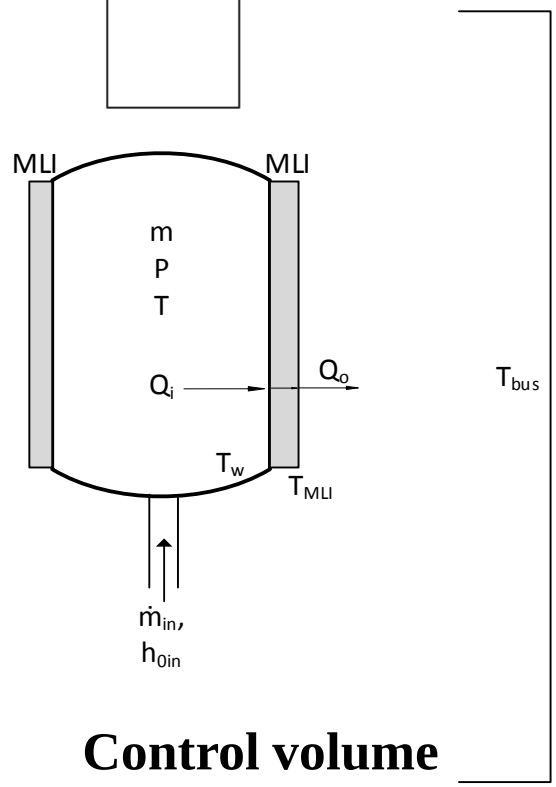
Key Assumptions (cont'd)

- Tank volume for 29" and 46" OD tanks scaled to final fill pressure based on Xenon mass at 40°C ground load
- Radiation heat transfer to spacecraft bus from Xenon tank(s) based on ARRM configuration
- Constant inlet mass flow rate at constant temperature (for each case analyzed)
- Initial wall and MLI temperature 30 ^{0}C (heater control range is 20-40 ^{0}C)
- Thermal conductivity and specific heat of carbon fiber and epoxy are constant
- $h_{0,in} \approx h_{in}$ (experience with Xenon ground loading and lower inlet velocity)
- The analysis is design specific and will need to be updated once a spacecraft vendor is on board.

Approach

Right: Nodal network used to solve transient heat transfer problem.





- Discretize Xenon gas, COPV wall, MLI, into single node each
- Perform energy balance on each node to yield a governing equation per node
- Use an explicit, forward marching finite difference method to solve the governing equations for each node

Governing Equations: Gas Temp

- NRG balance on Xe in tank: $\frac{d}{dt}(mu) = \dot{m}_{in} h_{0in} - \dot{Q}_i$ (1)
- $\dot{Q}_i = \frac{1}{R_t}(T_g - T_w)$ (2)
- $m\,{}^{du}/_{dt} = \dot{m}(h_{0in} - u) - \dot{Q}_i$ but ${}^{du}/_{dt} \approx c_v\,{}^{dT}/_{dt}$
- $mc_v\,{}^{dT}/_{dt} = \dot{m}(h_{0in} - u) - \frac{\mathbf{1}}{\boldsymbol{R_t}}(T_g - T_w)$ (3)
- Assumed uniform bulk gas temperature T_g
  - Low thermal diffusivity of gas at initial and final conditions indicates real gas behavior will not be uniform, but short of performing CFD analysis this simplifying assumption is used in the analysis
  - Knudsen # throughout loading was Kn~10^{-8}
  - General criterion for continuum heat transfer is Kn < 0.01

Governing Equations: Wall temp

- Energy balance on COPV: $\frac{dU_W}{dt} = (C_t)_W\left(\frac{dT_W}{dt}\right) = \dot{Q}_i - \dot{Q}_r$ (4)
- $\dot{Q}_r$ is radiation from the MLI
- Assume uniform COPV wall temperature
  - Biot number approximated throughout analysis using conductivity of T1000 Carbon Fiber (CF) overwrap for various geometric sections of the tank (see Inside Heat Transfer Coefficient slides)
  - CF used because it is 82% of the total thickness of the COPV
  - Highest Biot # throughout loading was for dome ends and was 0.42
  - General criterion for lumped capacitance is Bi < 0.1
  - Max Biot # for cylindrical section is 0.1 and cylindrical section accounts for 83% of tank surface area and 75% of the mass, so uniform temperature assumption is okay

Finite Difference Equations

- Let t=pΔt
- Superscript p indicates the value of the variable at the current time step
- Solving Equations 3 and 4 for the temperatures in the following time step yields:

$$T_g^{p+1} = \frac{\Delta t}{\left(\frac{m_g^p + m_g^{p+1}}{2}\right) c_v^p}\left[\dot{m}\left(h_{0,in}^p - u^p\right) - \frac{1}{R_t}\left(T_g^p - T_w^p\right)\right] + T_g^p \qquad (5)$$

$$T_w^{p+1} = \frac{\Delta t}{C_{t,w}}\left[\frac{1}{R_t}\left(T_g^p - T_w^p\right) - Q_r^P\right] + T_w^p \qquad (6)$$

Steady State Gas Conduction with Uniform Heat Generation

- Steady state gas conduction with uniform heat generation for a solid cylinder:
  - .

$$T(r) = \frac{\dot{q} r_0^2}{6k}\left(1 - \frac{r^2}{r_0^2}\right) + T_w \qquad \textbf{(7)}$$

- Steady state gas conduction with uniform heat generation for a solid sphere:
  - .

$$T(r) = \frac{\dot{q} r_0^2}{4k}\left(1 - \frac{r^2}{r_0^2}\right) + T_w \qquad \textbf{(8)}$$

  - .

$$\dot{q} = \frac{Q}{V} \qquad \textbf{(9)}$$

  - .

$$R_t = \frac{\Delta T}{Q} \qquad \textbf{(10)}$$

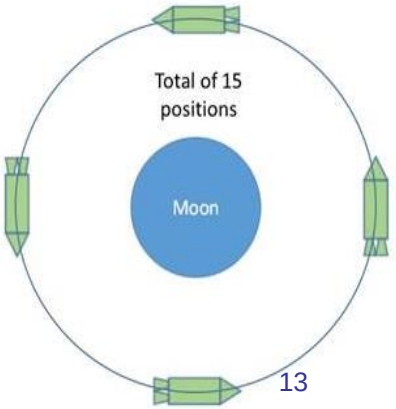
***Fundamentals of Heat and Mass Transfer [1], Appendix C**

Steady State Gas Conduction with Uniform Heat Generation

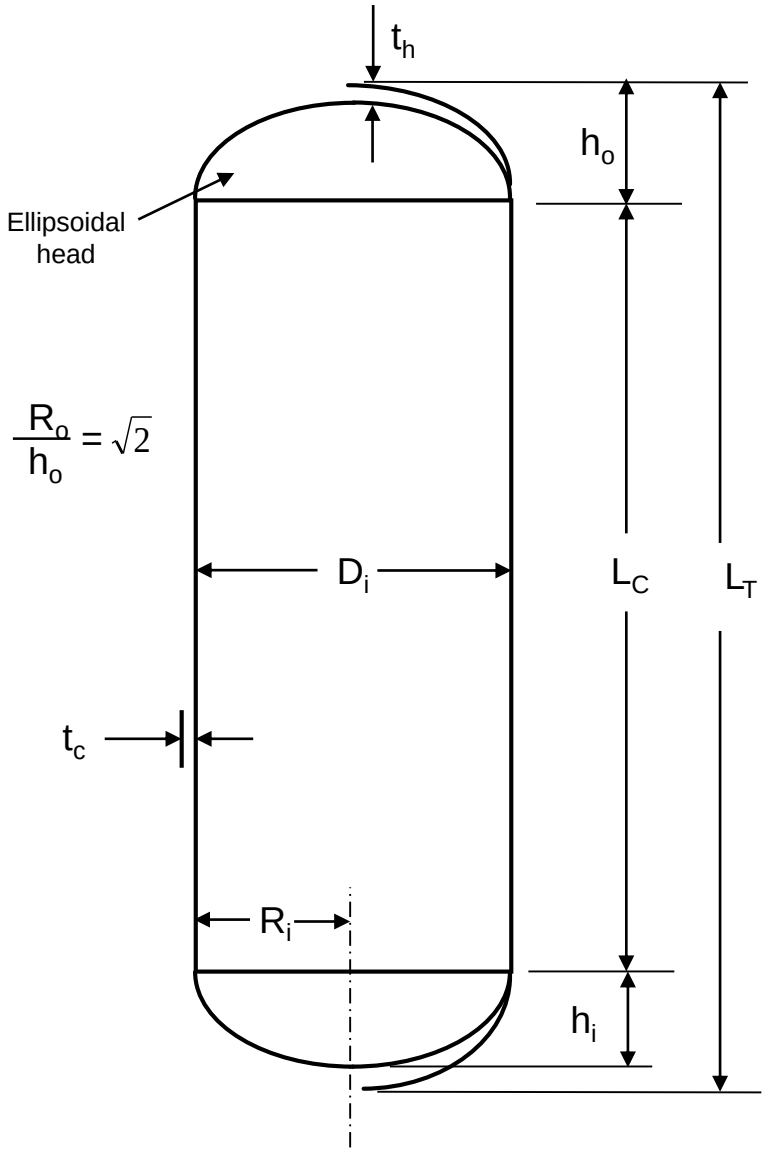
- Solving equations 7, 9, and 10, and 8, 9, and 10 for thermal resistance at r=0 yields:
  - $$R_{t,cond,cyl} = \frac{\Delta T}{Q} = \frac{r^2}{4kV} = \frac{1}{4\pi kL} \quad \textbf{(11)}$$
  - $$R_{t,cond,head} = \frac{\Delta T}{Q} = \frac{r_0^2}{6kV} = \frac{1}{4\pi k D_0} \quad \textbf{(12)}$$
  - $$\frac{1}{R_{t,cond,total}} = \frac{1}{R_{t,cond,cyl}} + \frac{1}{R_{t,cond,head}} \quad (13)$$
  - $$Q_i = \frac{T_g - T_w}{R_{t,cond,total}} \quad \textbf{(14)}$$

Other Assumptions

- Constant inlet mass flow rate at constant temperature
  - Allows for time (and mass) to be marched forward
- Initial wall and MLI temperature 30 ºC (heater control range is 20-40 ºC) and initial tank pressures of 34 psia, 80 psia, 89 psia, and 107 psia for the 1000 psia case, 1500 psia, 1750 psia case, and 3000 psia case, respectively (corresponds to a 98% propellant utilization efficiency).
- Thermal conductivity and specific heat of carbon fiber and epoxy are constant
- $h_{0,in} \approx h_{in}$ (experience with Xenon ground loading and lower inlet velocity)
- Constant bus temperature at -15 ^{0}C (based on thermal analysis by John Siamidis for ARRM [4])



COPV Tank Diagram & Sizing Equations



$$h_o = R_o / \sqrt{2}$$

$$h_i = h_o - t_h$$

$$D_i = D_o - 2\,t_c$$

$$L_C = L_T - 2\,h_o$$

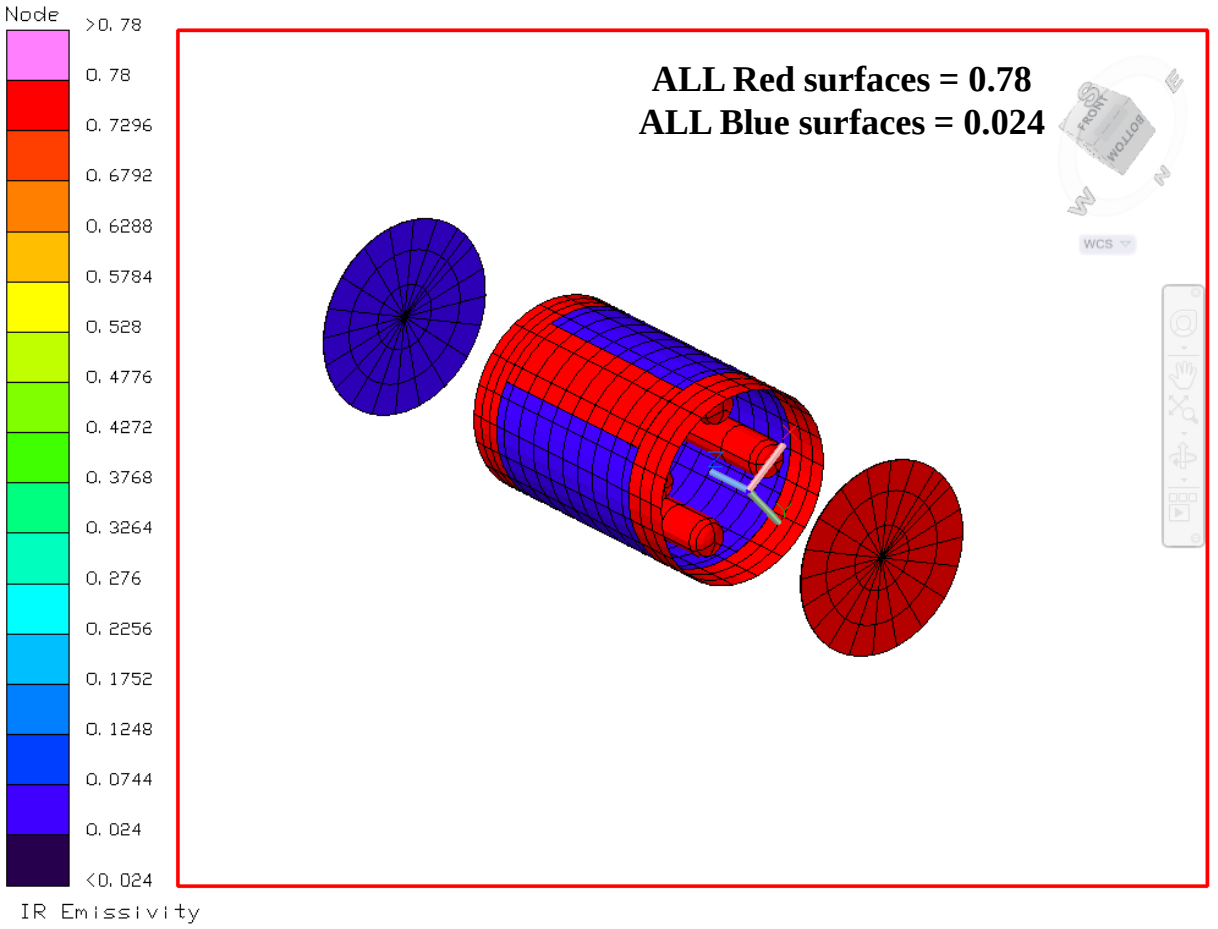
$$V_C = \frac{\pi}{4} D_i^2\, L_C$$

$$V_h = 2\left[\frac{\pi\, D_i^2}{4}\left(h_i - \frac{h_i}{3}\right)\right]$$

$$V_{Tc} = V_C + V_h$$

- For the four pressure cases, a constant D_i of 29” and 46” were used.

