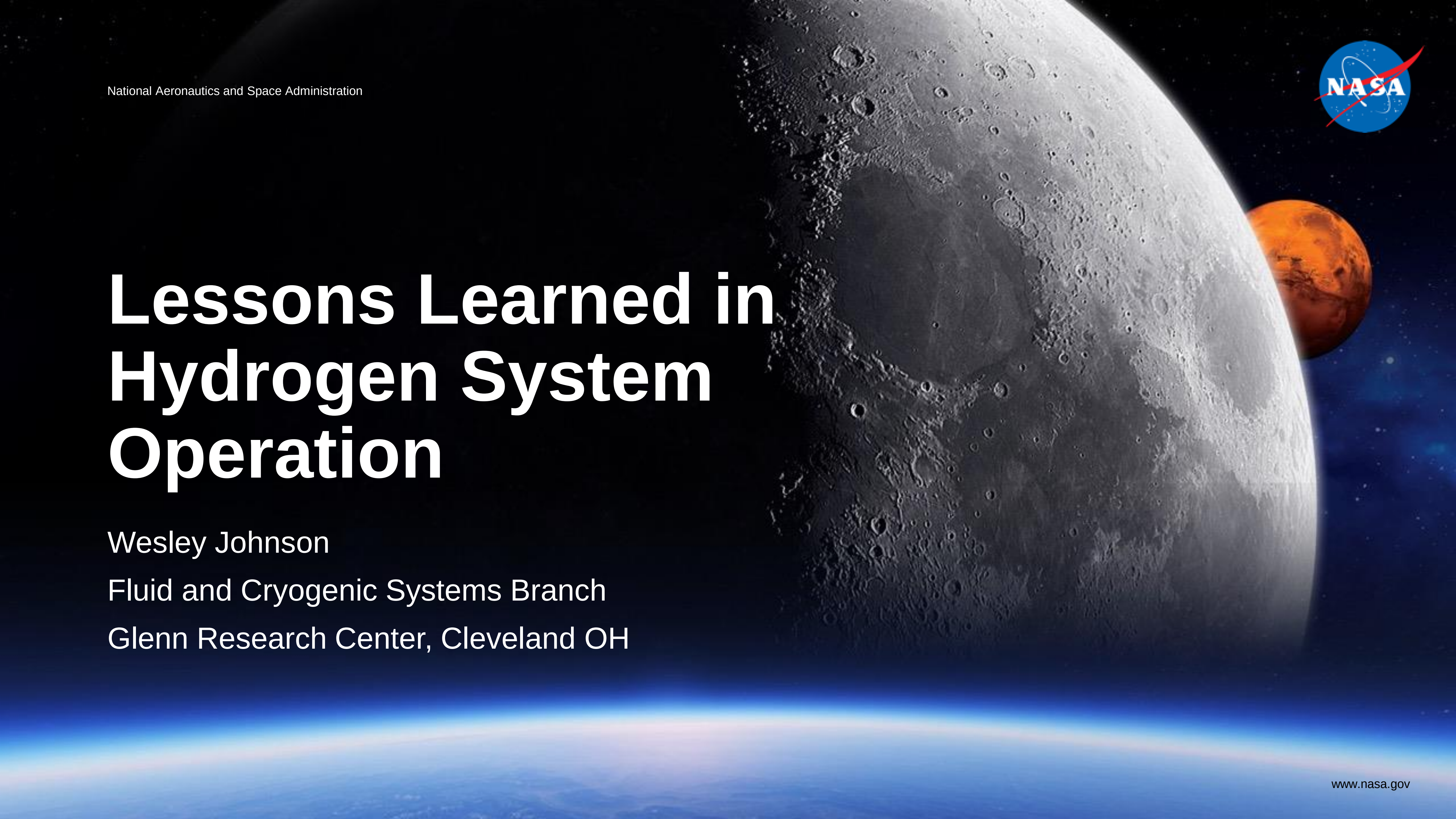
National Aeronautics and Space Administration



