Modeling ARRM Xenon Tank Pressurization using 1D Thermodynamic and Heat Transfer Equations

Ryan Gilligan & Thomas Tomsik
NASA GRC

Presented By
Ryan Gilligan

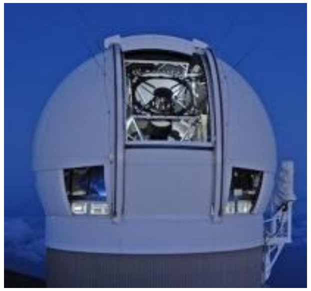
Thermal & Fluids Analysis Workshop
TFAWS 2016
August 1-5, 2016
NASA Ames Research Center
Mountain View, CA

Contents

- Asteroid Redirect Robotic Mission (ARRM)
- Scope & Why Loading Analysis ?
- Flight Tanks – Basis & Description
- Concept Ground Loading System (GSE) Block & ConOps
- Tank Loading Model Description & Approach
- Model Validation Cases
  - DAWN
  - GH2 Cylindrical tank Fill
- ARRM Loading Analysis Results
- Conclusions

Three Main Segments in Asteroid Mission

Identify



Asteroid Identification Segment:

Ground and space based NEA target detection, characterization and selection

Redirect

Asteroid Redirection Segment:

Solar electric propulsion (SEP) based asteroid capture and maneuver to trans-lunar space

Explore

Asteroid Crewed Exploration Segment:

Orion and SLS based crewed rendezvous and sampling mission to the relocated asteroid

Source: http://www.nasa.gov/pdf/740684main_LightfootBudgetPresent0410.pdf

Problem Statement

- ARRM needs to load 5 to 10 metric tons of xenon propellant into the spacecraft flight tanks in a timely manner while the spacecraft is on the Launchpad
    - Xenon’s high heat of compression combined with the low maximum allowable temperature of the composite tank allowable temperature make this difficult
    - Provisions for cooling the tanks need to be planned and in place ahead of time (Lesson Learned from Dawn mission)
- Modeling effort undertaken to understand how long loading will take in addition to requirements for external cooling provisions

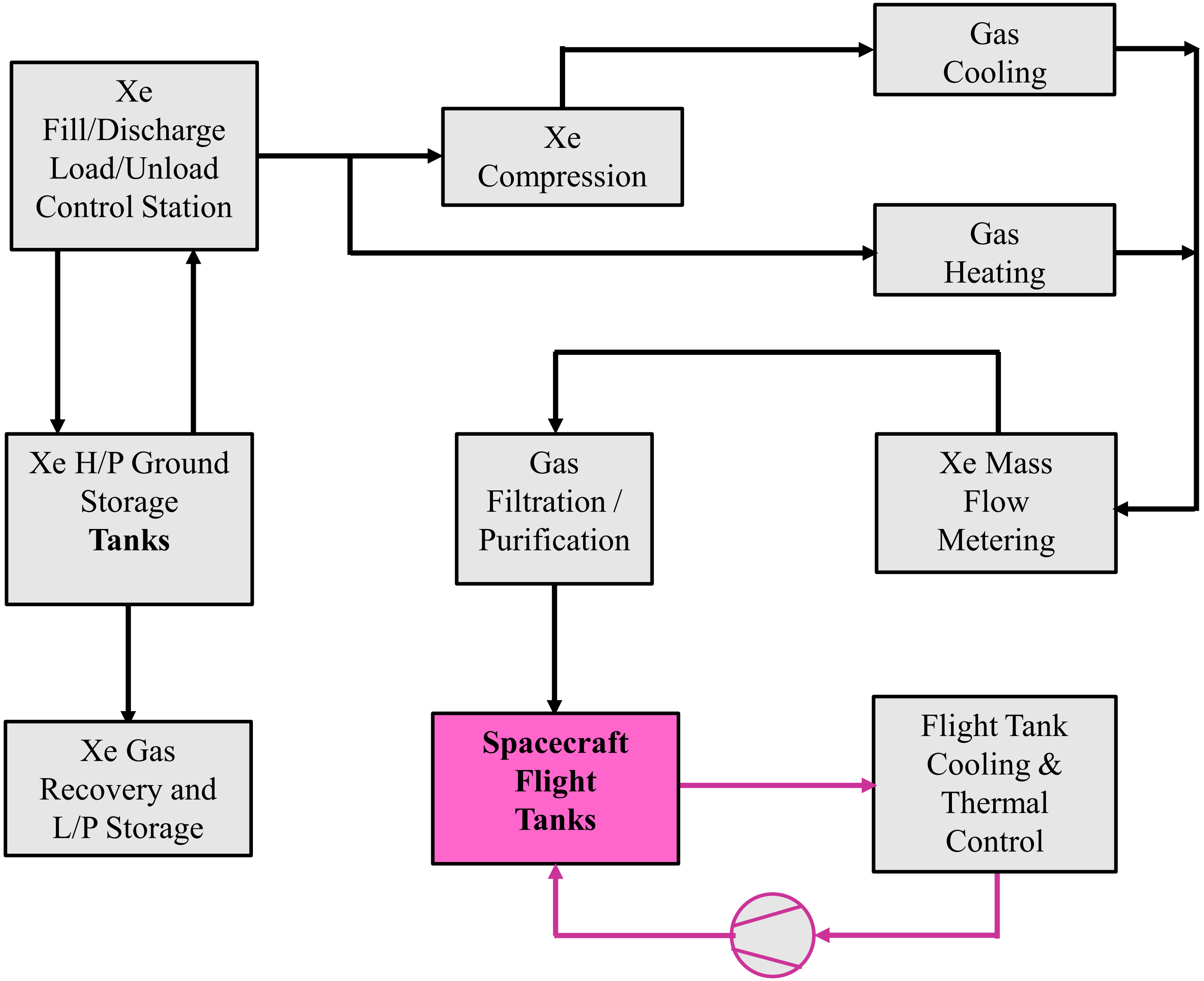
Scope of Xenon Tank Ground Loading Analysis

- Xenon Tanks
  - Initial Conditions: 14.7 psia, 20 °C (pure Xe inside tanks at these conditions)
  - Final Conditions: 1750 psia, 40 °C max. target temp. w/2000 kg/MCR Tank and 1250 kg/Post-MCR IDAC3 Tank
  - During loading, the maximum allowable gas/wall temperature is 55 °C
- Loading Analysis (What we need to understand)
  - How long will it take to load all 4 / 8 tanks (MCR / Post-MCR) ?
  - What will the Xenon flow rates be ?
  - What provisions for cooling Xenon will be needed to :
    - Reduce Xenon Loading Time Line by increasing Pumping Speed
    - Keep Gas Bulk temperature and Tank Wall not to exceed 55 °C
    - What are the cooling rates needed (watts, Btu/sec)
    - Single tank loading or Loading all 4 / 8 tanks simultaneously
    - Variable xenon loading flow rates can be used during tank charging
    - Cooling can be by free or forced convection over tank surfaces and/or using a Xenon pre-cooler heat exchanger on the Ground side of the XFS

ATK COPV

***Credit*: G. Kawahara and S. McCleskey, *Titanium Lined, Carbon Composite Overwrapped Pressure Vessel*, AIAA 96-2751, 1996.**

Block Diagram of Xenon GSE



Xe Fill/Discharge Load/Unload Control Station

Xe Compression

Gas Cooling

Gas Heating

Xe H/P Ground Storage **Tanks**

Gas Filtration / Purification

Xe Mass Flow Metering

Xe Gas Recovery and L/P Storage

Spacecraft Flight Tanks

Flight Tank Cooling & Thermal Control

Subsystems

- Electrical and Command & Control Subsystem
- Leak Detection Subsystem
- Sampling **Subsystem w/Propellant Analyzer**
- Vacuum Subsystem
- Chiller Subsystem