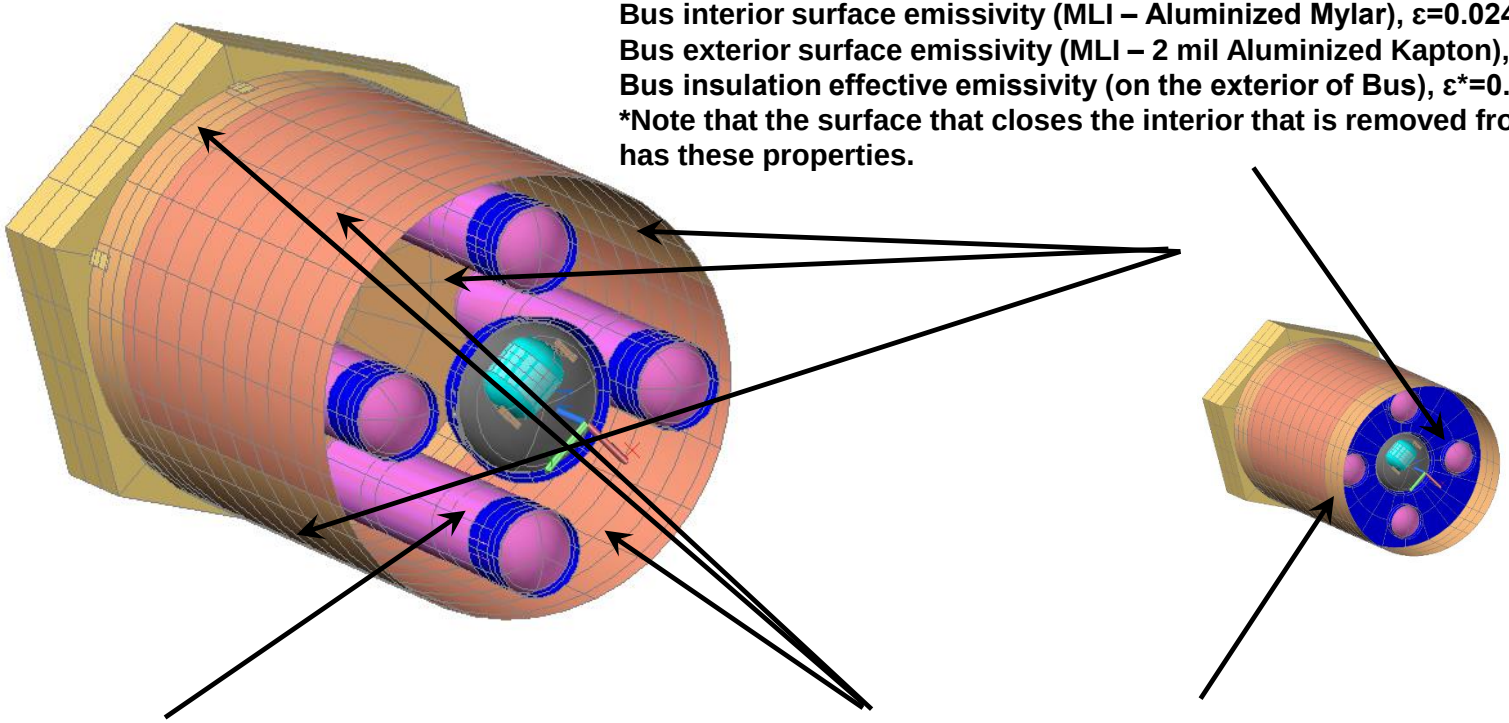
Spacecraft Emissivity Information [3]



- **Note that the model is not considering heat transfer from the bus exterior surface to space so the important emissivity is that of the inner surface which is 0.024**

Radiation Heat Transfer: Spacecraft Emissivity Information [3]

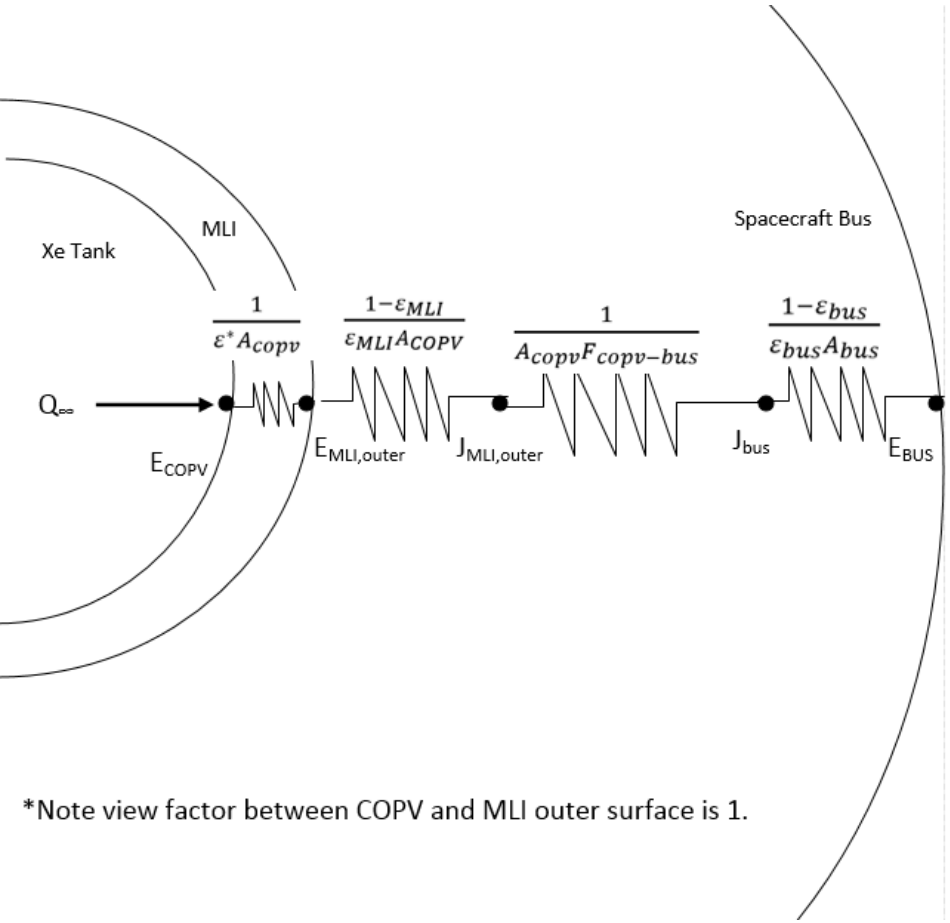
For the orange surfaces:
Bus interior surface emissivity (MLI – Aluminized Mylar), ε=0.024
Bus exterior surface emissivity (MLI – 2 mil Aluminized Kapton), ε=0.78
Bus insulation effective emissivity (on the exterior of Bus), ε*=0.025
***Note that the surface that closes the interior that is removed from this picture has these properties.**



Tank MLI Surface Emissivity (MLI -2 mil Aluminized Kapton), ε= 0.78
Tank MLI insulation effective emissivity, ε*=0.025

For the pink surfaces and one orange surface:
Bus interior AND exterior surface emissivity (MLI – Aluminized Mylar), ε=0.024
Bus insulation effective emissivity (on the exterior of Bus), ε*=0.025
***Note that these surfaces are a bit different because they are under the radiators/coldplates so they have a lower exterior surface emissivity.**
***Note that the additional orange/beige surface that extends has these properties.**

Radiation Heat Transfer-Thermal Circuit



*Note view factor between COPV and MLI outer surface is 1.

Definition of Terms

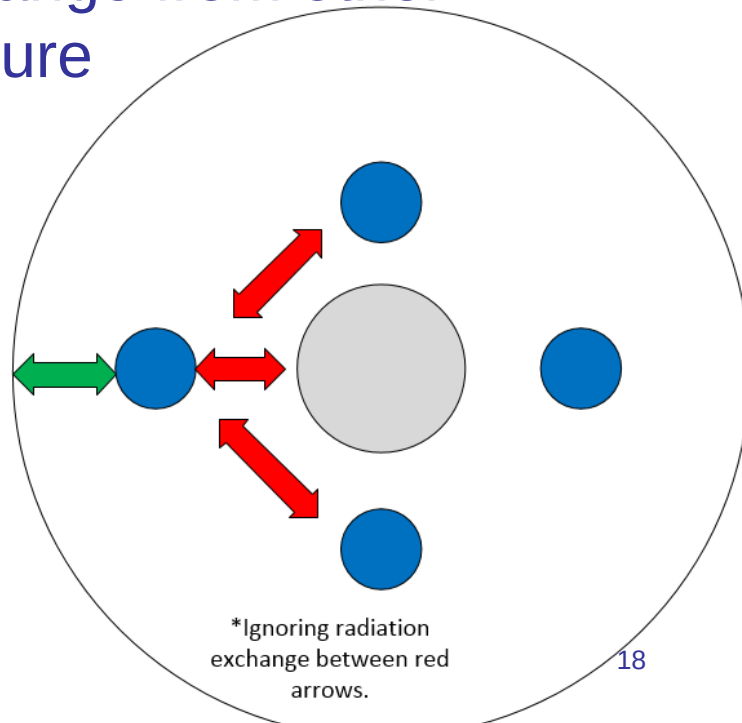
- E: blackbody emissivity (σT^4)
- J: radiosity (E+ρG)
- where ρ is reflectivity & G is irradiation
- F: view factor
- ε*: MLI blanket effective insulation emissivity =0.024
- ε_{MLI}: tank MLI Surface Emissivity (MLI - 2 mil Aluminized Kapton), ε= 0.78
- ε_{bus}: bus interior surface emissivity (MLI – Aluminized Mylar), ε=0.024
- Q_r: radiative heat rejected from Xe tank wall to spacecraft bus

External Radiation Heat Transfer Continued

- Need to consider 3 surfaces: COPV, outer layer of MLI, and inside of spacecraft bus
- Using the Thermal circuit to calculate the heat transfer:

$$Q_r = \frac{\sigma(T_{copv}^4 - T_{bus}^4)}{\left(\frac{1}{\varepsilon^* A_{copv}} + \frac{1-\varepsilon_{MLI}}{\varepsilon_{MLI} A_{COPV}} + \frac{1}{A_{copv} F_{copv-bus}} + \frac{1-\varepsilon_{bus}}{\varepsilon_{bus} A_{bus}}\right)}$$

- Note still neglecting radiation exchange from other tanks and interior spacecraft structure
- Majority of heat transfer should be to spacecraft bus
  - If tanks are loaded simultaneously can assume they are at the same temperature so net heat transfer between tanks equals zero



View Factor

- Equation for view factor for parallel cylinders of different radii [1]:

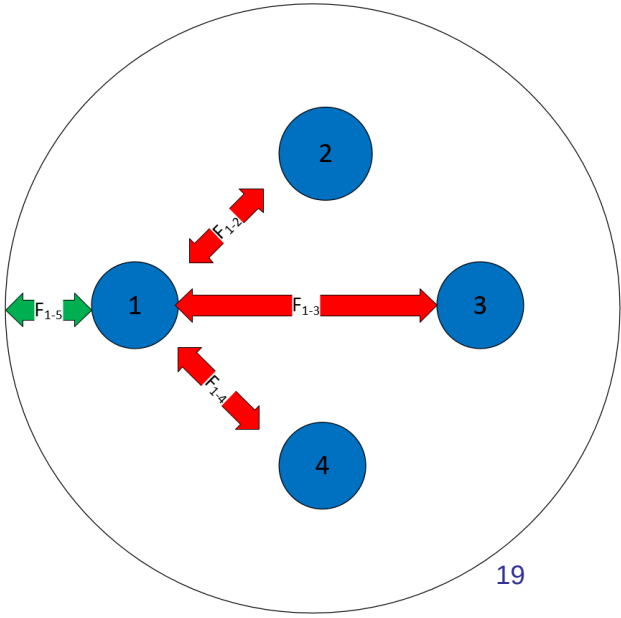
$$F_{ij} = \frac{1}{2\pi}\{\pi + [C^2 - (R+1)^2]^{1/2} - [C^2 - (R-1)^2]^{1/2} + (R-1)\cos^{-1}\left[\left(\frac{R}{C}\right) - \left(\frac{1}{C}\right)\right] - (R+1)\cos^{-1}[\left(\frac{R}{C}\right) + \left(\frac{1}{C}\right)]\}$$

Where $R = \frac{r_j}{r_i}$ $C = 1 + R + S$ $S = {}^{s}/_{r_i}$

- s=distance between the edges of the cylinders
- r_i is the radius of the xenon tank
- Since the tanks are not different radii

set R=1 one and solve for view factor between tank 1 and tanks 2, 3, 4

$\sum_{1}^{n} F_{1-n} = 1$ so $F_{1-5} = 1 - F_{1-2} - F_{1-3} - F_{1-4}$



Assumptions

- The following conditions must be met for the thermal circuit to be valid
  - Opaque surfaces ✓
  - Treated as "gray surfaces" EITHER must be true:
    - Need diffuse irradiation –assume diffuse radiation from COPV
    - OR diffuse surface- aluminized Mylar shiny (spectral) ✗
  - Kirchoff's law applies (α=ε) need either
    - α_λ & ε_λ are independent of λ –unsure
    - OR Irradiation corresponds to emission from blackbody at surface temp T therefore G=E(T) ✓
      - MLI has polished finish (high ε) so behaves like blackbody
      - Spacecraft forms an enclose, can assume blackbody behavior

Gas Temperature Control Scheme

- If gas temperature exceeds 50 ^{0}C in the loading model, mass flow stops and the gas is allowed to cool to a set lower value (22 ^{0}C) before resuming loading
  - Upper gas temperature limit for flow shutoff results in cycling xenon flow on/off during refuel.
- The flow rate input was varied in an effort to characterize the time required to fill the two different tanks with 2000 kg and 2500 of Xenon

Xenon Tank Parameters

Case: Small (2) Tank OD	Pressure (psia)	Diameter (m)	Volume (m^3)	Total Length (m)	Tank Mass (kg) (1)	Outside Surface Area (m^2)
Low	1000	0.7366	3.27	7.88	215	18.70
Medium	1500	0.7366	1.36	3.38	100	8.12
Nominal	1750	0.7366	1.21	3.05	92	7.34
High	3000	0.7366	1.00	2.56	80	6.19

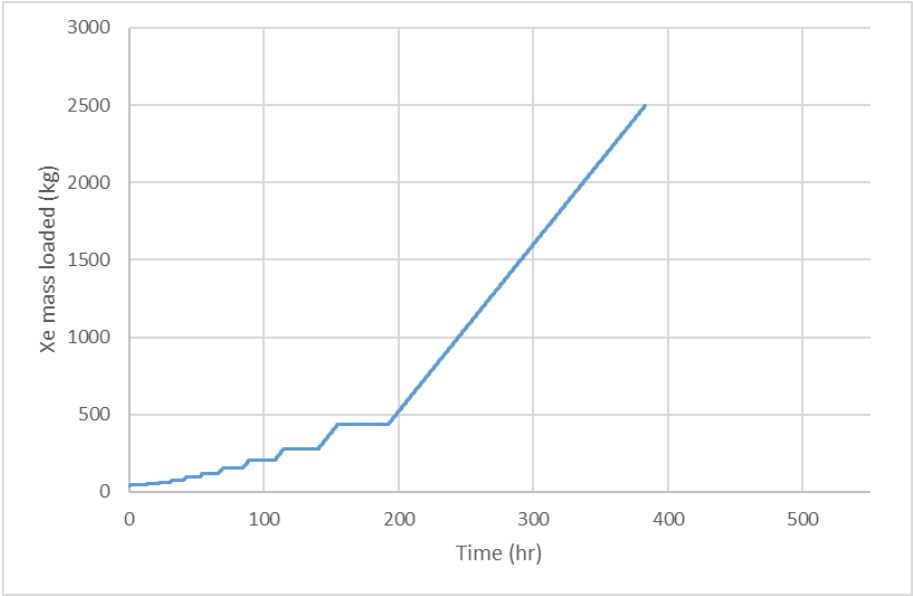
(1) Tank mass consists of carbon fiber and aluminum liner.
(2) Tank sizes based on 2000 kg of xenon capacity at 40° C (ground load temperature rating)

Case: Large (4) Tank OD	Pressure (psia)	Diameter (m)	Volume (m^3)	Total Length (m)	Tank Mass (kg) (3)	Outside Surface Area (m^2)
Low	1000	1.1684	4.09	4.12	203	15.7
Medium	1500	1.1684	1.69	1.89	113	7.43
Nominal	1750	1.1684	1.52	1.72	106	6.82
High	3000	1.1684	1.26	1.48	96	5.92

(3) Tank mass consists of carbon fiber and aluminum liner.
(4) Tank sizes based on 2500 kg of xenon capacity at 40° C (ground load temperature rating)