Lessons Learned in Hydrogen System Operation

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Glenn Research Center, Cleveland OH

Outline

- Insulation Systems
- Temperature Gradients in a Liquid Hydrogen System
  - How temperature gradients naturally form
  - How to drive gradients via system design
- Concepts associated with heat load reduction via cooling at intermediate temperatures
- Liquid Hydrogen Fittings

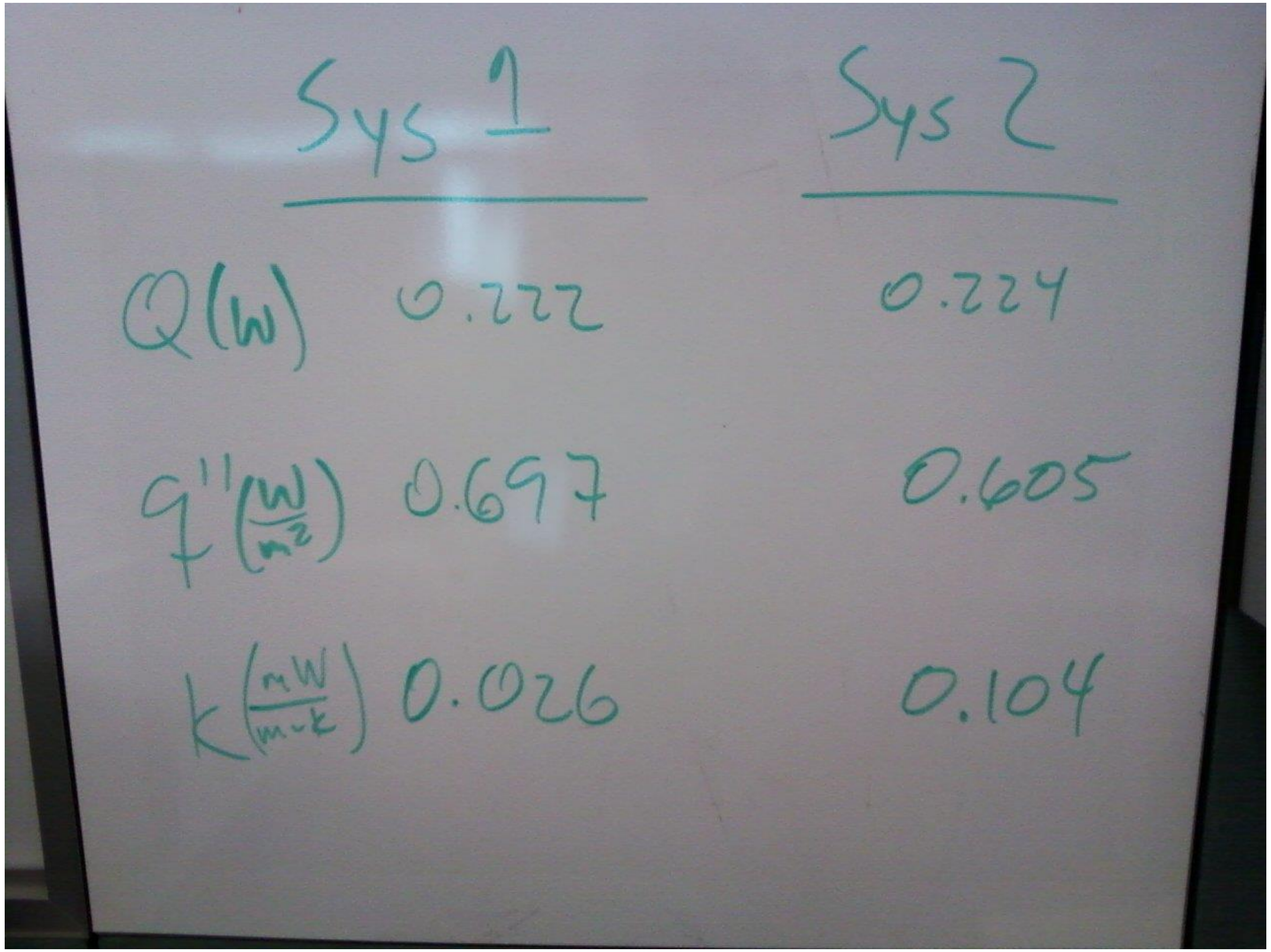
Insulation Systems

- MLI
- Foam
- Aerogel
- Fiberglass
- Loose Fills

Insulation

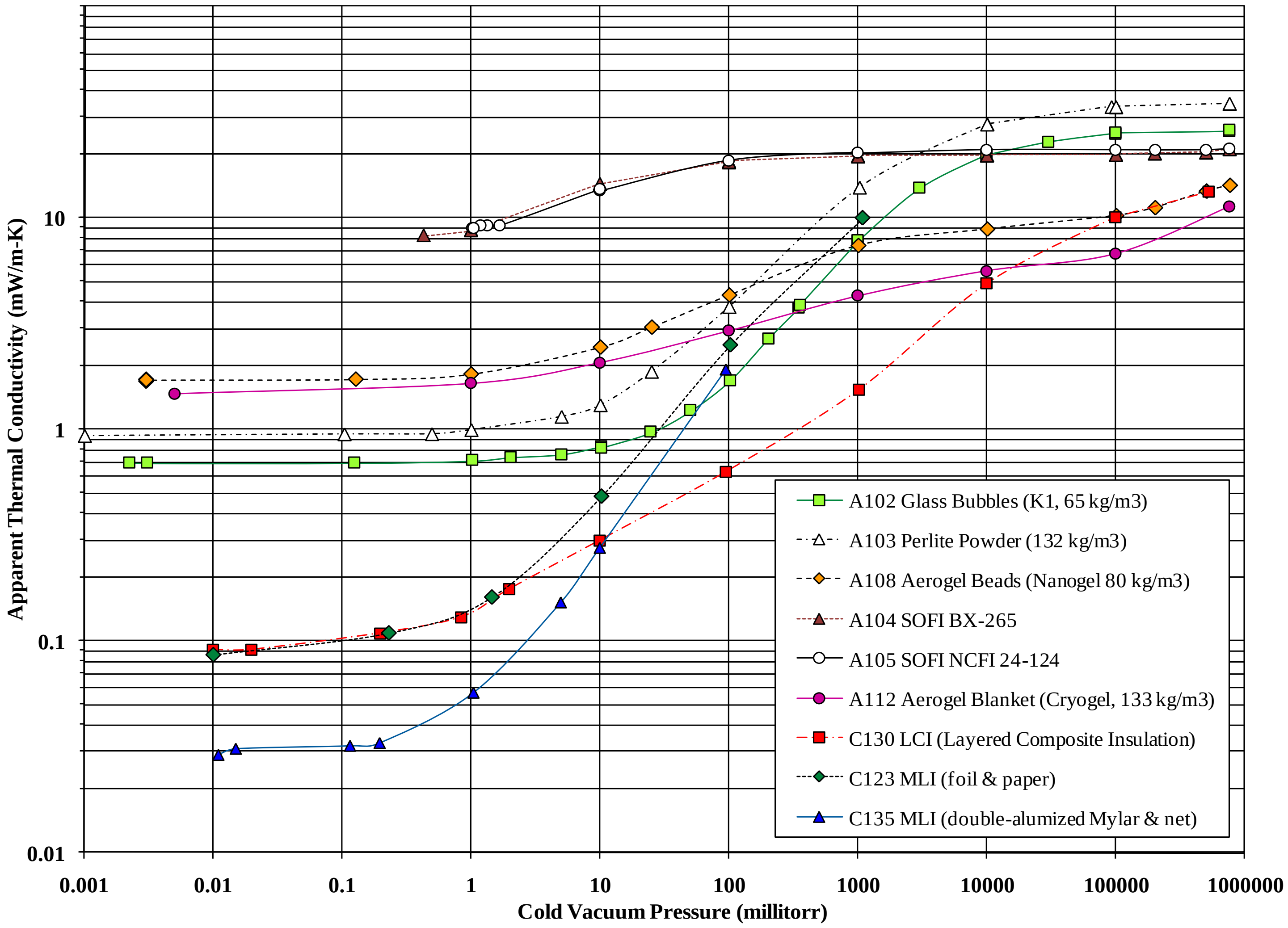
- Environment is everything
- Conductive insulation works as a function of ΔT & T_{mean}
  - Material properties change with both the gradient across the insulation specimen and the temperatures encompassed.
  - Lead to multiple different methodologies of testing.
- Radiative insulations work as a function mainly of T_H
  - Wavelength and temperature dependent properties can make solutions become complicated quickly.
- Vacuum also plays a large role in system level performance.
- A working tool box
  - Different materials work in different situations
  - No global solution