TANK LOADING MODEL DESCRIPTION & APPROACH

Xenon Loading Model

- Model was created in Excel to predict xenon temperatures and pressures within the COPV throughout loading
- Model inputs include: mass flow rate (constant or variable), time step, tank properties (geometry and material), inlet xenon temperature, external coolant fluid (air, N2, etc), velocity, and temperature
  - Initial mass load, temperature, and pressure within the COPV must also be specified
- Model uses marching analysis technique
  - Time and mass within the COPV are marched forward and the remaining variables are calculated at each time step
- NIST REFPROP used to calculate fluid thermodynamic and transport properties

Calculation Approach

- Equations governing loading of COPV [4]:

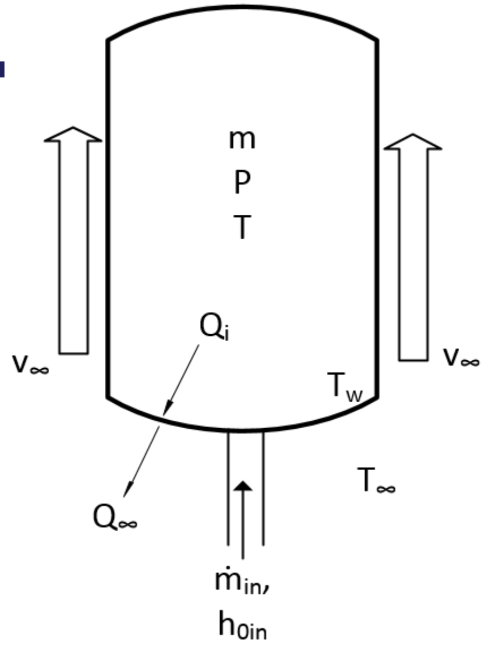
$$\frac{d}{dt}(mu) = -\dot{Q}_i + \dot{m}_{in} h_{0in}$$

$$\frac{dU_w}{dt} = (W_c)_w \left(\frac{dT_w}{dt}\right) = \dot{Q}_i - \dot{Q}_\infty$$

$$\dot{Q}_i = \left(h_q A_w\right)_i \left(T - T_w\right)$$

$$\dot{Q}_\infty = \left(h_q A_w\right)_\infty \left(T_w - T_\infty\right)$$

- Q : heat transfer rate
- u : xenon internal energy within COPV
- $\dot{m}$: mass flow rate
- h_{0in} : stagnation enthalpy of inlet flow
- W_c : thermal capacitance of COPV wall
- A_w : wall area
- h_q : convection coefficient



Assumptions - ARRM

- Uniform COPV wall temperature
- Inlet mass flow at constant temperature (20 ^{0}C)
- Xe within COPV is uniform temp
- External coolant flow in axial direction of cylindrical COPV
- $h_{0in} \approx C_p T_{0in}$
- No MLI on outer COPV surface

Calculation Approach (cont'd)

Combining equations on previous slide and applying assumptions yields 2 ODEs:

$$\dot{m} * m\left(\frac{dT}{dm}\right) + \left[\frac{(h_q A_w)_i}{C_v}\right](T - T_w) + \dot{m}(T - \gamma T_{0\ in}) = 0$$

$$\dot{m}\left(\frac{dT_w}{dm}\right) + \left[\frac{\left(h_q A_w\right)_i + \left(h_q A_w\right)_\infty}{\left(W_c\right)_w}\right]T_w - \left[\frac{\left(h_q A_w\right)_i}{\left(W_c\right)_w}\right]T - \left[\frac{\left(h_q A_w\right)_\infty}{\left(W_c\right)_w}\right]T_\infty = 0$$

- Solved above for ${}^{\Delta T}/_{\Delta M}$ and $\Delta Tw\ /\ \Delta M$
- ${}^{\Delta T}/_{\Delta M}$: change in Xe temp with respect to change in mass inside COPV
- $\Delta Tw\ /\ \Delta M$: change in COPV wall temp with respect to change in mass inside COPV

Heat Transfer Correlations

Natural Convection

- Vertical cylinder can be approximated as vertical flat plate using Churchill and Chu correlation[ref5]:

$$\overline{Nu}_{VP} = \left\{ .825 + \frac{.387 Ra_L^{\frac{1}{6}}}{\left[1 + \left({.492}/{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2$$

Ra: Rayleigh #

Pr: Prandtl #

Nu: Nusselt #

- Relevant on both inside and outside surface

Forced Convection

- For laminar flow in the axial direction of a vertical cylinder[ref6]:

$$Nu=0.134(Re^{0.668})$$

- For turbulent flow:

$$Nu=0.155(Re^{0.674})$$

Where Re is Reynolds #

- Forced convection only relevant on external surface of COPV

MODEL VALIDATION CASES

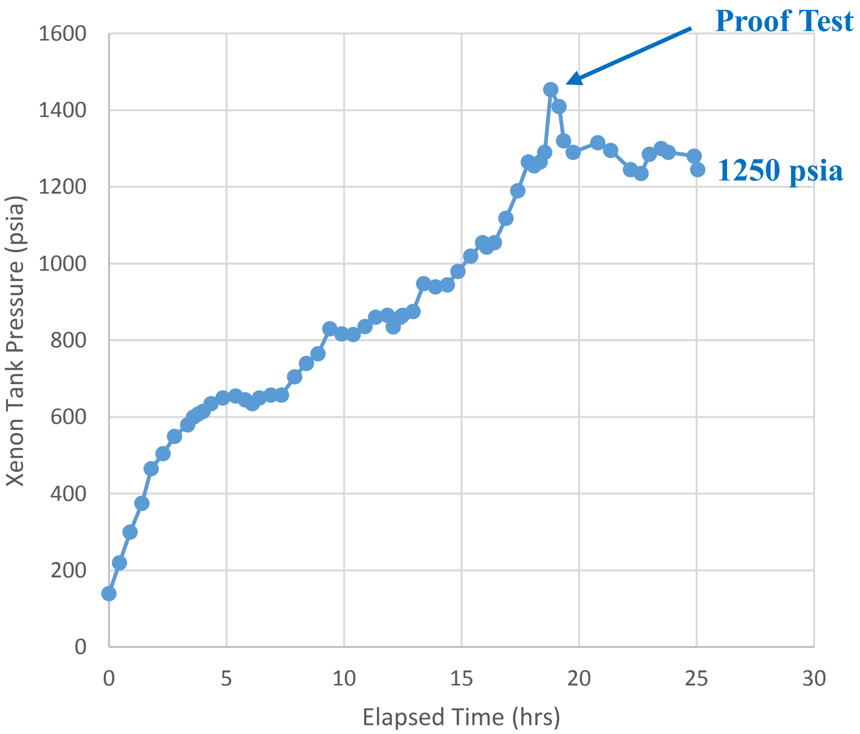
- ✓ ***DAWN Data***
- ✓ ***GH2 Cylindrical Tank Fill Data***