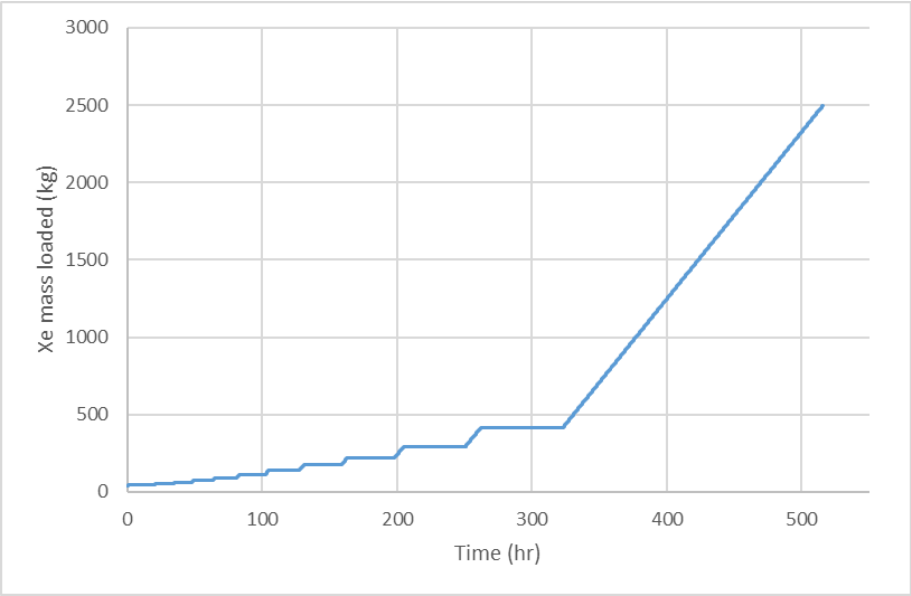
Xenon Mass Loaded vs Time -
29” tank vs 46” tank

Loading to 2500 kg Xe at 10.8 kg/hr*, 3000 psia, 29” tank (383 hrs)



29” Diameter Tank

Loading to 2500 kg Xe at 10.8 kg/hr*, 3000 psia, 46” tank (516 hrs)

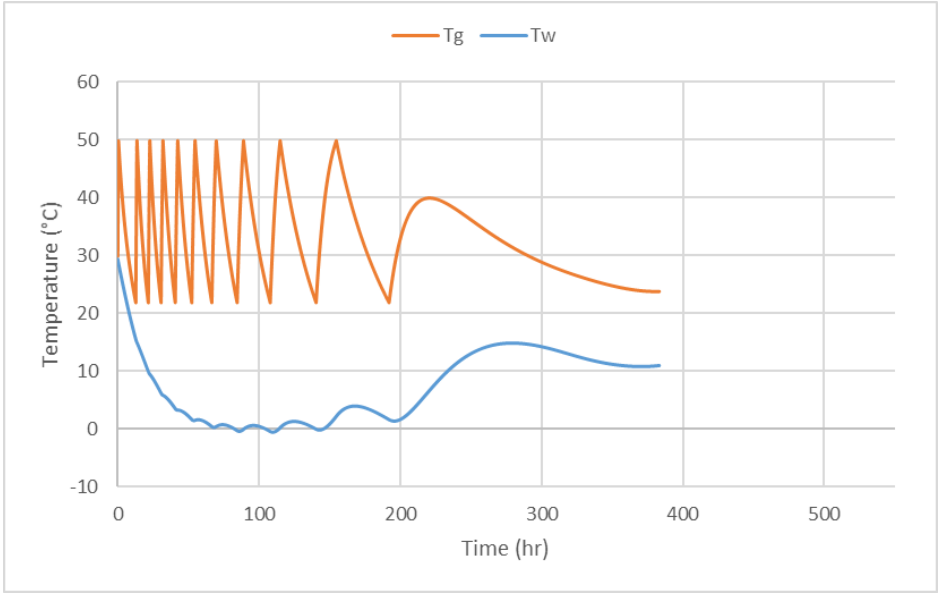


46” Diameter Tank

*A 10.8 kg/hr flow rate was selected to correspond with ESA’s 3 g/s design point. [5]

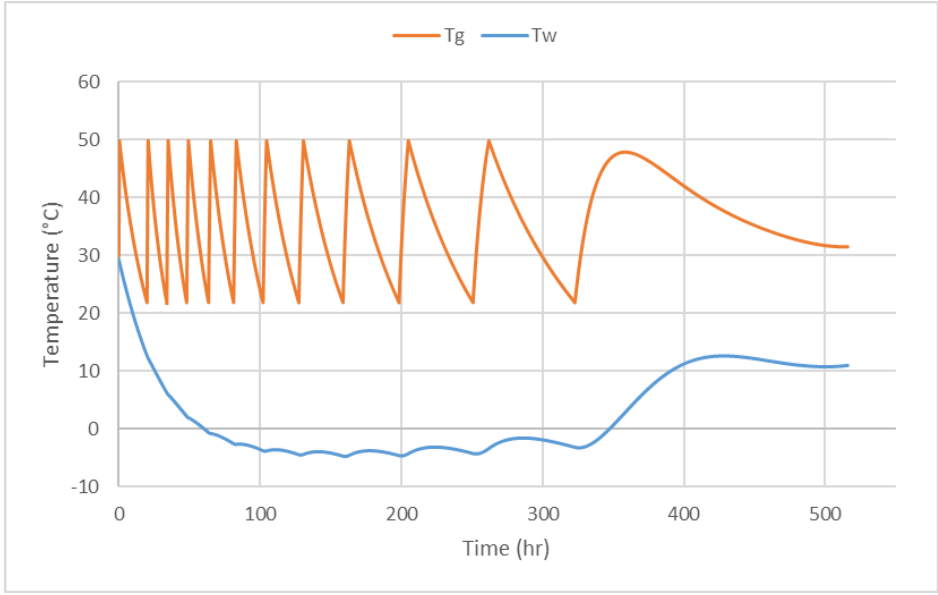
Temperature of Gas and Wall vs Time - 29” tank vs 46” tank

Loading to 2500 kg Xe at 10.8 kg/hr*, 3000 psia, 29” tank (383 hrs)



29” Diameter Tank

Loading to 2500 kg Xe at 10.8 kg/hr*, 3000 psia, 46” tank (516 hrs)



46” Diameter Tank

***A 10.8 kg/hr flow rate was selected to correspond with ESA’s 3 g/s design point. [5]**

Trade Study Refueling Time Summary of Results

Constant tank diameter of 29” (Tank length varied based on mass and pressure)

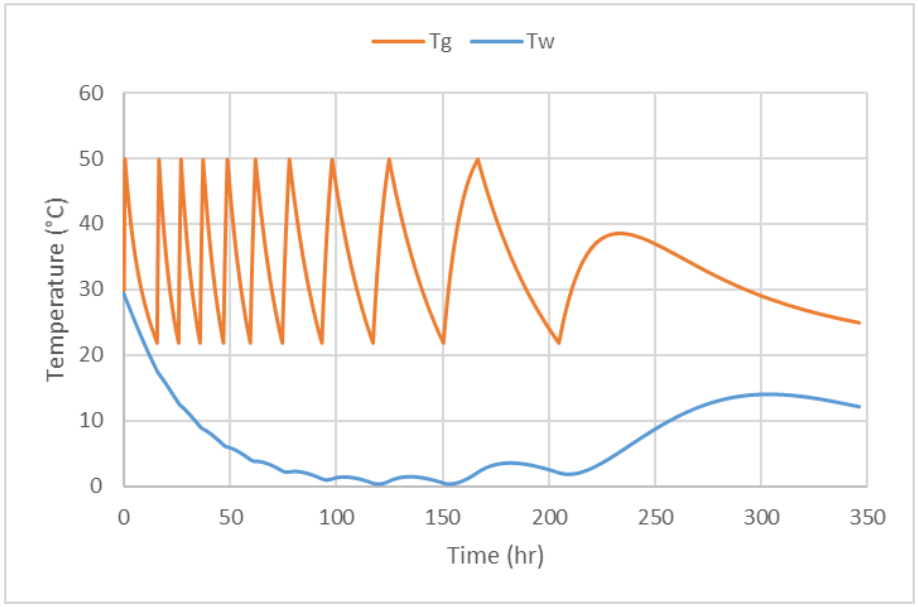
Case	Pressure (psia)	Mass (kg)	Time @ 11 kg/hr (hr)	Time @ 20 kg/hr (hr)	Time @ 40 kg/hr (hr)
Low	1000	2000	285.8	288.9	272.8
Medium	1500	2000	341.0	274.2	307.6
Nominal	1750	2000	359.1	292.0	272.8
High	3000	2000	334.6	277.4	261.3

Constant tank diameter of 46” (Tank length varied based on mass and pressure)

Case	Pressure (psia)	Mass (kg)	Time @ 11 kg/hr (hr)	Time @ 20 kg/hr (hr)	Time @ 40 kg/hr (hr)
Low	1000	2500	484.2	511.2	552.4
Medium	1500	2500	604.1	532.3	537.6
Nominal	1750	2500	539.6	479.1	477.4
High	3000	2500	510.3	456.1	456.9

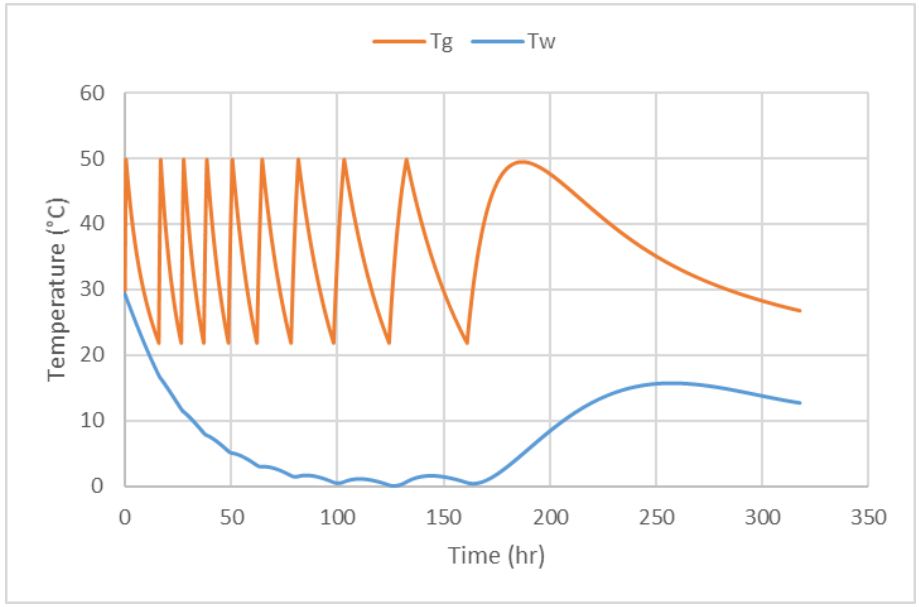
Temperature of Gas and Wall vs Time

Loading to 2000 kg Xe at 10.8 kg/hr*, 1500 psia (346 hrs)



29” Diameter Tank

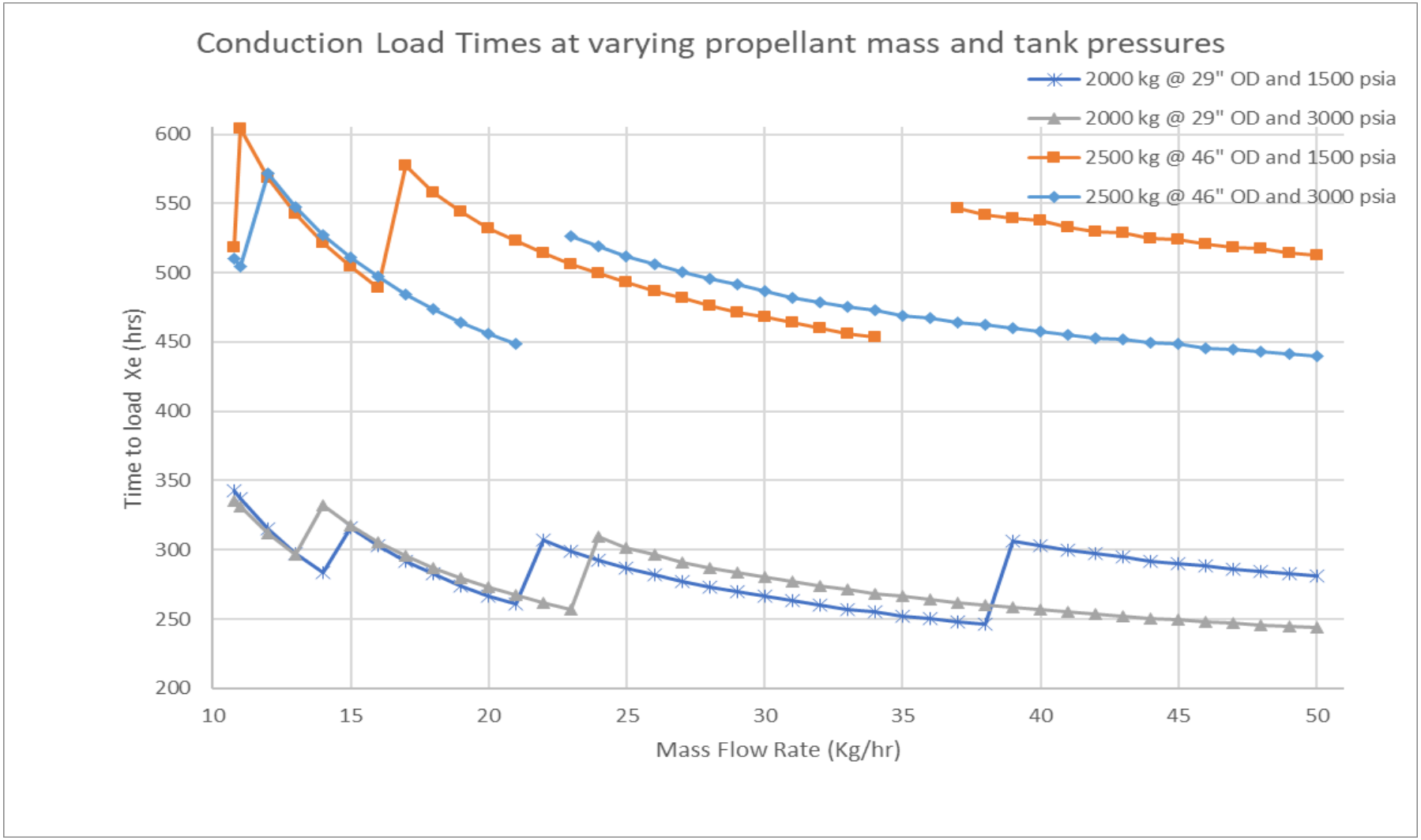
Loading to 2000 kg Xe at 10.8 kg/hr*, 3000 psia (339 hrs)



29” Diameter Tank

*A 10.8 kg/hr flow rate was selected to correspond with ESA’s 3 g/s design point. [5]

PPE On-Orbit Xenon Propellant Refueling

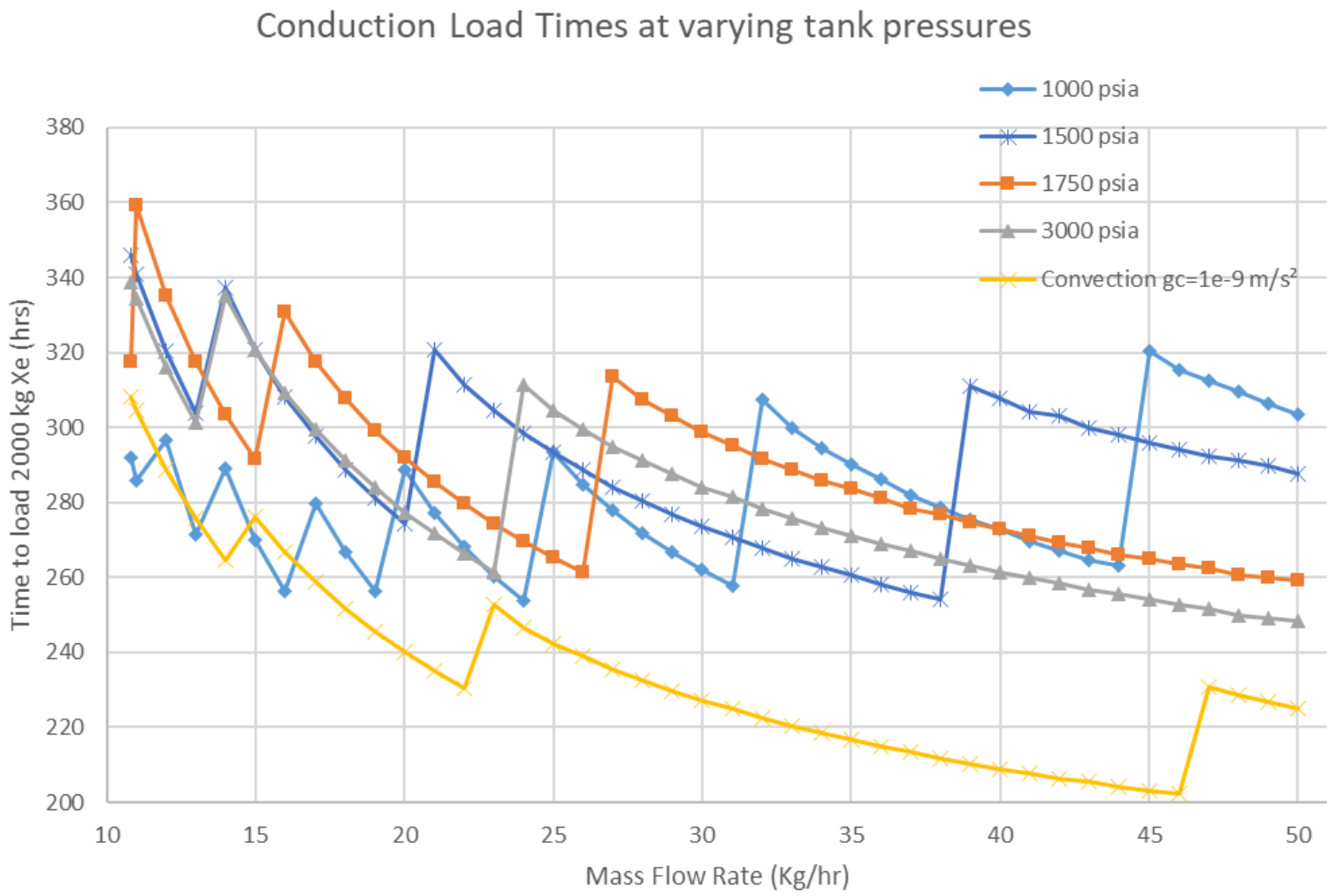


Mass flow rate notes:

10.8 kg/hr corresponds to ESA's 3 g/s design point [5]

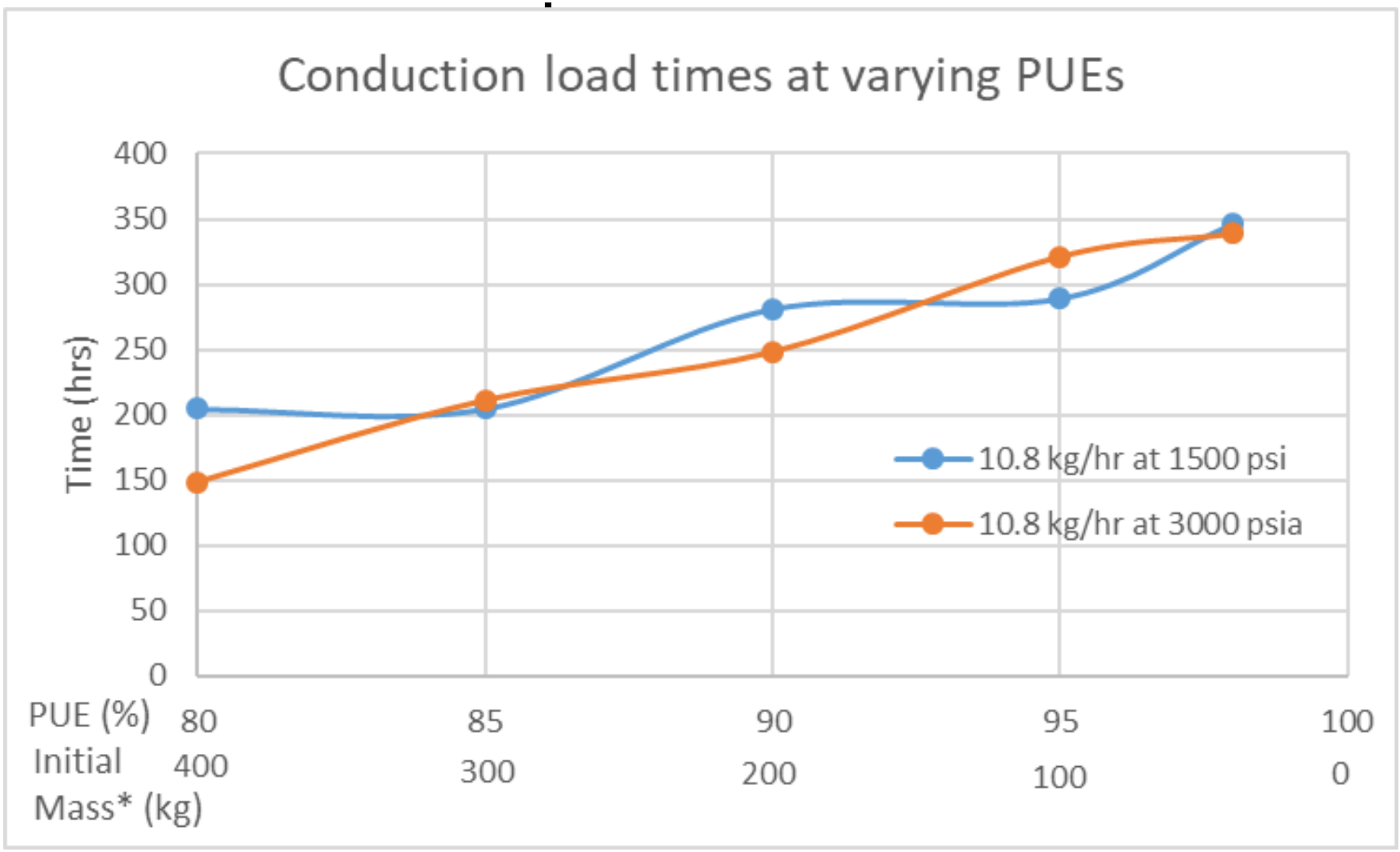
14 kg/hr corresponds to NDS (NASA docking system) fluid transfer coupling requirements

Conduction vs Convection Load Times, 29” Tank OD



PPE On-Orbit Xenon Propellant Refueling

Loading times for 2000 kg, 29” OD tank at different PUE*



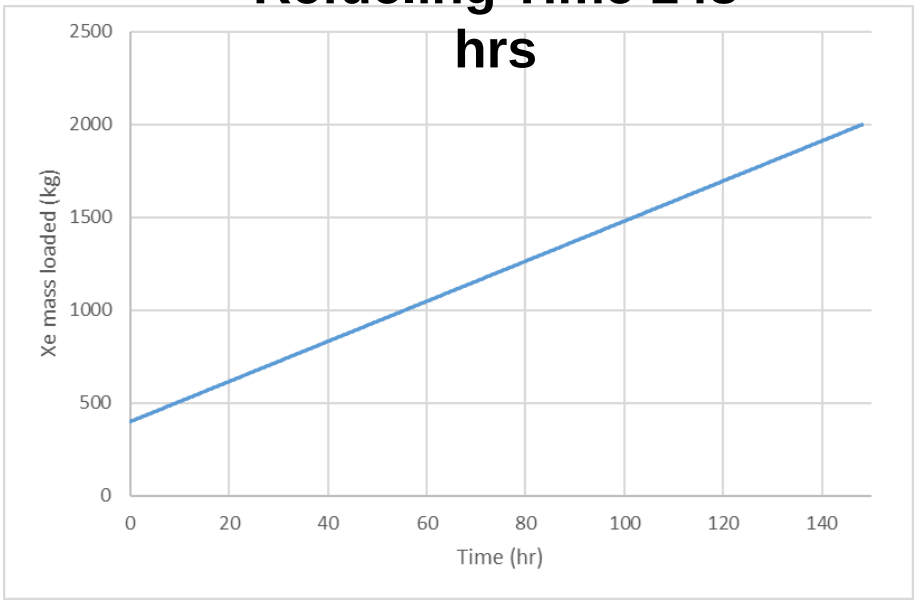
$$PUE = \frac{m_i - m_f}{m_i} \text{ x } 100\% = \frac{2000 - m_f}{2000} \text{ x } 100\%$$

*Initial mass prior to refueling.

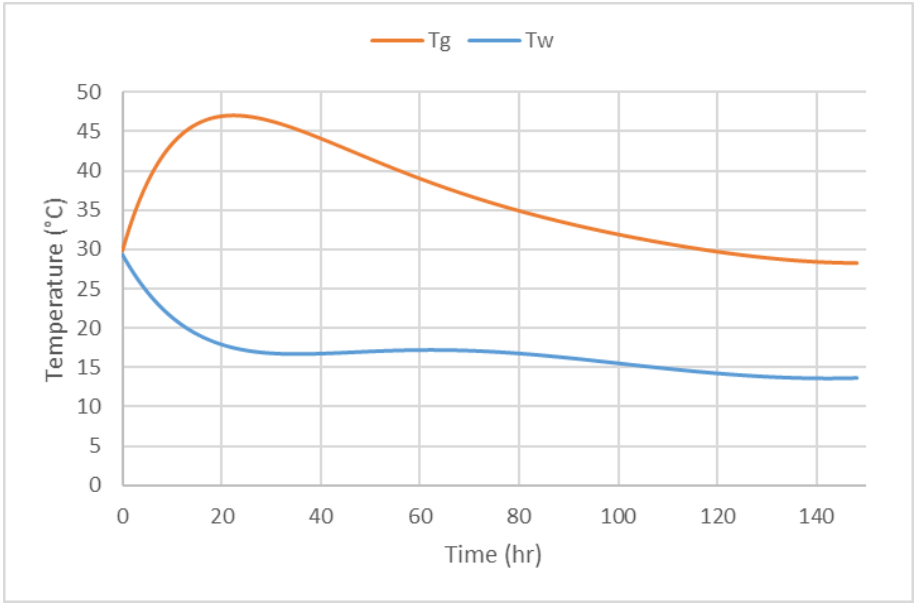
Impact of initial xenon tank mass with loading time

- 400 kg of initial xenon mass in 2000 kg capacity, 29” tank with 3000 psia design pressure

Refueling Time 148 hrs



29” Diameter Tank

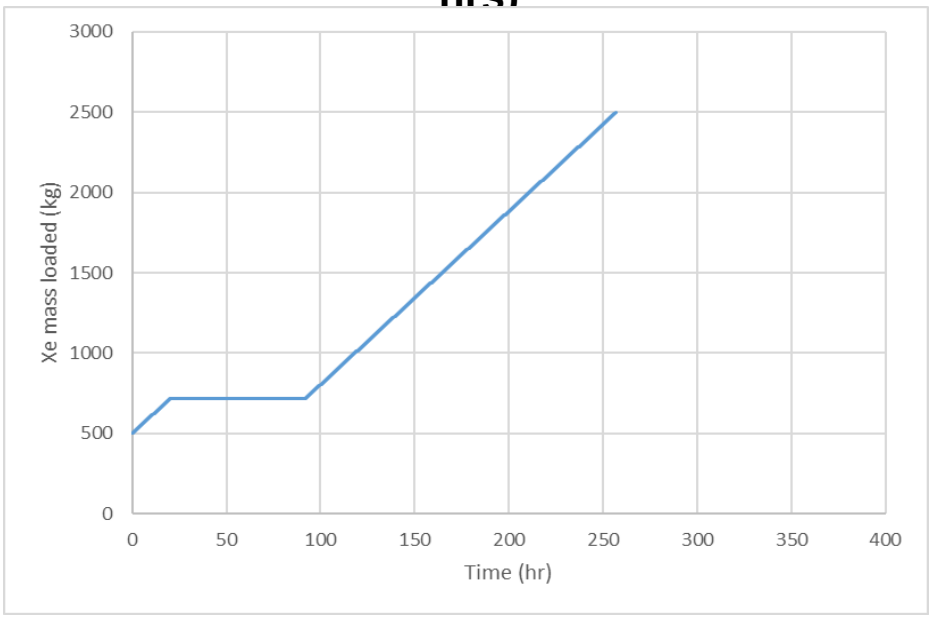


29” Diameter Tank

Mass flow is never cycled on/off since the shutoff temperature is never exceeded.
Total load time is 148 hours, reducing the time by 56% compared to the 40 kg initial xenon mass.

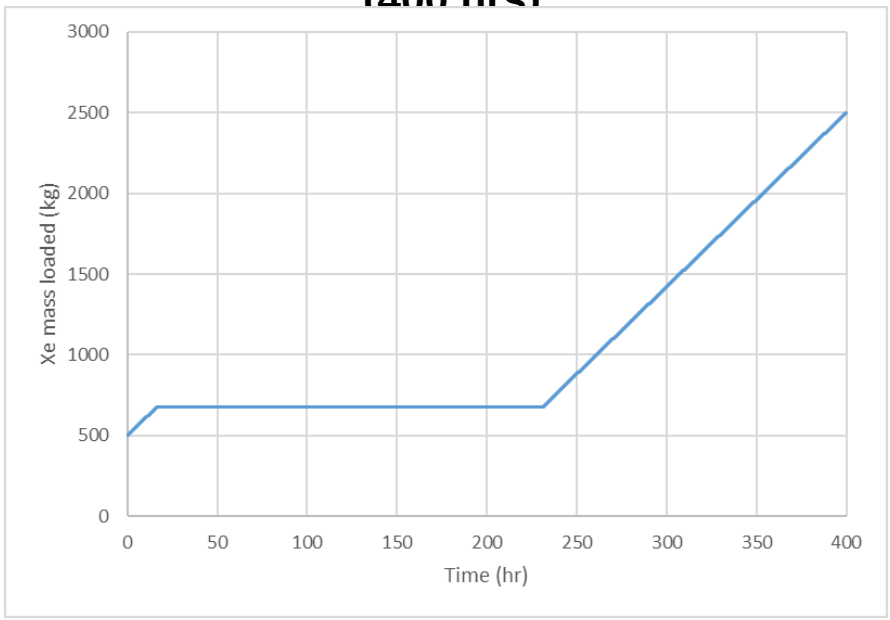
Xenon Mass Loaded vs Time - 0° C Bus Temp vs 20° C Bus Temp

Loading to 2500 kg Xe at 10.8 kg/hr*, 1500 psia, 29" tank, 0° C Bus Temp (257 hrs)



0° C Bus Temp

Loading to 2500 kg Xe at 10.8 kg/hr*, 1500 psia, 29" tank, 20° C Bus Temp (400 hrs)



20° C Bus Temp

***A 10.8 kg/hr flow rate was selected to correspond with ESA's 3 g/s design point. [5]**

Bus Temperature Trade Study
Refueling Time Summary of Results

Constant tank diameter of 29”

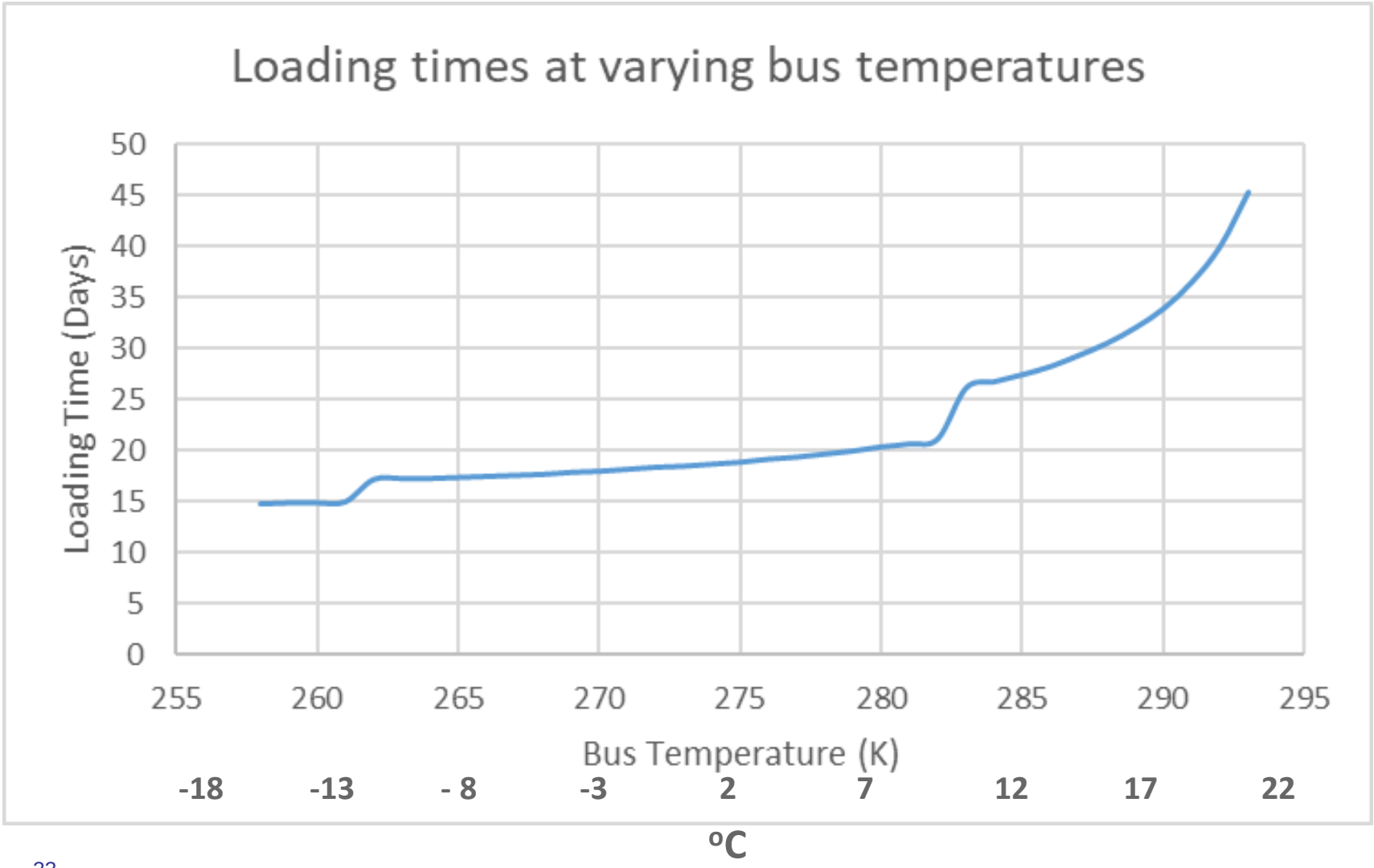
Case	Pressure	Mass (kg)	PUE	Loading Time @ 10.8 kg/hr (days)
-15°C Bus Temp	1500	2500	80%	7.7
0°C Bus Temp	1500	2500	80%	10.7
20°C Bus Temp	1500	2500	80%	16.7