Which Insulation System is Better?



	Sys 1	Sys 2
Q(W)	0.222	0.224
$q''\left(\frac{W}{m^2}\right)$	0.697	0.605
$k\left(\frac{mW}{m\text{-}k}\right)$	0.026	0.104

Apparent thermal conductivity data (k-values) for different cryogenic insulation materials (293 K / 77 K)

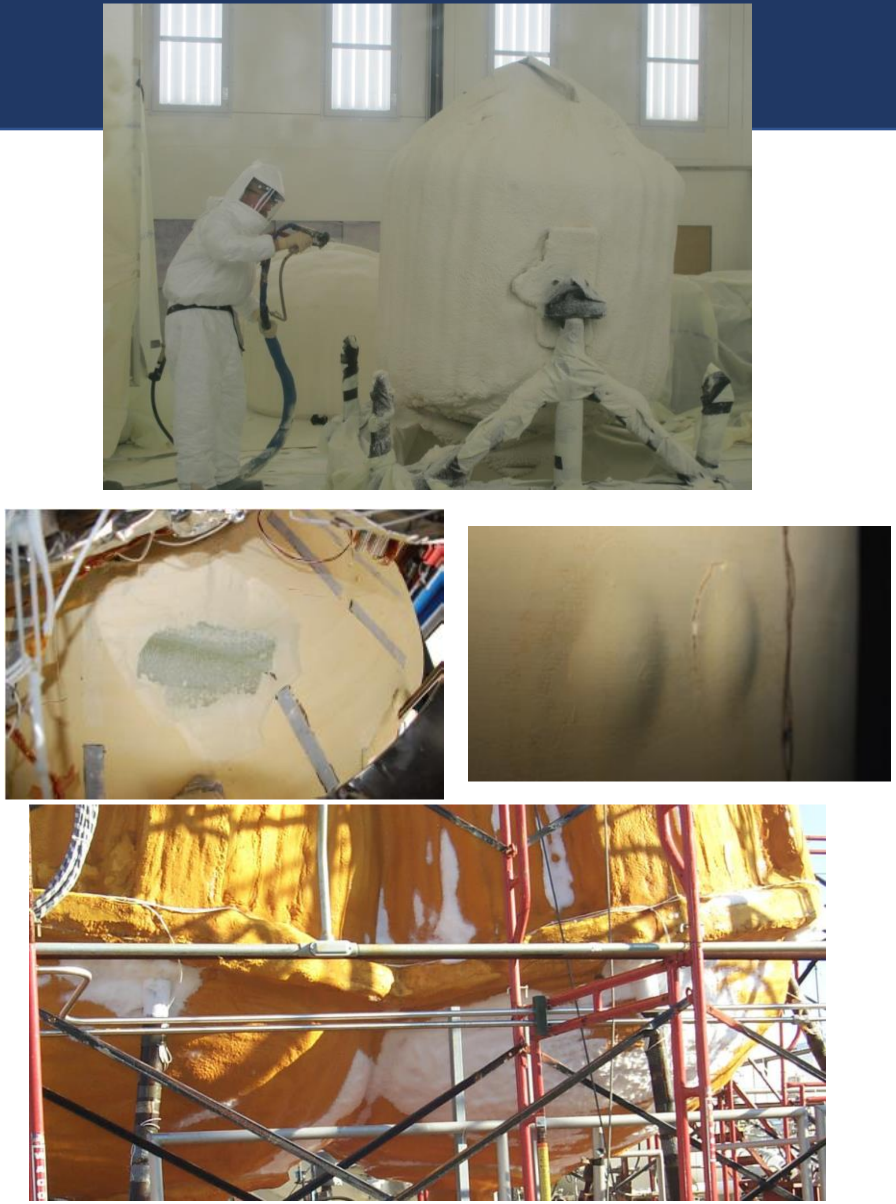


Foams

- Generally have relatively good thermal performance
  - 30 – 40 mW/m/K at ambient pressure and room temperature
  - Don’t gain much in vacuum
  - Essentially a bunch of cells that are filled with a “blowing agent” (i.e. freon) that dominates the conductivity
  - Density ~ 10 – 30 kg/m^3
- Closed Cell = 90% closed cell
  - Will change with aging
- Can be cheap (buy “Great Stuff” at Home Depot)
- Easy to apply [incorrectly]