Model Comparison with Dawn Data

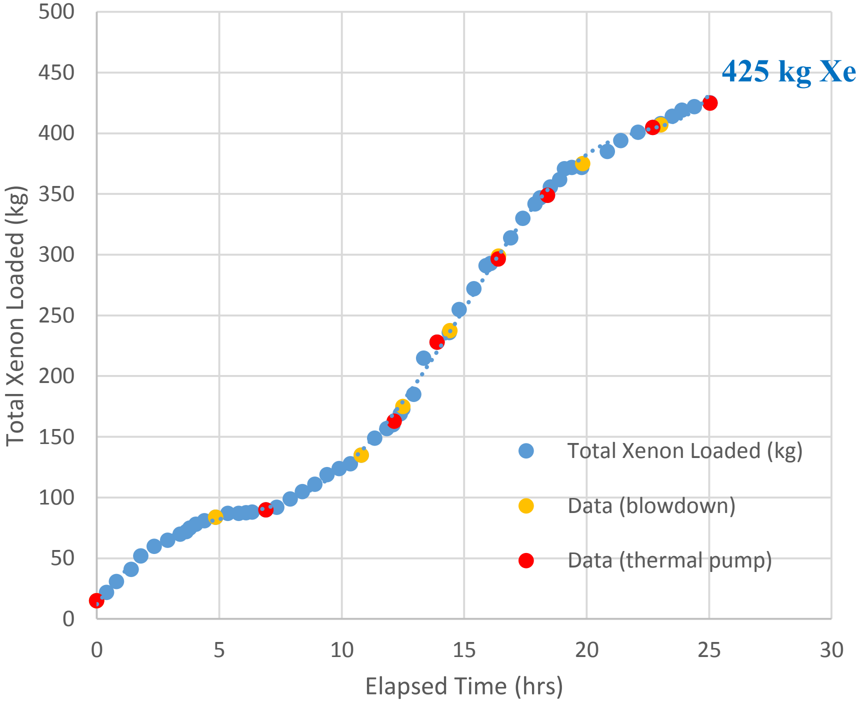
- Dawn spacecraft was launched in 2007 and similar to ARRM uses an ion propulsion system with Xe propellant
- Lessons learned from Dawn prompted this analysis as gas heating was an issue during ground loading
- Paper by Brophy et al. "*Dawn Ion Propulsion System- Getting to Launch*" [ref 7] contains plots of mass and pressure vs time data during ground loading of Xe into the flight COPV
  - Tank was forced-air flow cooled during Xe loading
- Mass and time data were used as inputs into the model to compare the model predictions to data reported for gas pressure and temperature
  - Temperature data points had to be back calculated T (P, ρ_{Xe}) from tank pressure and density data as REFPROP inputs ($\rho_{Xe}= M_{Xe}/ V_{tank}$)
- Launch pressure for the xenon tank was 1250 psia

Dawn Flight Tank Loading Data

Xenon Tank Pressure during Loading [ref 7]

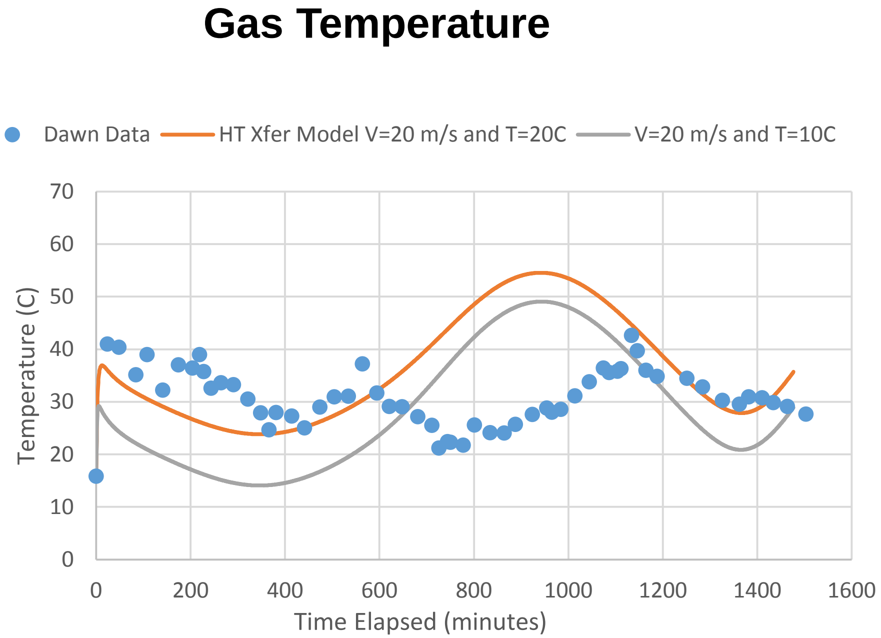


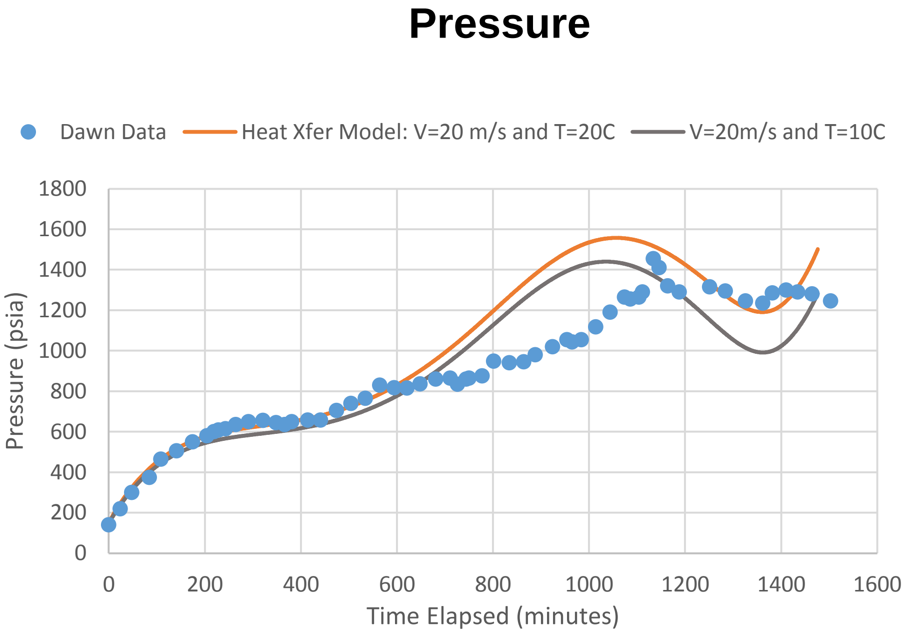
Mass of Xenon Loaded [ref 3, 7]



- 410 kg of Xe loaded in 25 hrs, 15 kg initial Xe mass, 1250 psia final P_{tank}
- Dawn engineers implemented a make-shift cooling system to reject the heat of compression during loading
- Dawn cooling conditions used during loading unknown (air speed & air temperature). Vortex coolers produce a “refrigeration effect”.