Case	Pressure	Mass (kg)	PUE	Loading Time @ 10.8 kg/hr (days)
-15°C Bus Temp	3000	2500	80%	7.7
0°C Bus Temp	3000	2500	80%	7.7
20°C Bus Temp	3000	2500	80%	7.7

Case	Pressure	Mass (kg)	PUE	Loading Time @ 10.8 kg/hr (days)
-15°C Bus Temp	3000	2500	98%	14.7
0°C Bus Temp	3000	2500	98%	18.4
20°C Bus Temp	3000	2500	98%	45.3

Propellant Loading Time vs Bus Temperature

- 2500 kg, 29” OD, 10.8 kg/hr, 98% PUE



Discussion and Conclusions

- For 29” COPV, the analysis predicts a 14.4 day time for loading 2000kg of Xenon at a design pressure of 1500 psia, a feed rate of 10.8 kg/hr of Xenon and a spacecraft bus temperature of -15C. With a design pressure of 3000 psia, this loading time would drop to 14.1 days.
  - The maximum refueling time per ESA report is a combined 20 days for xenon and hydrazine refueling. [5]
- Due to temperature spike at the beginning of loading (with very little Xenon in the tank), the 50°C limit of the temperature control band is quickly reached which results in many oscillations between “fill” and “cool down” states for the first 6-7 days of loading.
  - The duration of the “fill” state increases throughout loading as with each cycle the Xe in the tank has more thermal capacitance, reducing the temperature rise rate
- The spikes in loading time at specific mass flow rates makes selecting an optimal mass feed rate less straight forward.
- A conduction only heat transfer model yields higher loading times than a natural convection only model.
- The initial mass of propellant in the 29” tank has a large effect on the overall loading time.
  - For 400 kg of initial xenon mass (20% residual), the model predicts a loading time of 6.2 days and eliminates the cycling of the xenon flow during refuel for the 3,000 psia tank design pressure case.

Discussion and Conclusions (continued)

- Analysis predicts a 21.6 day loading time for 2500 kg of xenon in a 46” COPV at a design pressure of 1500 psia, a feed rate of 10.8 kg/hr and a spacecraft bus temperature of -15C. With a design pressure of 3000 psia, this loading time would drop to 21.5 days.
  - The maximum refueling time per ESA report is a combined 20 days for xenon and hydrazine refueling. [5]
- The loading time difference between a 2000 kg 29” tank and a 2500 kg 46” tank is due more to the increase in tank diameter than propellant mass. 2500 kg of xenon in a 3000 psia 29” tank has a load time of 16 days, compared to 21.5 days in a 3000 psia 46” tank.
  - A 46” tank provides 25% less surface area to radiate heat to the S/C bus than a 29” tank at equal design conditions of 3000 psia and 2500 kg of xenon.
- At low initial Xenon mass prior to refueling (98% PUE), elevated bus temperatures have a significant impact on Xenon cooldown time, with the potential impact to increase loading time to 45 days.
  - Higher bus temperatures lowers the gas to wall conduction heat transfer rate and radiation heat transfer rate significantly.
  - The lower heat transfer rate at higher bus temperatures is caused by the reduced ΔT from the tank wall to cooler heat sink

Discussion and Conclusions (continued)

- For the high pressure design case (3000 psia), constant loading is still achievable with an 80% propellant utilization efficiency, allowing for a load time of 7.7 days over a bus temperature ranging from -15 °C to 20 °C.
  - The constant loading timelines over the bus temp. range occurs because the gas never reaches the 50 °C shutoff temperature limit. Then with 500 kg initially in the tank, the Xe flow remains on and the flow rates constant throughout the loading cycle and the refuel time is simply:

$$t = \frac{m}{\dot{m}} = \frac{2000\ kg}{10.8\ {}^{kg}/_{hr}\ 24\ {}^{hr}/_{day}} = 7.7\ days$$

- From these preliminary analysis trade studies for PPE, the following design and operational parameters were shown to result in reduced Xenon refueling times:
  - Smaller tank diameter for equal Xe capacity
    - Same as increased tank L/D ratio
  - Larger initial Xenon mass prior to refuel
  - Increased design pressure at constant tank diameter
    - Secondary effect which is not true for all $\dot{m}$ conditions
  - Lower bus temperature

Major Observations

- Tank pressure over 1500-3000 psi range does not significantly affect refuel time
- Amount of xenon remaining in tank at refuel events can significantly affect refuel time
- Ability to move heat from tank to spacecraft dependent on thermal resistance between tank and spacecraft bus.
  - Xenon tanks need to be insulated but insulation results in restricting thermal flow path to spacecraft bus during refueling
- These set of analysis with associated assumptions are refueling-method generic
  - PPE Aft Refueling via commercial interface
  - ESPRIT to PPE Aft refueling
  - Refueling vehicle (at Radial UM port) to ESPRIT
- Applying the assumptions made for this analysis, refueling of xenon can be accomplished within the 21 day, between-Orbit-maintenance, limit.

References

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2. Malroy. “Free Molecular Heat Transfer Programs for Setup and Dynamic Updating the Conductors in Thermal Desktop” NASA Johnson Space Center. Internal report.
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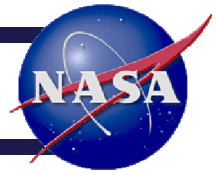
4. Siamidis, John. “SEP ARRM-Option B. Thermal Control System (TCS) Design & Thermal Analysis for DAC-3, 8-Tank configuration.” July 1, 2015. NASA internal document. File name: SEP ARM DAC3 OptionB MegaFlex 07012015.pptx
5. ESA/TAS-F/OHB/ADS-F. “IECST – ESPRIT Refuelling Splinter.” July 9, 2018. File name: IECST-09072018-ESPRIT-Refueling-v1.1-1.pptx
6. Bussi G., Colasurdo G. “Heat Transfer Analysis in Pressurizer Tank Under Microgravity”, SAE Transactions, Vol. 95 Section 7: Aerospace, pp. 272-277, 1986.

BACKUP



Xenon Properties

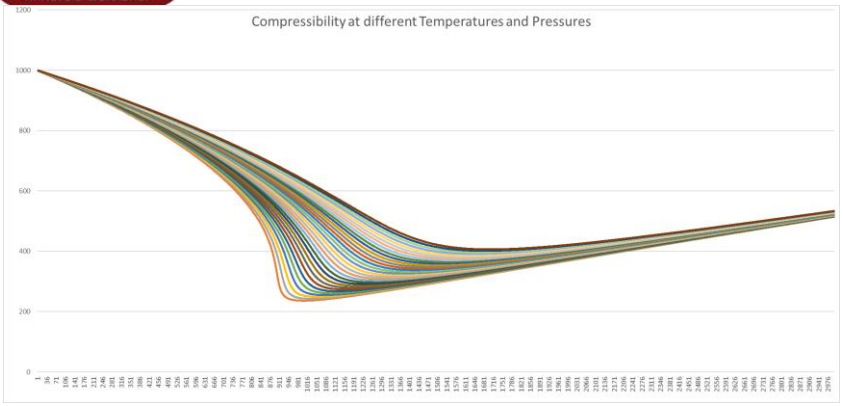
- **Xenon**
  - **Symbol: Xe**
  - **MW: 131.293 lb/lb-mol**
  - **Acentric Factor: 0.00363**
  - **Normal Boiling Point: 297.09 ^{o}R (-108.1 ^{o}C / 165.05 K)**
  - **Triple Point:**
    - **Temperature: 290.5 ^{o}R (-111.7 ^{o}C)**
    - **Pressure: 11.86 psia**

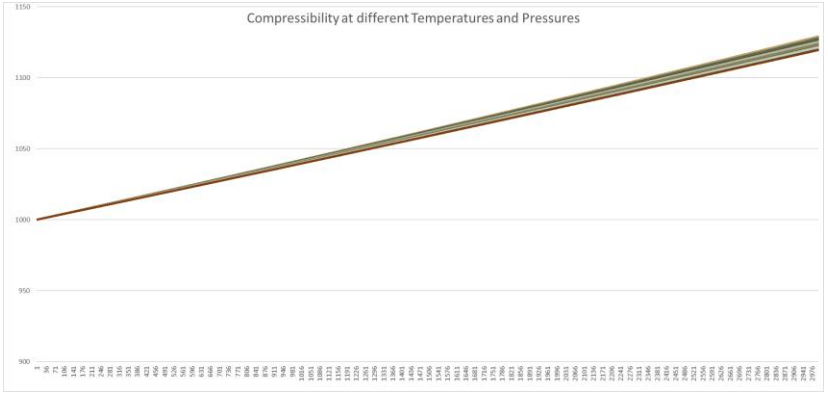
- **Xenon Critical Properties**
  - **State: Supercritical fluid**
  - **Critical Temp: 61.9 ^{o}F (16.6 ^{o}C / 289.75 K)**
  - **Critical Pressure: 847.3 psia**
  - **Critical Density: 68.85 lb/ft^3 (1.103 g/cm^3)**
  - **Entropy at T_c, P_c: 0.0648 Btu/lb$_m$-^{o}R**

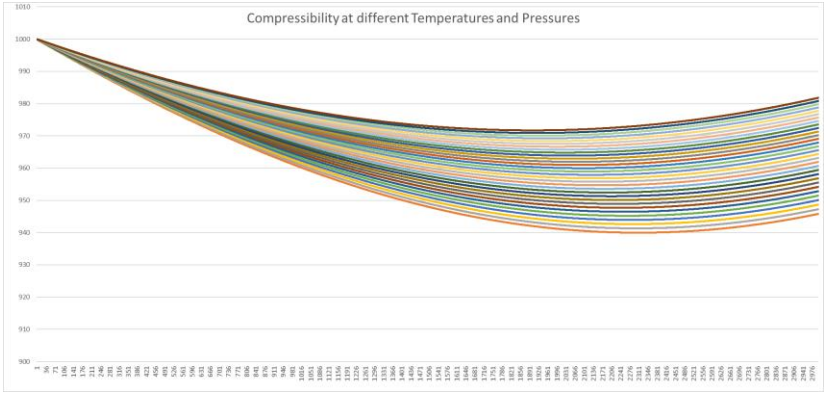
- **Xenon at Standard Conditions (STP)**
  - **Temp: 77 ^{o}F (20 ^{o}C)**
  - **Pressure: 14.696 psia**
  - **Density: 0.3427 lb/ft^3 (5.49 x 10^{-3} g/cm^3)**
  - **Compressibility Factor:**
  - **γ = Cp/Cv : 1.678**
  - **State: Gas**

Source: NIST Refprop

Xenon Properties vs Hydrogen/Argon - Compressibility





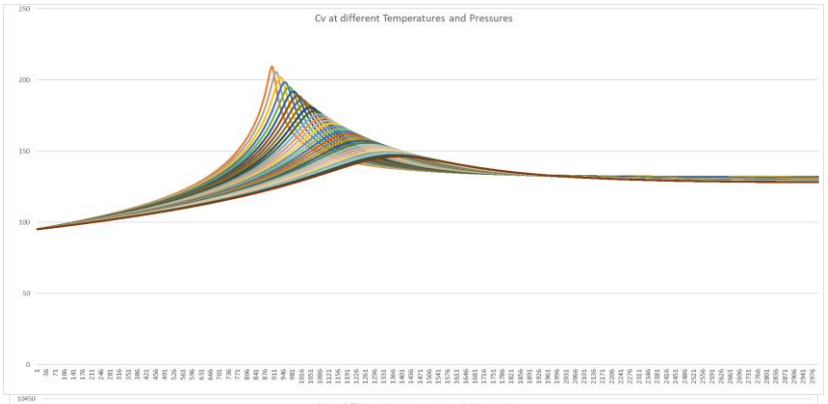


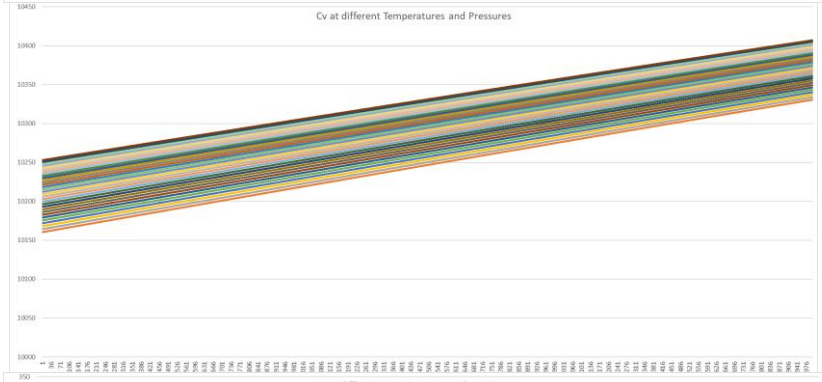
Xenon – X-axis is pressure, Y-axis is property, each line is a different constant Temperature.