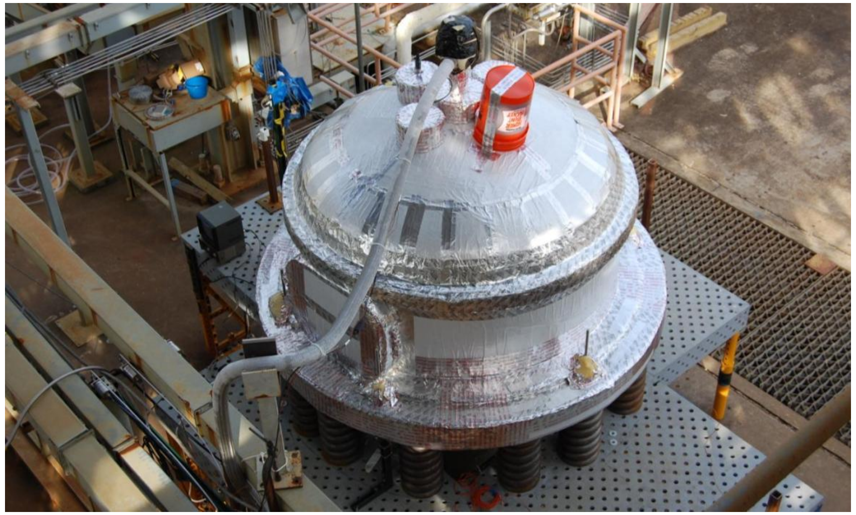
Foams

- Challenges:
    - Cracking
    - Divoting
    - Icing
    - Moisture uptake
    - Degrade in UV light (i.e. outside)
    - Structural properties
    - Aging



Aerogels

- Lightest solid known
  - Usable form density ~ 80 – 120 kg/m^3
  - Have been made at much lower density
- Lowest conductivity solid known
  - Nanoporous
  - Useful forms ~ 15 mW/m/K at STP
- Multiple forms
  - Beads/Granules
  - Blankets
  - Films
- Multiple Chemistrys
  - Polymer
  - Silica
- Multiple functions (general energy absorptance)
  - Thermal insulation
  - Acoustic impedance/insulation
  - Vibrational damping
  - Structural properties
  - MMOD protection
- Can be made hydrophobic
- Used for thermal control of satellites when MLI not required