Dawn Comparison – Model Results w/Cooling





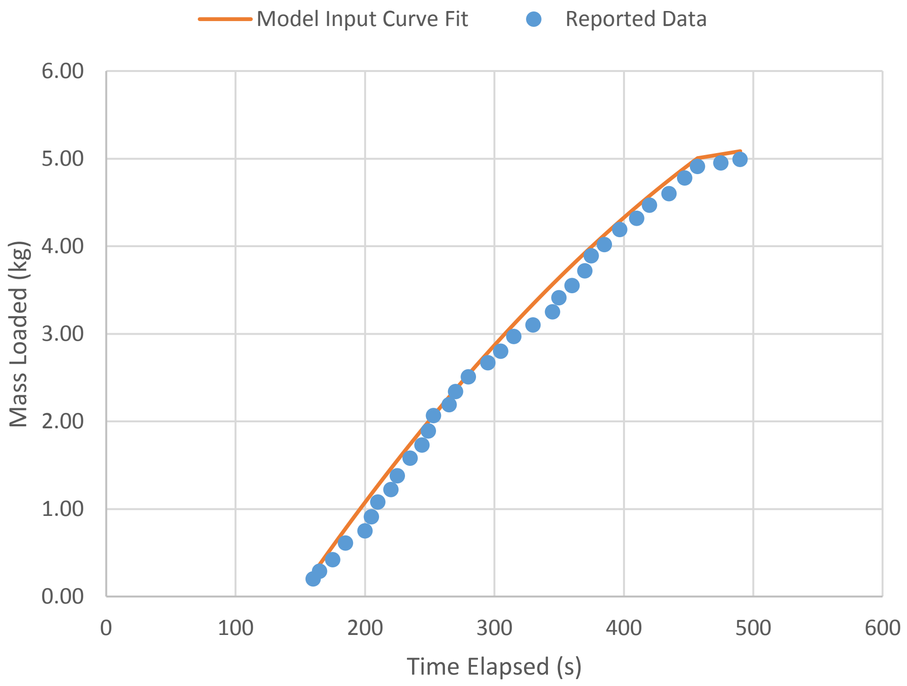
- Model predictions with forced air cooling at 20 ^{0}C and 20 m/s show excellent agreement with Dawn except from 600-1100 minutes
  - Model limited to constant cooling parameters throughout loading while Dawn engineers varied coolant parameters to keep xenon temperature within a desired range

Model Comparison with GH2 Cylinder Fill Data

- Experimental investigation studying the “fast fill” of a high pressure COPV with 3 – 5 kg of GH2 at 5,100 – 10,150 psi
- Paper by Woodfield and Monde [ref 8] provide data plots of loaded mass, in-tank temperature and pressure vs time data
- Test COPV was a vertical cylindrical vessel with aluminum liner, an internal volume of 205 liters and estimated mass of ~83 kg
  - Tank was NOT subject to forced-air cooling during GH2 loading
  - Only free convection cooling occurred during cylinder fill test
- Inputs to the model [ref 8] were inlet mass flow rate, inlet GH2 temperature and vessel geometry & wall mass/thermal data
- Single data set analyzed 5 kg of GH2 loaded over 5.5 minutes to a final tank pressure of 5,890 psia

GH2 Loading Data [ref 8]

Mass of GH2 Loaded - Input



Experimental Set-Up

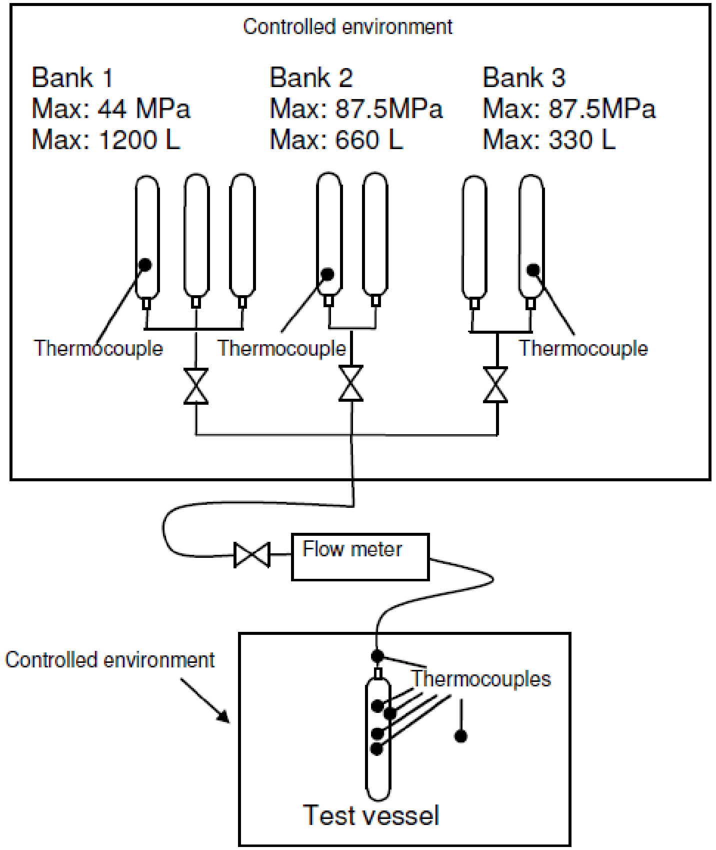
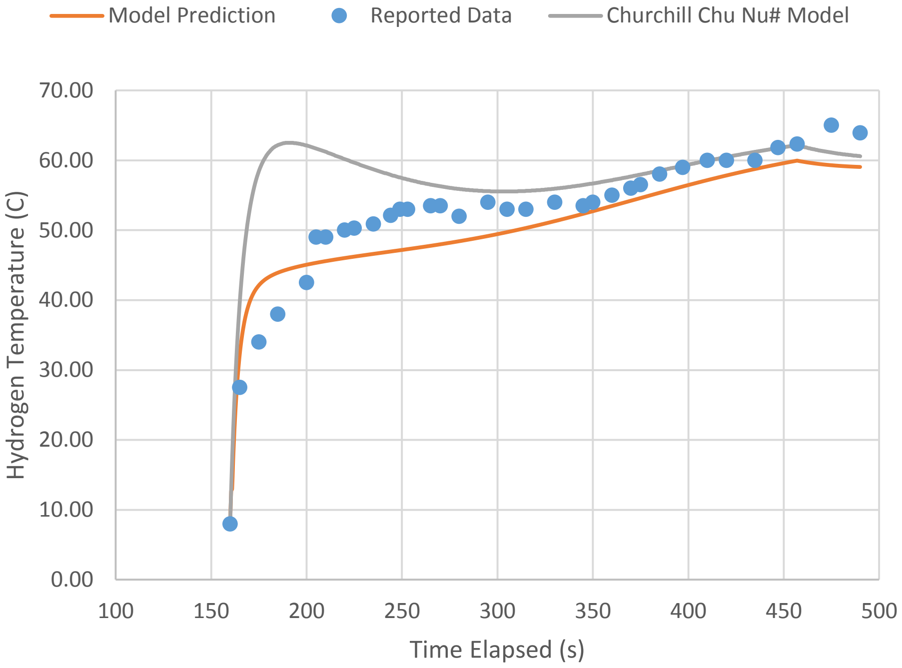
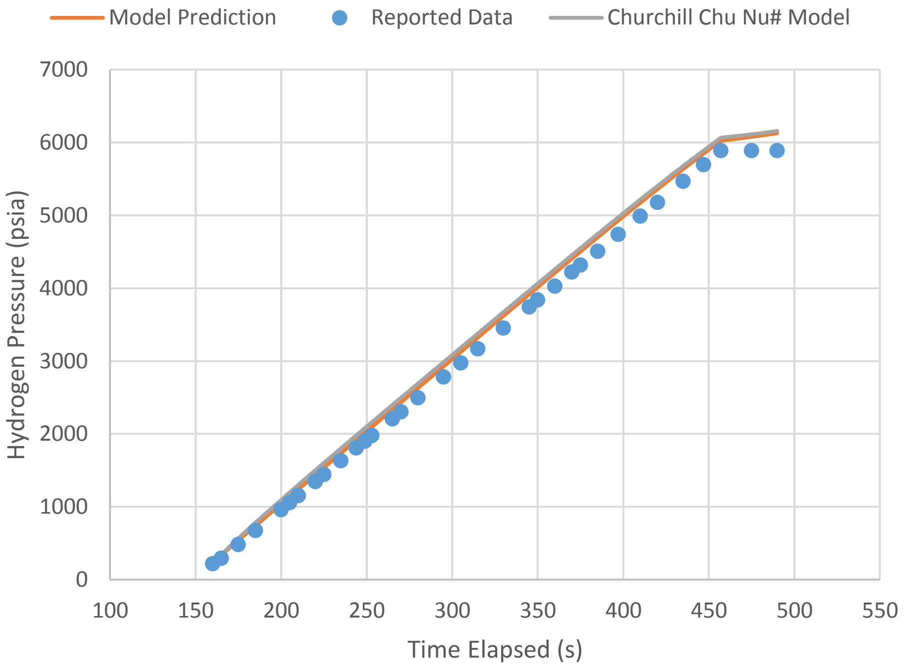