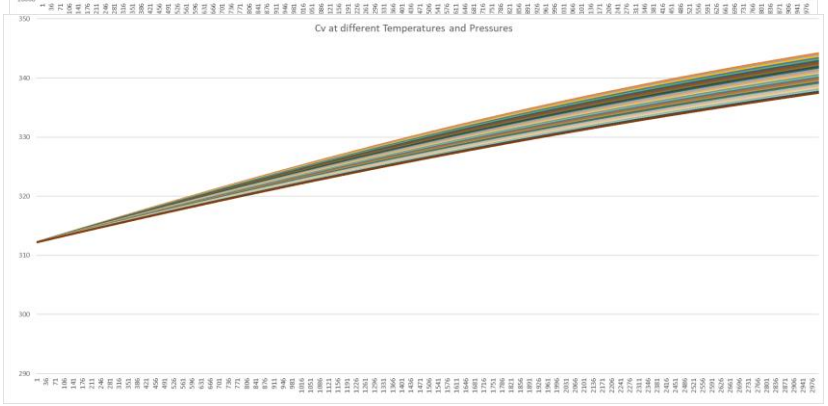
Hydrogen

Argon

Xenon Properties vs Hydrogen/Argon - Cv





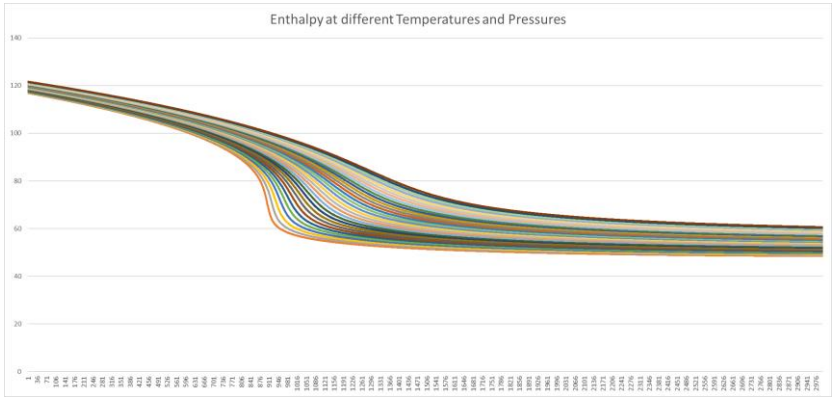


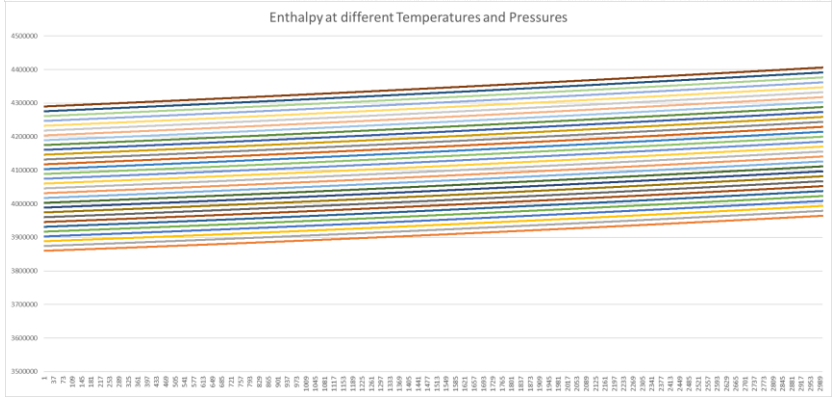
Xenon – X-axis is pressure, Y-axis is property, each line is a different constant Temperature.

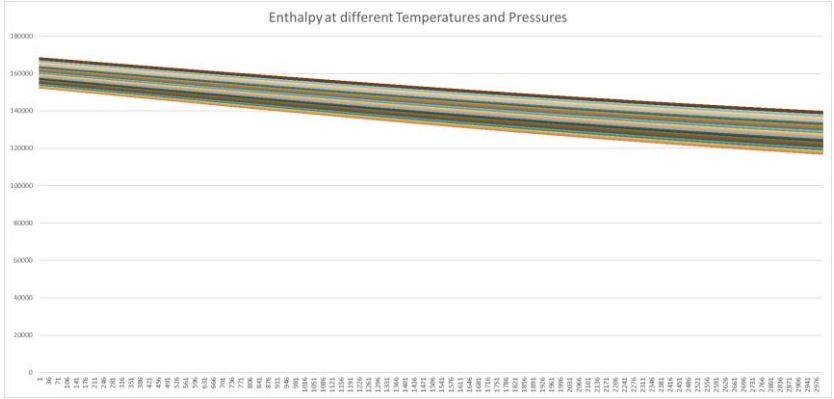
Hydrogen

Argon

Xenon Properties vs Hydrogen/Argon - Enthalpy





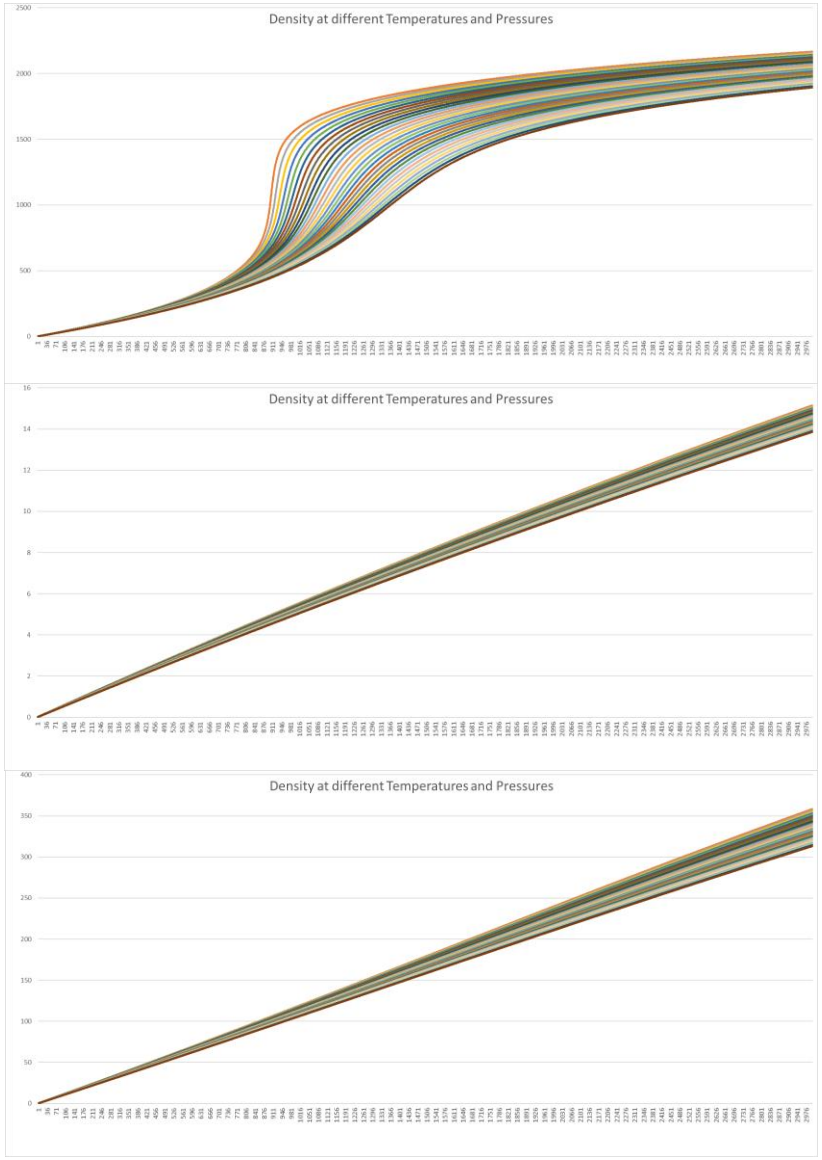


Xenon – X-axis is pressure, Y-axis is property, each line is a different constant Temperature.

Hydrogen

Argon

Xenon Properties vs Hydrogen/Argon - Density

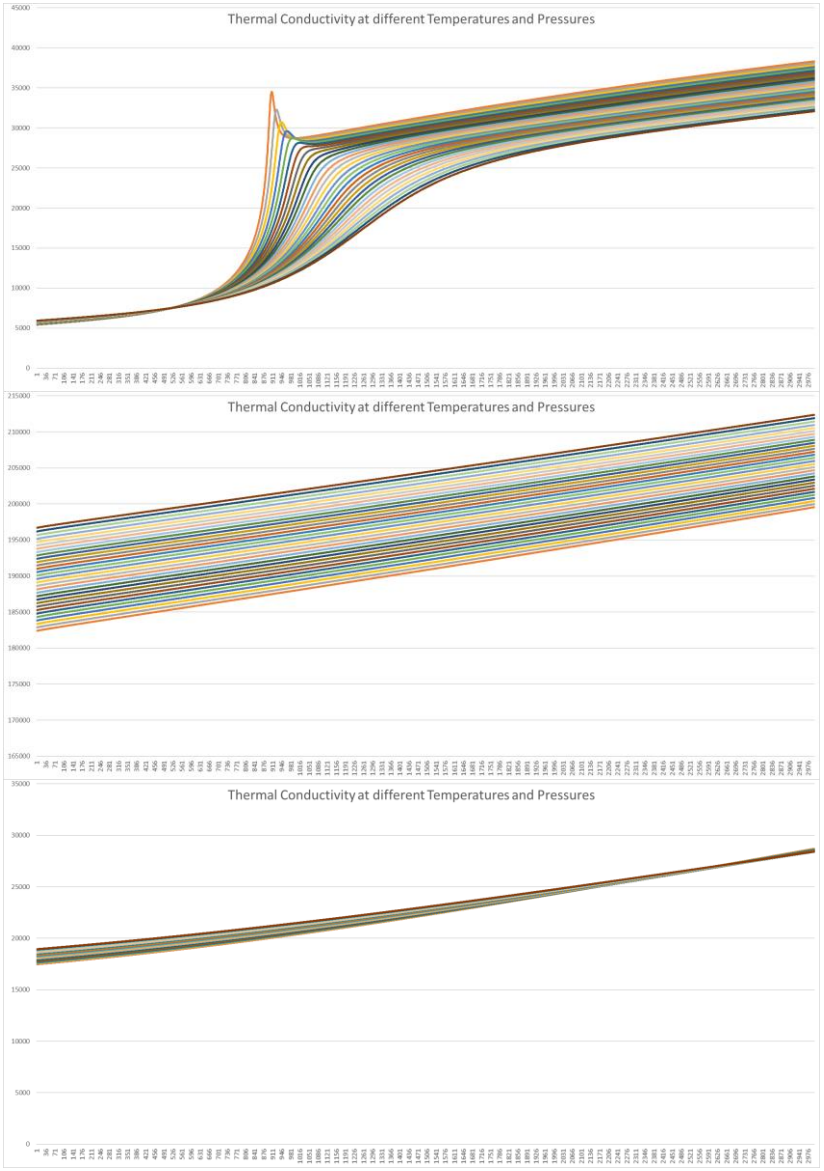


Xenon – X-axis is pressure, Y-axis is property, each line is a different constant Temperature.

Hydrogen

Argon

Xenon Properties vs Hydrogen/Argon – Thermal Conductivity

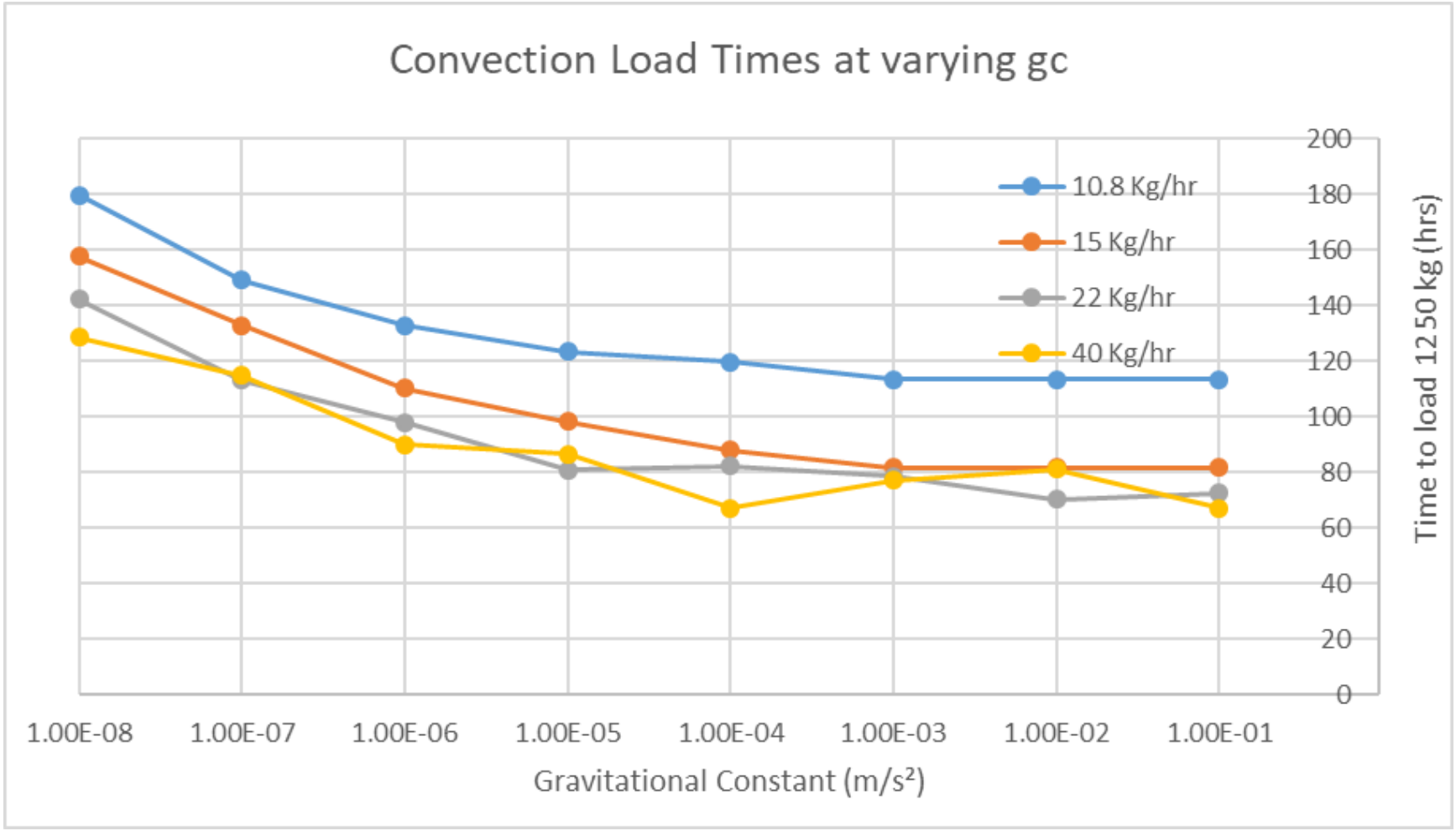


Xenon – X-axis is pressure, Y-axis is property, each line is a different constant Temperature.

Hydrogen

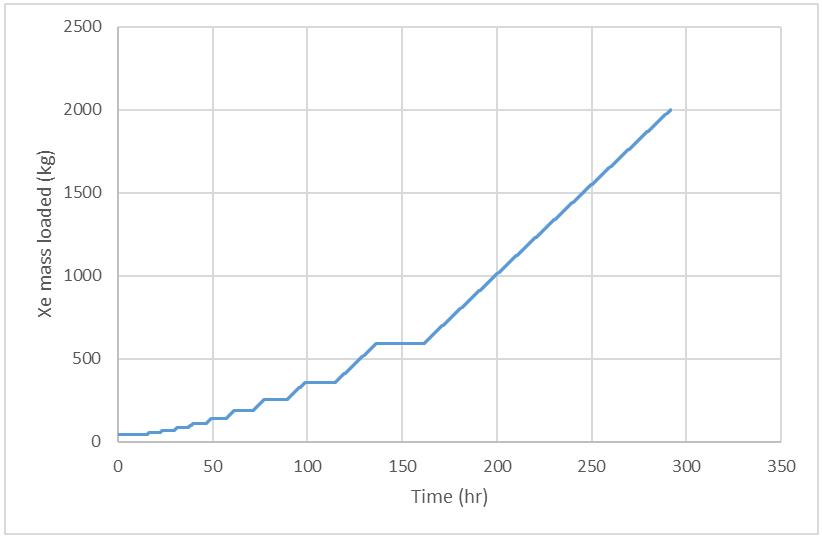
Argon

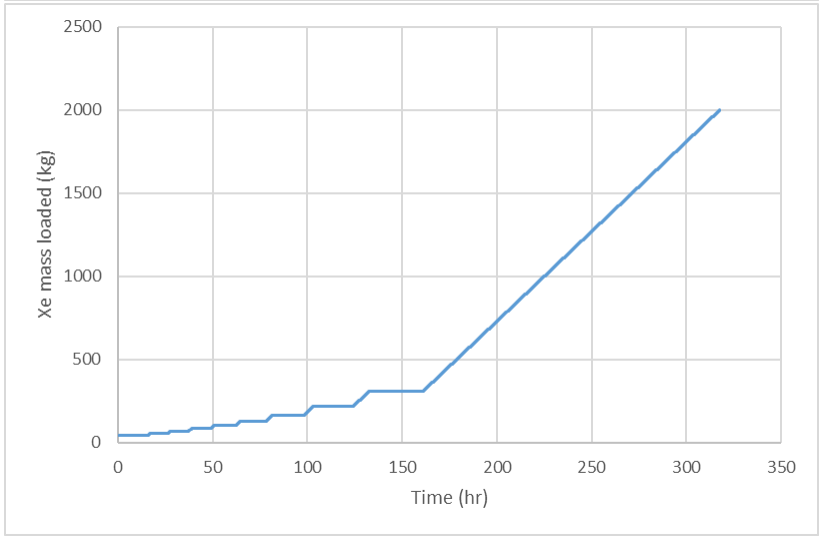
Comparing convection load times at varying mass flows and different gravitational constants