Figure 1. Experimental set up for pressure vessel filling system

GH2 Comparison – Model Results



Gas Temperature



Pressure

- Model predictions with free convection cooling at 20 °C ambient show excellent agreement with GH2 data
- Choice of free convection Nusselt number model taken from Woodfield and Monde [ref 8] yields same results
- Largest deviation between model and data occurs with in-tank gas temperature prediction during start of load via Churchill-Chu

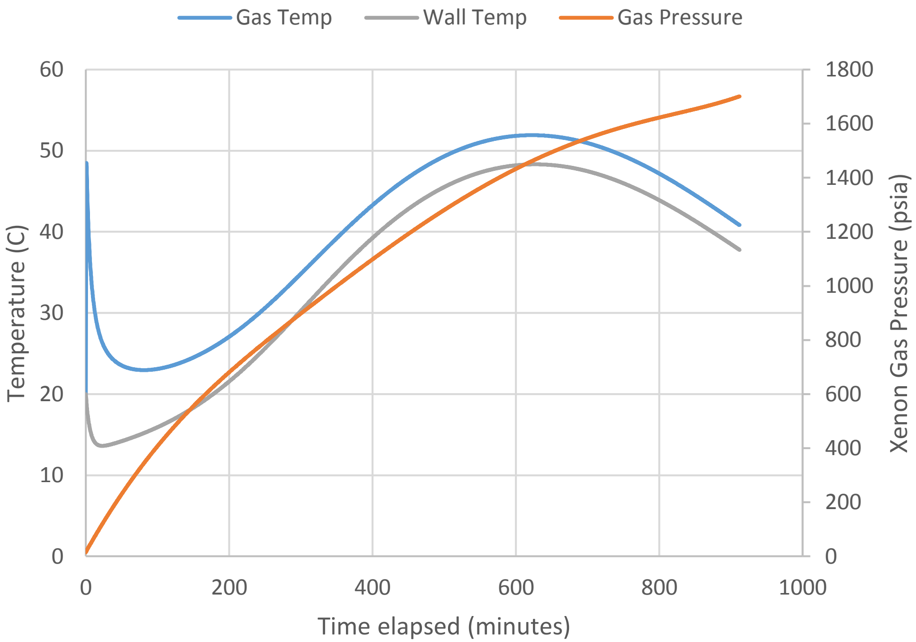
$$Nu_D = 0.56\ Re_d^{0.67} + 0.104\ Ra_D^{0.352}$$

$$\overline{Nu}_{VP} = \left\{ .825 + \frac{.387 Ra_L^{\frac{1}{6}}}{\left[1 + \left({.492}/{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2$$

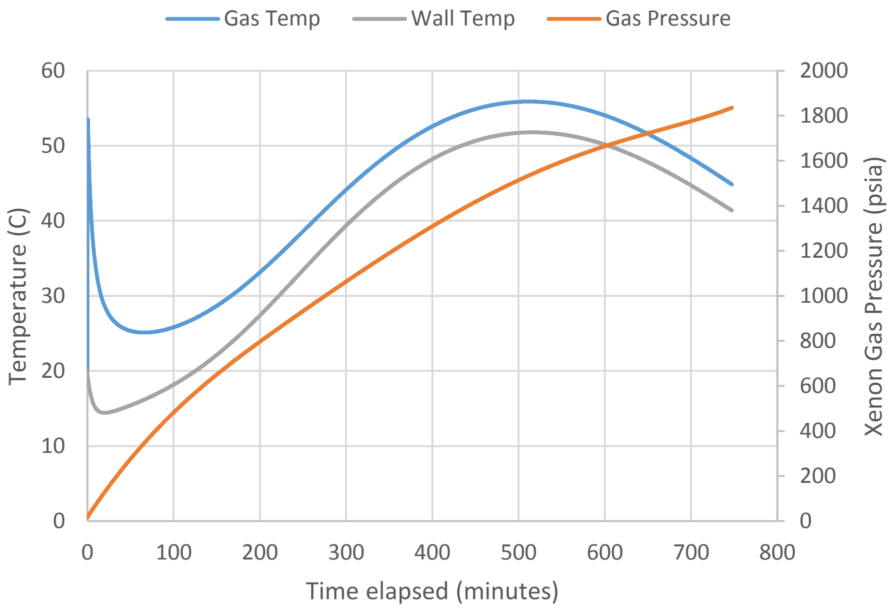
ARRM LOADING ANALYSIS RESULTS

Results – Constant mass flow with External Cooling

Mass flow: 82 kg/hr Load time: 15.25 hrs.
Coolant V=6.5 m/s & T=10 ^oC



Mass flow: 100 kg/hr Load time: 12.5 hrs.
Coolant V=6.5 m/s & T=10 ^oC



Remarks:

Moderate cooling results in final pressure of 1700 psia and 40 ^oC, satisfying the final condition requirements.

Faster fill rate at the same coolant conditions results in a peak temperature and pressure of 56 ^oC and 1835 psia.

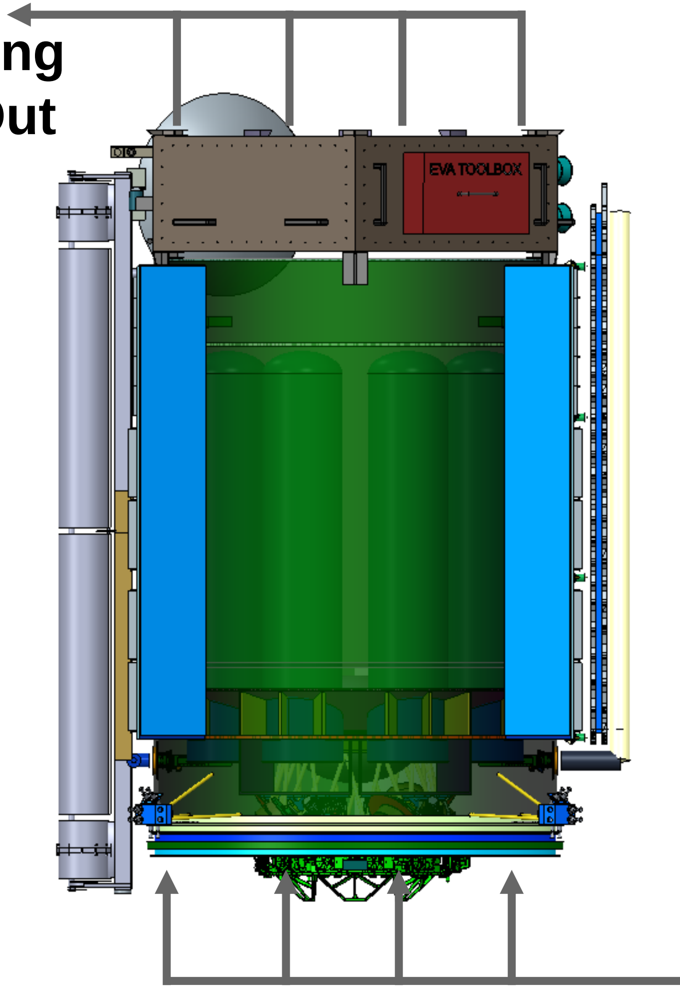
Results – Constant $\dot{m}$ with External Cooling (cont'd)

- Peak and final xenon temperatures and pressures were recorded for various coolant conditions for loading at 100 kg/hr:
  - The green highlight indicates that the coolant conditions satisfies the ARRM design criteria of a fully loaded COPV

Coolant Velocity	Coolant Temperature	Peak Xenon Temperature	Final Xe Temperature	Peak/Final Xe Pressure
m/s	ºC	ºC	ºC	psia
2	20	79	70	2689
5	20	65	55	2179
8	20	59	49	1972
14	20	49	40	1673
2	10	74	64	2471
5	10	60	49	1957
8	10	53	42	1747
2	0	69	54	2370
5	0	55	43	1755
8	0	49	36	1546

Prelim. Estimate of Flight Tank Cooling Air Flow Rates

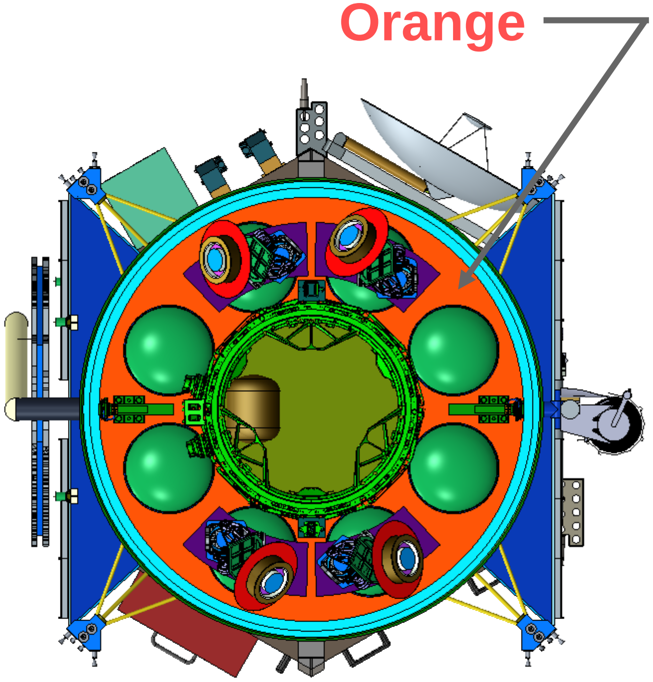
Post MCR IDAC-3 Block 1: 10t Xenon



Cooling Air Out

Cooling Air In

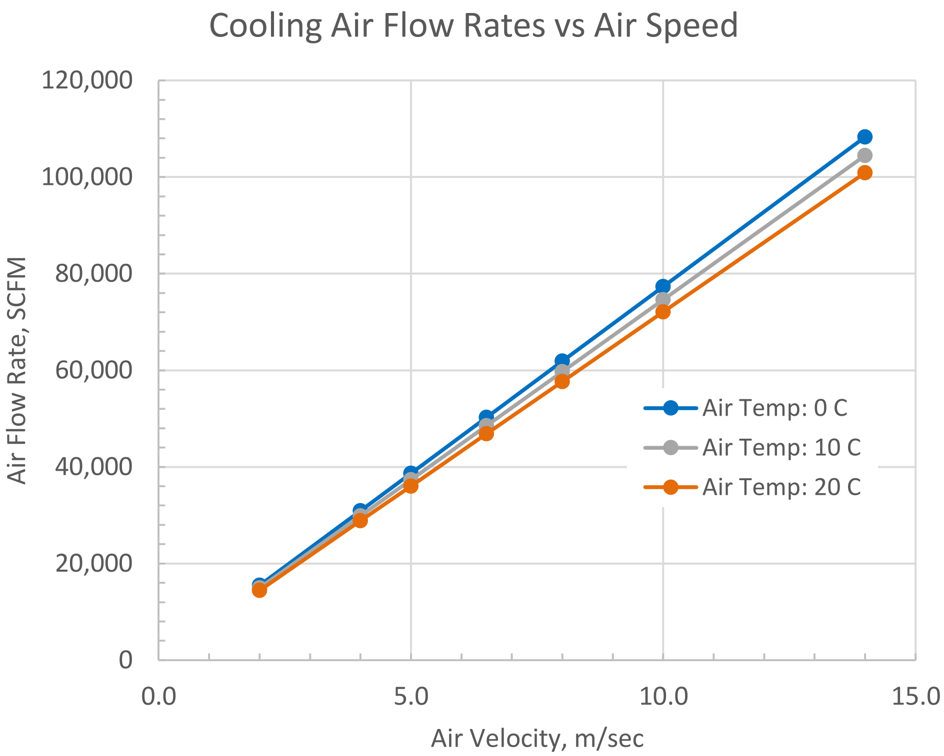
Cooling Air Flows thru Annulus Area Shown below in Orange



Annulus Flow Area thru Bus

Analysis Results: Cooling Air Flow Rates

Air Velocity m/sec	Cooling Air Flow Rates, SCFM		
	at High Air Temp. 20.0 °C	at Medium Air Temp. 10 °C	at Low Air Temp. 0 °C
2.0	14,411	14,921	15,467
4.0	28,823	29,841	30,934
5.0	36,029	37,302	38,668
6.5	46,837	48,492	50,268
8.0	57,646	59,683	61,869
10.0	72,057	74,603	77,336
14.0	100,880	104,445	108,271



- **Three possible design point solutions exist for cooling during loading the 23.1" ID IDAC3 Tank in the Table above as highlighted in green.**

- **The green cells indicate that the final COPV pressure and temperature requirements are satisfied for any given pair of coolant conditions for the constant loading case of 100 kg/hr.**

Conclusions

- In order to keep gas temperature below 55 ^{0}C, moderate coolant velocities at below ambient temperatures are required at a constant loading flow rate
- Due to the long loading duration it seems logical to load all Xenon tanks simultaneously if plausible
  - Implication: design GSE to load multiple tanks and provide cooling for multiple tanks simultaneously
  - If not possible in GSE then fill 1 tank to temperature limit then begin filling other tanks while tank 1 is cooling
- Necessary cooling provisions include internal/in-line xenon precooling heat exchanger to control the inlet propellant to ≈20 ^{0}C
  - External cooling: a coolant system to flow cooled air or GN2 (≈ 0 to 10 ^{0}C) over the external surface of the flight COPVs at velocities on the order of a few meters per second (≈ 4 - 8 m/s)
- Loading time is on the order of 13 to 16 hours per 23.1” ø tank
- Hardware likely required to control the Xenon and cooling air flow rates in Ground Support Equipment for enabling ConOps margin