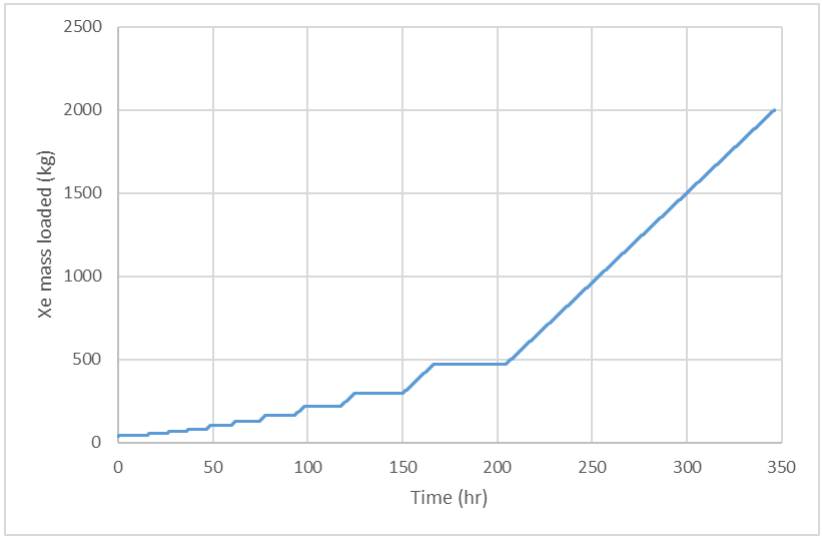
Xenon Mass Loaded vs Time

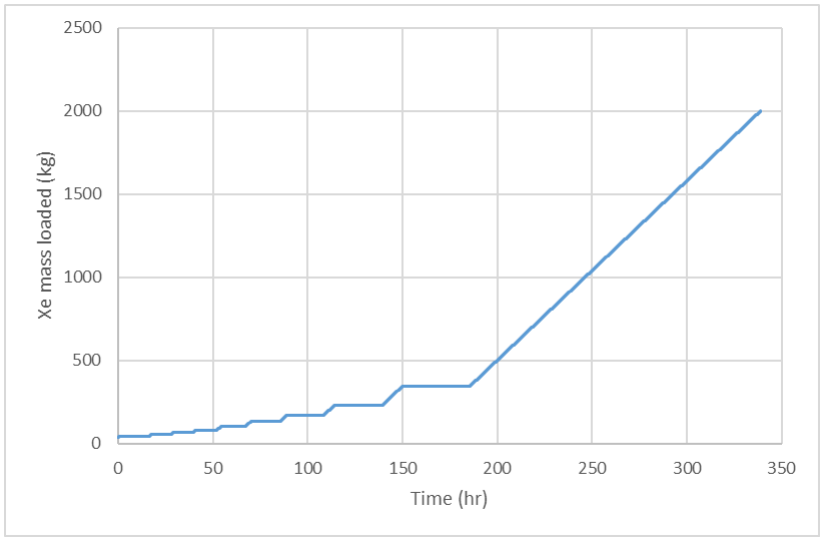
Loading to 2000 kg Xe at 10.8 kg/hr, 1000 psia (292 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 1750 psia (318 hrs) (Btm)





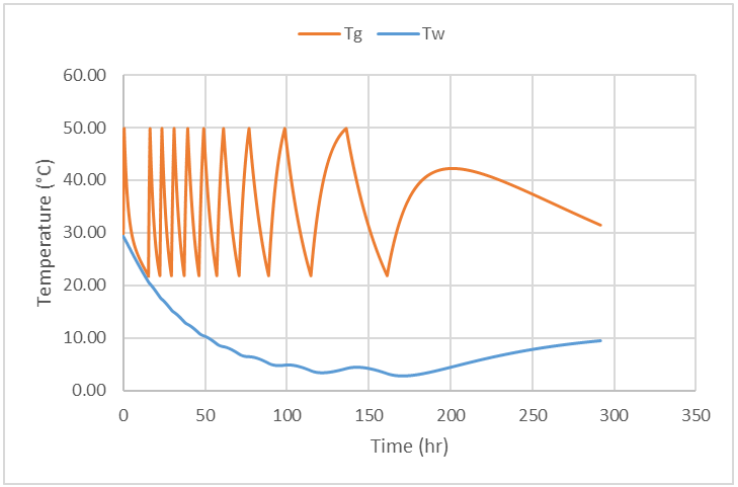
Loading to 2000 kg Xe at 10.8 kg/hr, 1500 psia (346 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 3000 psia (339 hrs) (Btm)

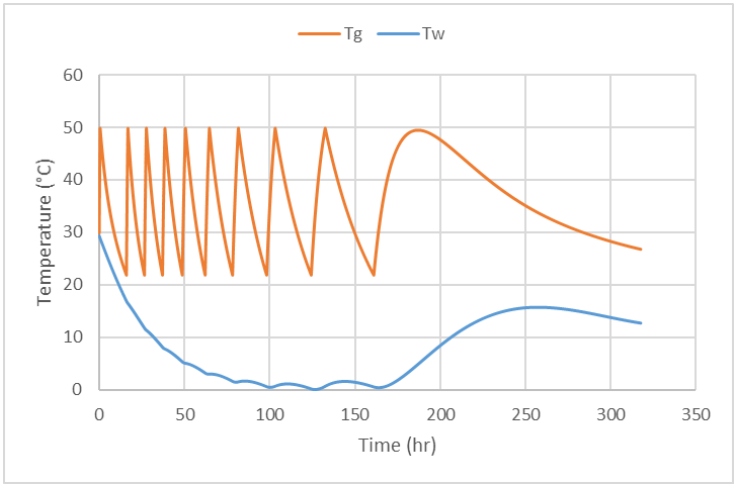




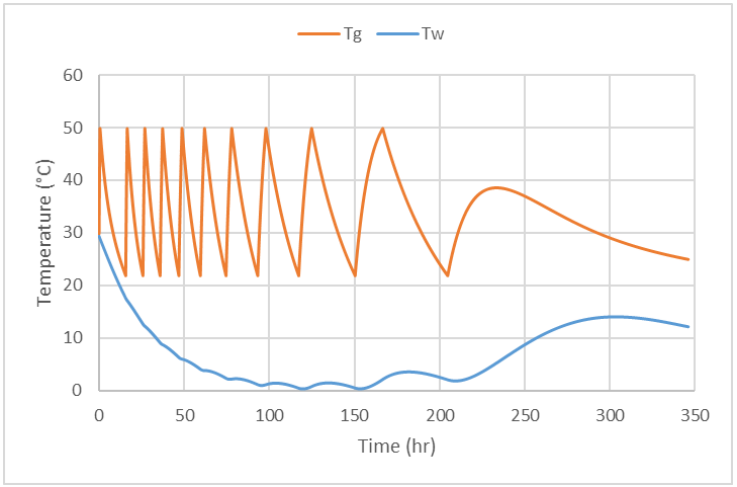
Temperature of Gas and Wall vs Time

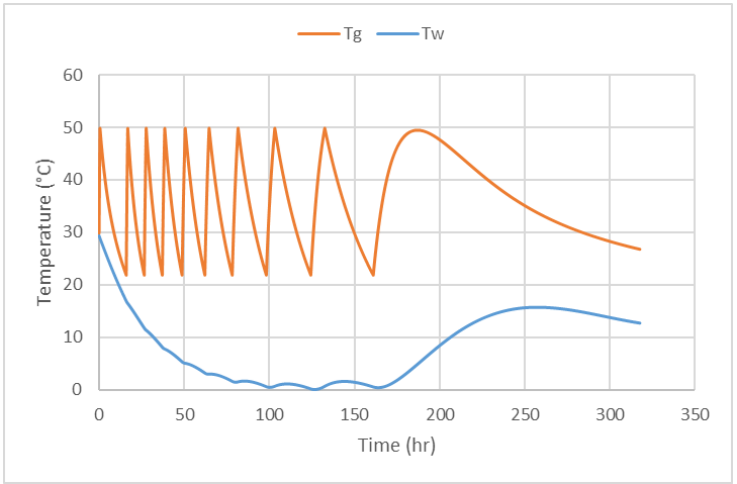
Loading to 2000 kg Xe at 10.8 kg/hr, 1000 psia (292 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 1750 psia (318 hrs) (Btm)





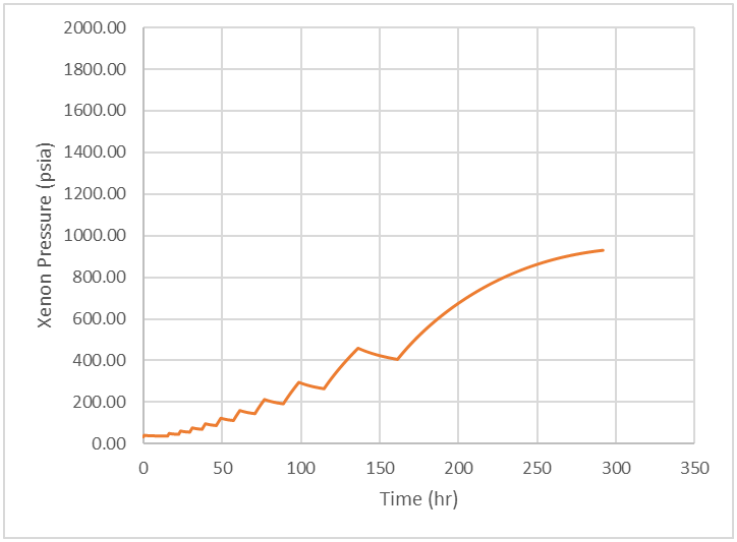
Loading to 2000 kg Xe at 10.8 kg/hr, 1500 psia (346 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 3000 psia (339 hrs) (Btm)

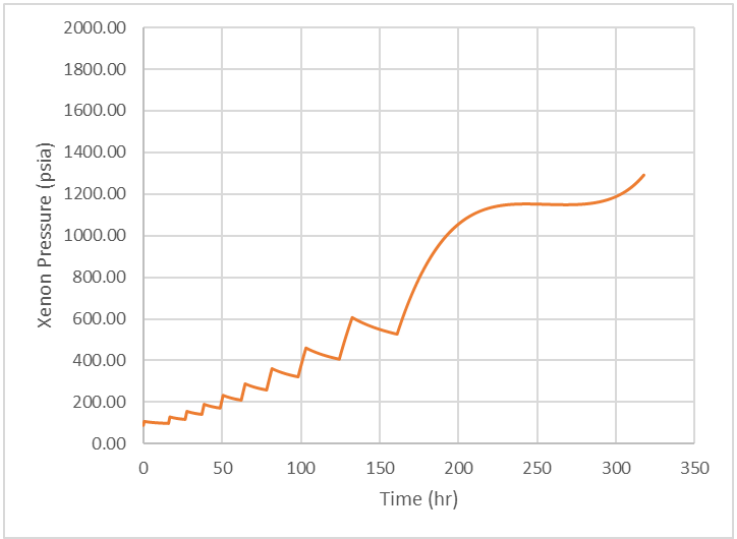




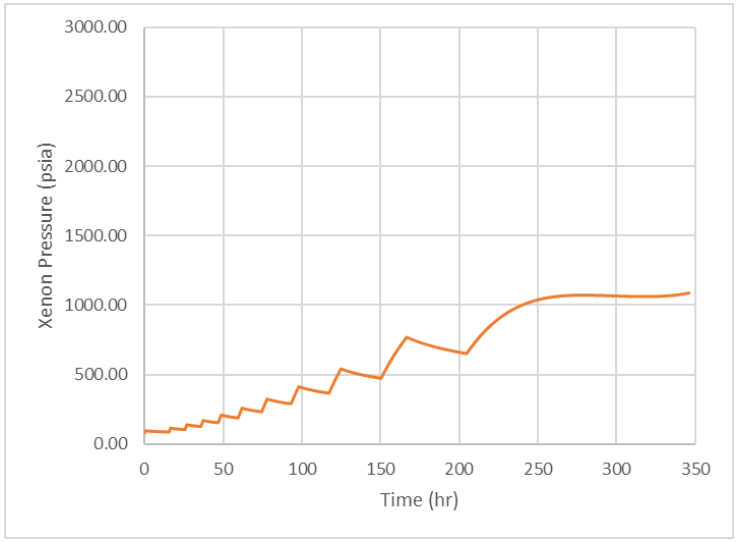
Tank Pressure vs Time

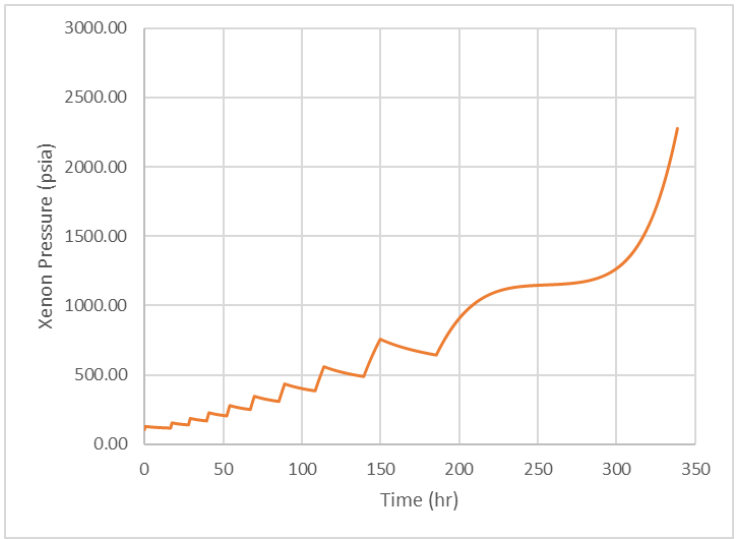
Loading to 2000 kg Xe at 10.8 kg/hr, 1000 psia (292 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 1750 psia (318 hrs) (Btm)





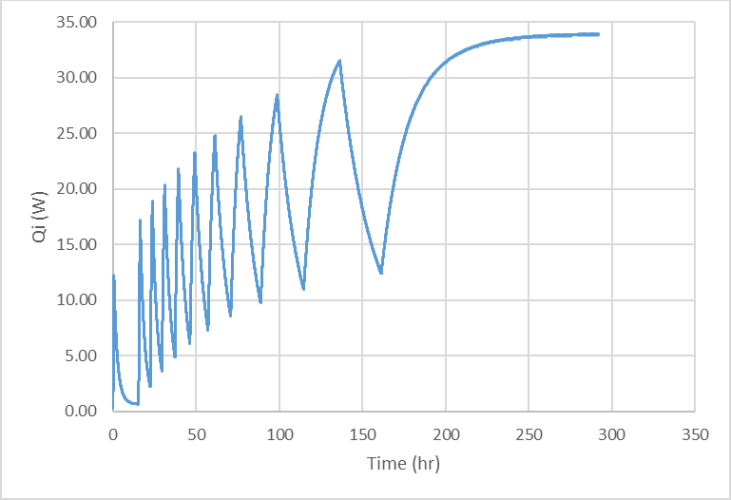
Loading to 2000 kg Xe at 10.8 kg/hr, 1500 psia (346 hrs) (Top
Loading to 2000 kg Xe at 10.8 kg/hr, 3000 psia (339 hrs) (Btm

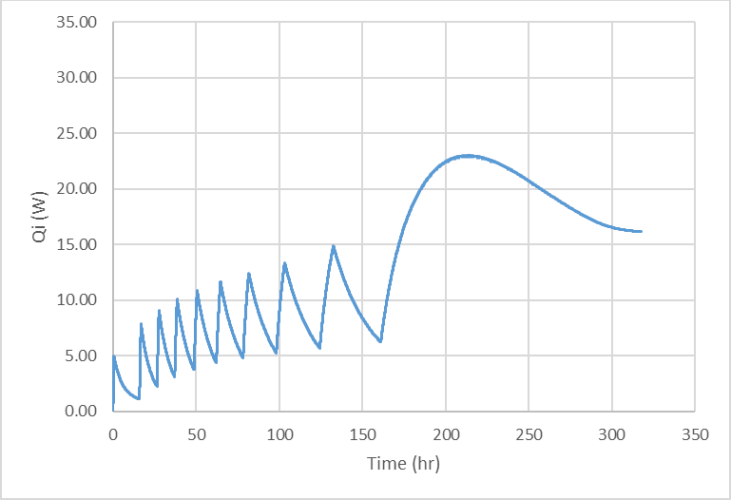




Gas to wall heat transfer rate vs Time

Loading to 2000 kg Xe at 10.8 kg/hr, 1000 psia (292 hrs) (Top)
Loading to 2000 kg Xe at 10.8 kg/hr, 1750 psia (318 hrs) (Btm)