BACK UP CHARTS

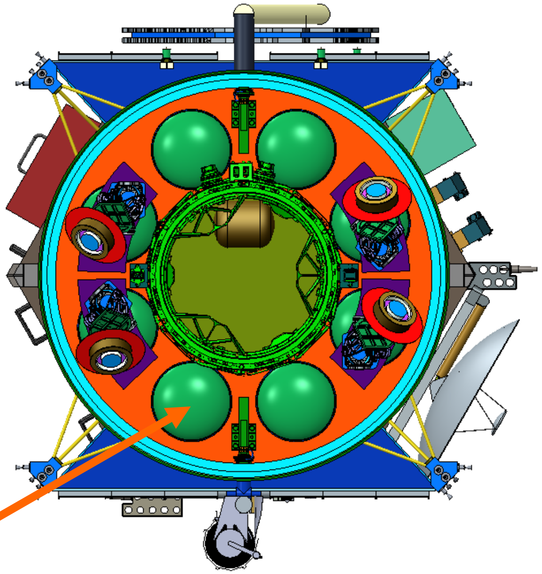
References

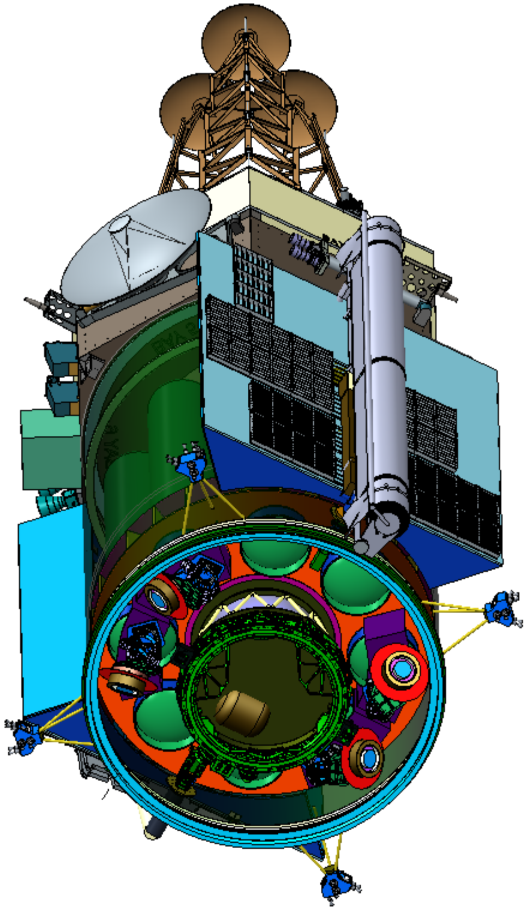
1. Hofer, Randolph, Oh, and Snyder. “Evaluation of a 4.5 kW Commercial Hall Thruster System for NASA Science Missions.” AIAA-2006-4469, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 2006.
2. Brophy et al. “The Dawn Ion Propulsion System – Getting to Launch.” 30th International Electric Propulsion Conference. September 2007.
3. M. Mizukami, B. Nakazono and M. F. Klatte, “Dawn Spacecraft Ion Propulsion Xenon Loading Operation”, JANNAF, 2008.
4. National Aeronautics and Space Administration. *Compressed Gas Handbook.* NASA Special Publication 3045, John F Kennedy Space Center, 1969.
5. Incropera, Dewitt, Bergman, and Lavine, *Fundamentals of Heat and Mass Transfer.* John Wiley & Sons, Inc., 2013.
6. Wiberg, Roland and Noam Lior. “Heat transfer from a cylinder in axial turbulent flows.” International Journal of Heat and Mass Transfer 48. Pages 1505-1517. 2005. http://www.seas.upenn.edu/~lior/documents/HeattransferfromacylinderinaxialIJHMT.pdf
7. Brophy, et. al., “Development and Testing of the Dawn Ion Propulsion System” AIAA-2006-4319, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. July 2006.
8. Woodfield, P.L and M. Monde, “A Thermodynamic Model for a High-Pressure Hydrogen Gas Filling System Comprised of Carbon-Fibre Reinforced Composite Pressure Vessels” 17th Australasian Fluid Mechanics Conference, December 2010.
9. Nakazono, Barry and David Vaughan, “ARM XFS and RCS Propulsion Systems.” *ARM ISP Peer Review RCS XFS-BN.* National Aeronautics and Space Administration.
10. Popiel, Czeslaw. “Free Convection Heat Transfer from Vertical Slender Cylinders: A Review.” *Heat Transfer Engineering, Vol 29, Issue 6.* Pages 521-536. October 2011. http://www.tandfonline.com/doi/full/10.1080/01457630801891557#.VJCitjHF81I

ARRM/SEP Structures Tank Configuration for Post-MCR IDAC-3 – Block 1

`	Post-MCR Block 1
Bus Topology	Cylindrical
Tank Inside Dia. (in)	23.1
# Tanks	8
Tank Length (in)	120
Prop Load (MT)	10

End View Block 1





10,000 kg Xenon – Block 1

Eight COPV Tanks - Composite Overwrapped Pressure Vessels w/aluminum liner

Requirements – Post-MCR Block 1 IDAC- 3 Flight Tanks
(assumed for this analysis)

- **Xenon Flight Tanks**
  - **10,000 kg** ***(total propellant load for Block 1 Post MCR IDAC-3 Tanks)***
  - **8 tank configuration (Block 1)**
  - **1,250 kg Xe / tank**
  - **Store and maintain the Xenon in a supercritical state**
  - **1750 psia MDP at 40 °C max. operating temp.**
  - **COPV seamless w/aluminium liner**
  - **23.1 inch I.D. by 120 inch long**
  - **Volume: 27.5 ft^3 / tank (0.779 m^3)**
  - **Burst Safety Factor of 1.5 X MDP**
  - **Vacuum rated to allow Xenon Loading at Vacuum**
  - **Tank dry target mass of 5% of propellant load**
    - **500 kg (1,100 lb_m) for 10,000 kg Xenon load**
    - **Unit weight: 62.5 kg/tank (137.5 lb_m/tank)**
    - **Weights do not include mounting hardware**
  - **Aluminum Liner: Al 6061-T6, 30 mil thick**

Post-MCR Xenon Flight Tank Physical Characteristics (assumed)

- **Wall Thickness Breakdown per Tank (assumed) :**
  - **Al Liner: 0.030 inch (0.762 mm)**
  - **Epoxy Film Adhesive: 0.005 inch (0.118 mm)**
  - **Composite Overwrap: 0.162 inch (4.109 mm)**
  - **Total Cylinder Wall: 0.196 inch (4.989 mm)**
  - **Head Wall near Boss: 0.612 inch (15.54 mm)**

- **Mass Breakdown per Tank (assumed) :**
  - **Al Liner: 13.3 kg (29.3 lb_m)**
  - **Composite Overwrap: 48.3 kg (106.6 lb_m)**
  - **Epoxy 0.9 kg (2.0 lb_m)**
  - **Total Tank Mass: 62.5 kg (137.9 lb_m)**

- **External Surface Area Breakdown per Tank (estimated) :**
  - **Cylinder: 52.8 ft^2**
  - **Heads (both): 9.7 ft^2**
  - **Total Tank Area: 62.5 ft^2**

Properties of T1000 Epoxy Composite Over Wrap

(assumed for this analysis)