Loading to 2000 kg Xe at 10.8 kg/hr, 1500 psia (346 hrs) (Top)
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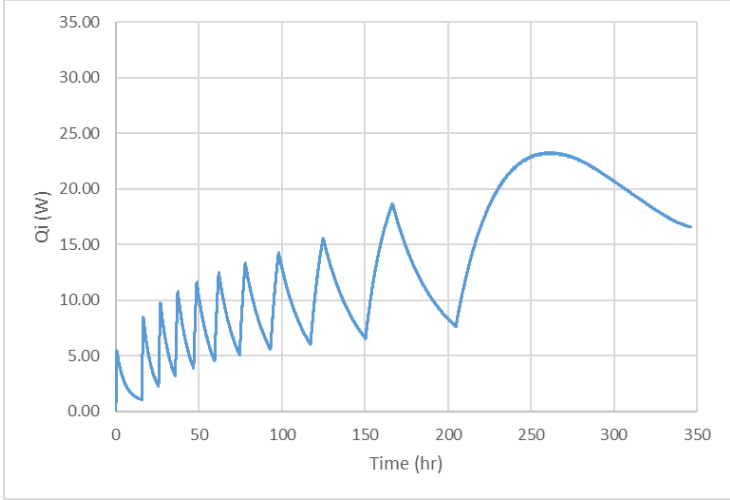
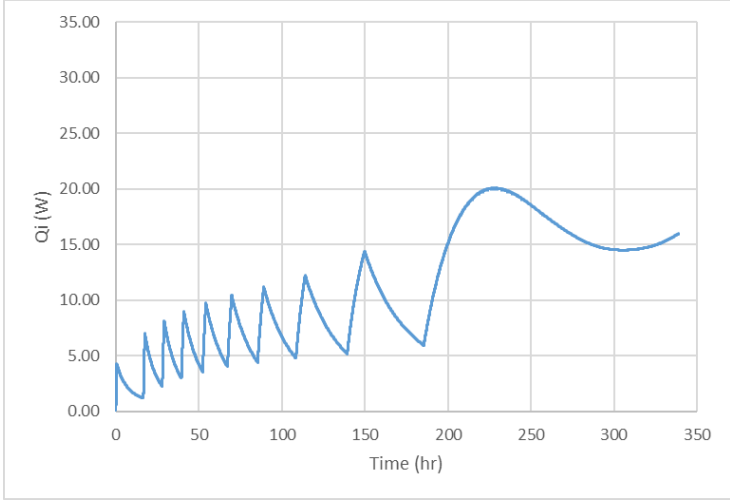
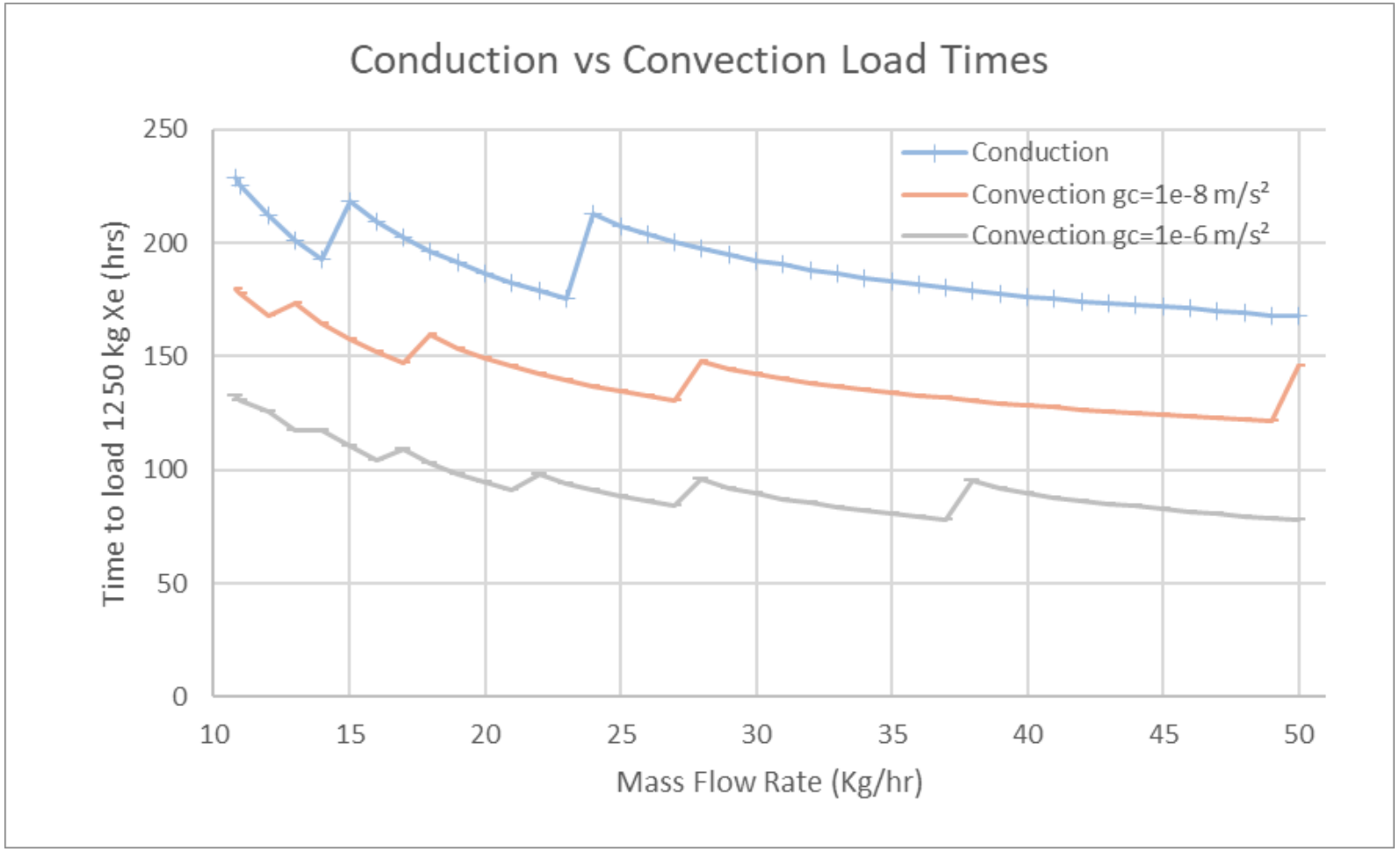


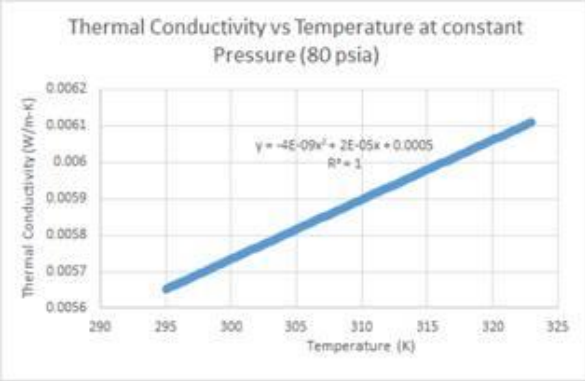


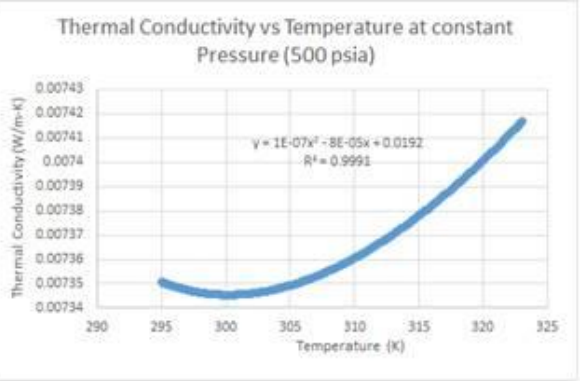
PPE On-Orbit Xenon Propellant Refueling

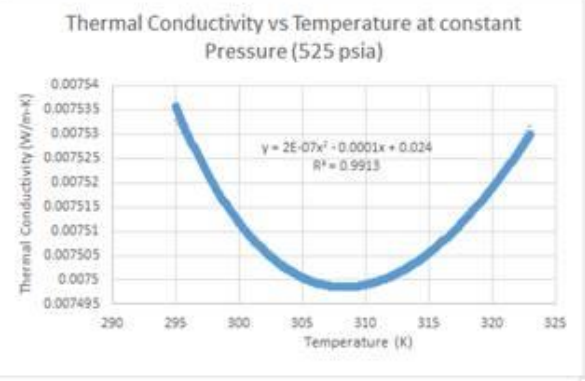
Comparing conduction and convection load times at varying mass flows and different gravitational constants, for ARRM case 1250 kg Xenon

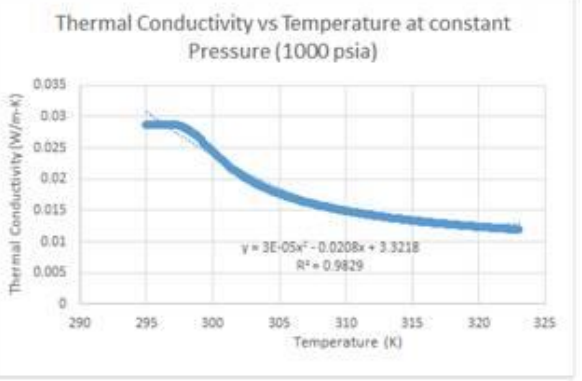


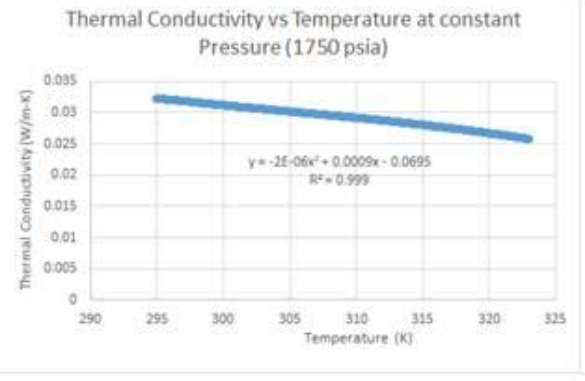
PPE On-Orbit Xenon Propellant Refueling

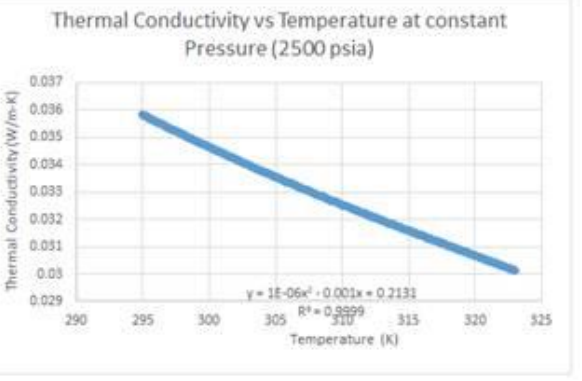






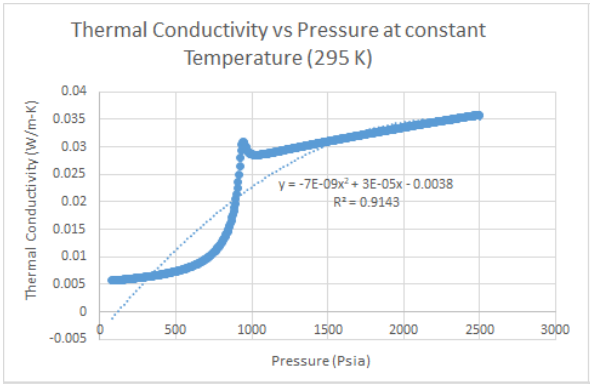


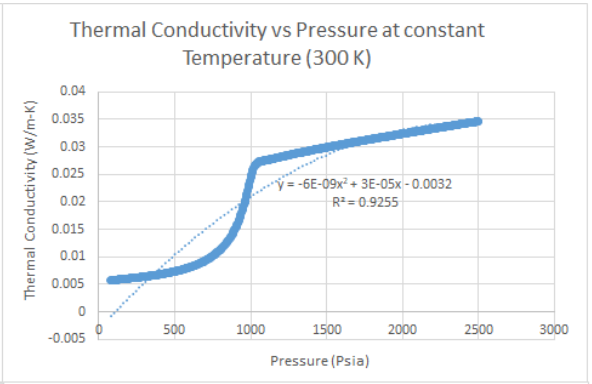


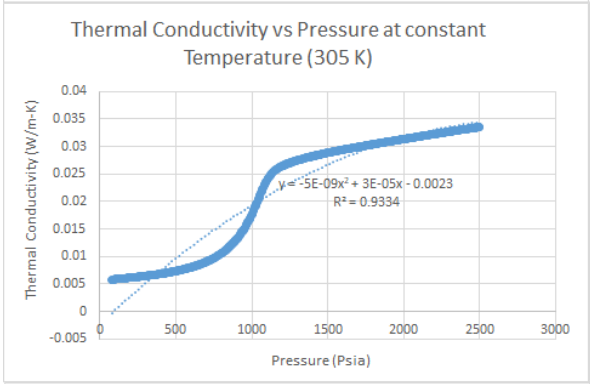


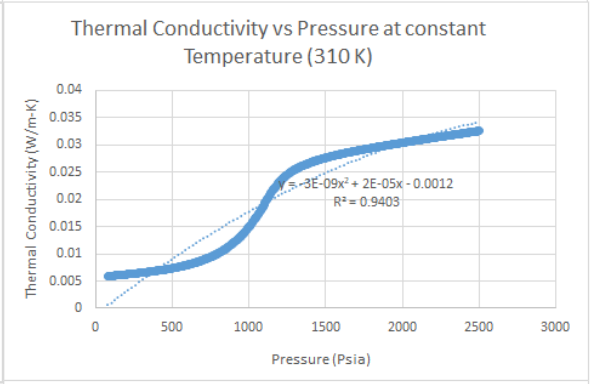
Comparing thermal conductivity vs temperature at different constant pressures.

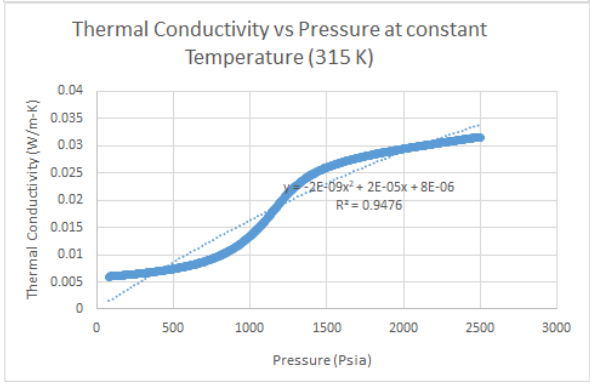
PPE On-Orbit Xenon Propellant Refueling

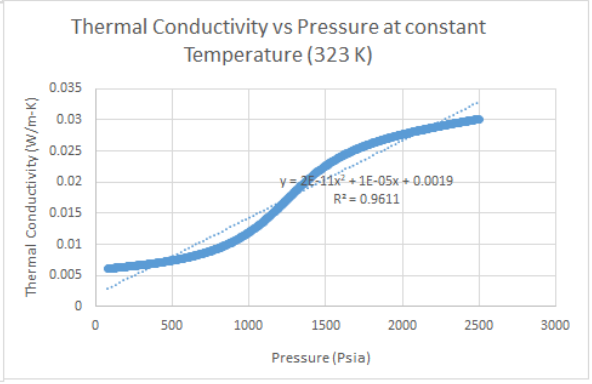












Comparing thermal conductivity vs pressure at different constant temperatures.