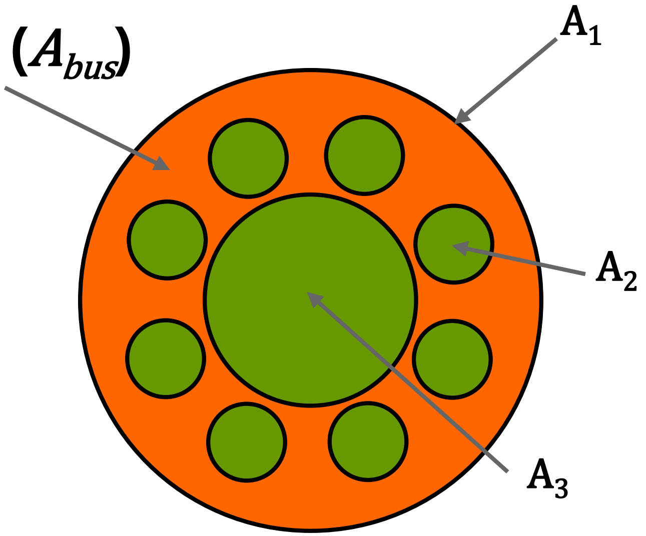
	English	***Metric***
T1000 Fiber		
Density:	**0.065 lb/in^3**	**1.80 g/cm^3**
Specific Heat:	**0.18 Btu/lb-°F**	**0.754 kJ/kg-°C**
Thermal Conductivity:	**18.5 Btu/hr-ft-°F**	**32.0 W/m-K**
Mass Ratio T1000 Fiber/Resin:	**2:1**	**2:1**
Cured Epon 826 Epoxy Resin (bis-phenyl)		
Density:	**0.042 lb/in^3**	**1.16 g/cm^3**
Specific Heat:	**0.50 Btu/lb-°F**	**2.09 kJ/kg-°C**
Thermal Conductivity:	**0.144 – 0.202 Btu/hr-ft-°F**	**0.25 – 0.35 W/m-K**

Source: 1) T1000 Carbon Fiber Technical Data Sheet, No. CFA-008, Toray Industries, www.torayusa.com
2) G. Kawahara and S. McCleskey, *Titanium Lined, Carbon Composite Overwrapped Pressure Vessel*, AIAA 96-2751, 1996.

Calculation Approach: Cooling Air Flow Rates

Estimate Section Flow Area thru S/C Bus (A_{bus})

$$A_{bus} = A_1 - (8A_2 + A_3)$$



Calculate Actual Flow Rate ($ACFM$)

$$ACFM = A_{bus} V$$

Convert Actual Flow to Standard Flow Rate ($SCFM$)

$$SCFM = ACFM \left(\frac{T_{STP} + 273}{T_\infty + 273} \right)$$

Where:

A_{bus} = bus cross sectional flow area, 37.2 ft^2
V = cooling air velocity, ft/min at T_∞
ACFM = actual flow, ft^3/min
SCFM = air flow at STP, 15 ^oC & 14.7 psia, ft^3/min

Carleton COPV Xenon Flight Tank – DAWN IPS

- **DAWN Xenon Tank Specs [ref 1, 2] :**
  - **MEOP: 1750 psi (de-rated to 1310 psig)**
  - **Design Burst Pressure: 2625 psig**
  - **Design temp: 50 °C (de-rated to 30 °C)**
  - **6AL-4V titanium liner**
  - **T1000 graphite fiber**
  - **Skirt-mounted**
  - **Tank Volume: 9.46 ft^3 (267.9 liter)**
  - **Max. Propellant Load: 450 kg Xenon**
  - **De-rated Load: 425 kg Xenon**
  - **Tank Dry Mass: 20.3 – 22.2 kg**
  - **Diameter: 35.5" (900 mm)**
  - **Height: 26.5" (670 mm)**

DAWN Tank prior to installation of MLI and external heaters.[ref1]

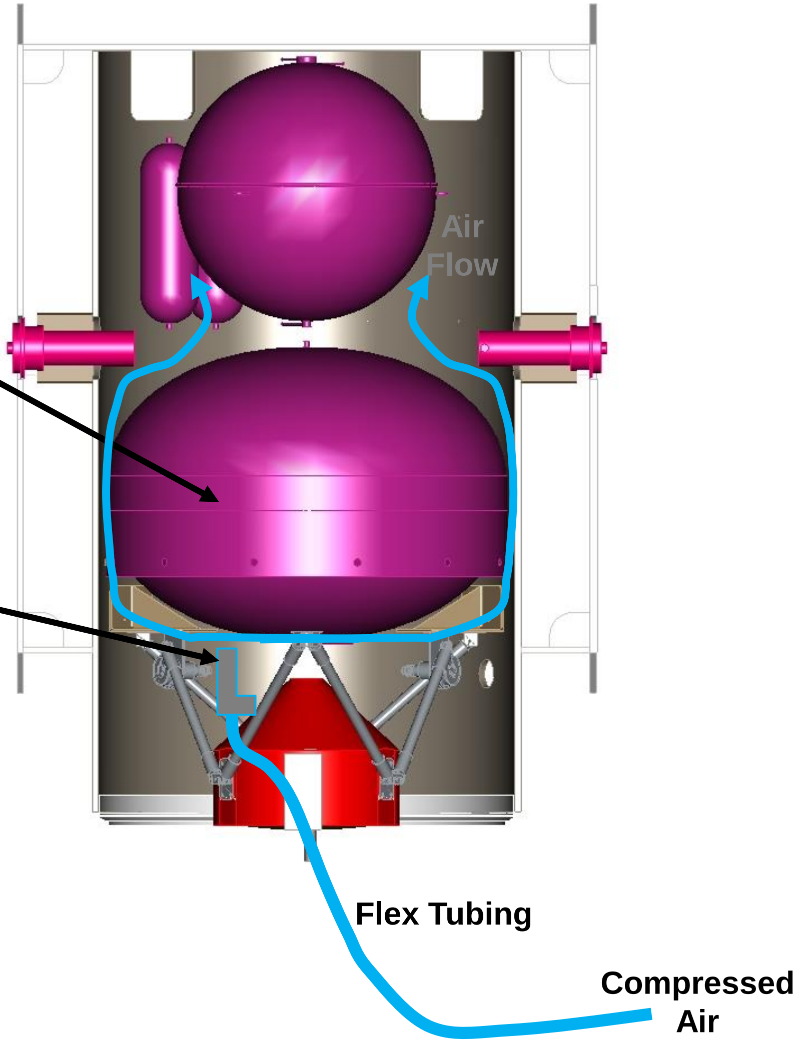
Dawn Analysis – Key Model Inputs

- Tank Volume: 0.2679 m^3
- Xenon Mass Flow Rate: curve fit based on test data dM/dt
- Inside/Outside Diameter: 0.9017 / 0.91 m
- Tank Height: 0.673 m
- Inside/Outside Area: 1.74 / 1.82 m^2
- Tank Wall Thermal Capacitance: 14,365 J/K
- Inlet Xenon Temp: 20 ^oC
- Time step: 0.5 min
- Forced Flow Velocity: varied 0 – 20 m/s
- Coolant Air Temp: varied 5 – 20 ^oC

Approximately How DAWN Implemented “*ad Hoc Last Minute*” Xenon Flight Tank Cooling ?

**DAWN
Xenon Tank
loaded with
425 kg Xe**

Vortex Cooler



“The rate of filling is primarily limited by the compressive heating of Xenon in the spacecraft tank and external cooling heat transfer rates”.

“The ability to cool the tank is limited by the MLI insulation wrapping the tank and accessibility of tank surface to cooling air”.

M. Mizukami *[ref 3]*

GH2 Cylinder Fill Data – Key Model Inputs

- Tank Volume: 0.205 m^3
- GH2 Mass Flow Rate: curve fit based on test data dM/dt
- Inside/Outside Diameter: 0.4074 / 0.43 m
- Tank Height: 0.5462 m
- Inside/Outside Area: 2.33 / 2.58 m^2
- Tank Wall Thermal Capacitance: 68,008 J/K
- Inlet GH2 Temp: curve fit based on test data
- Time step: 0.5 sec
- Forced Flow Velocity: 0 m/s
- Outside Air Temp: 20 ^{o}C