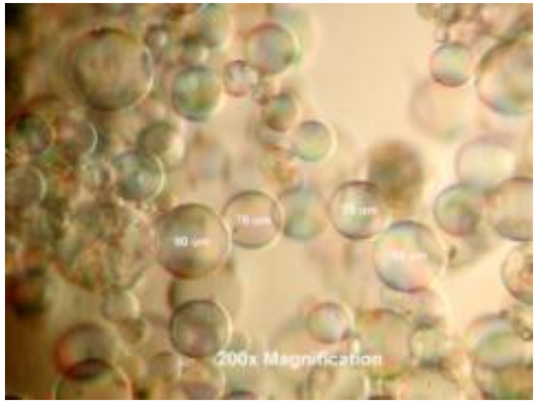


Aerogels

- Challenges:
  - Outgassing (non-polymer)
  - Sorption
  - Attachment mechanisms
  - Residues (non-polymer)
  - Cost (getting better)
  - Lack of material property data

Loose Fills

- Multiple different types
  - Perlite
  - Glass bubbles
  - Aerogel beads/granules
- Large double wall tanks (dewars)



Glass bubbles

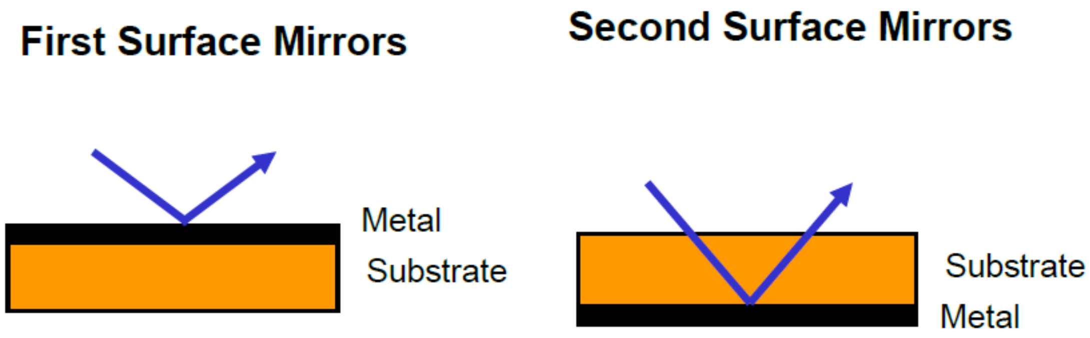
Multilayer Insulation (MLI)

- Fundamentally, MLI is an attempt to minimize all three forms of heat transfer:
  - Radiation: highly reflective layers stacked on top of each other
  - Conduction: reflective layers spaced by low conductivity spacer + low contact pressure between layers
  - Convection: always installed in a vacuum (< 10^{-4} Torr)
    - Performance of MLI at ambient pressure better than foam!
- Key notes:
  - Can’t use thermal conductivity (k-value) to define MLI performance
    - Performance varies with temperature as approximately T^3
  - Good looking MLI =/= Good performance MLI
  - Cannot determine IR emissivity by looking at a material

The Folly of 2nd Layer Reflectors

- It is very hard to spot 2nd surface reflectors with the naked eye when the substrate is transparent.
- The easiest way to tell is that generally, 1st surface mirrors have a backing on the tape, 2nd surface mirrors don't.
- Substrate is either FEP or Polyimide
- The radiative heat load onto a surface is proportional to the emissivity of the surface.

$$\dot{Q}_{rad} = \varepsilon \sigma A_{surf} (T_H^4 - T_C^4)$$

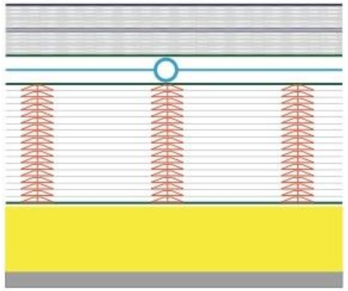


Metal	Typical Emittance (ε)
Gold	0.02
Silver	0.02
Aluminum	0.03

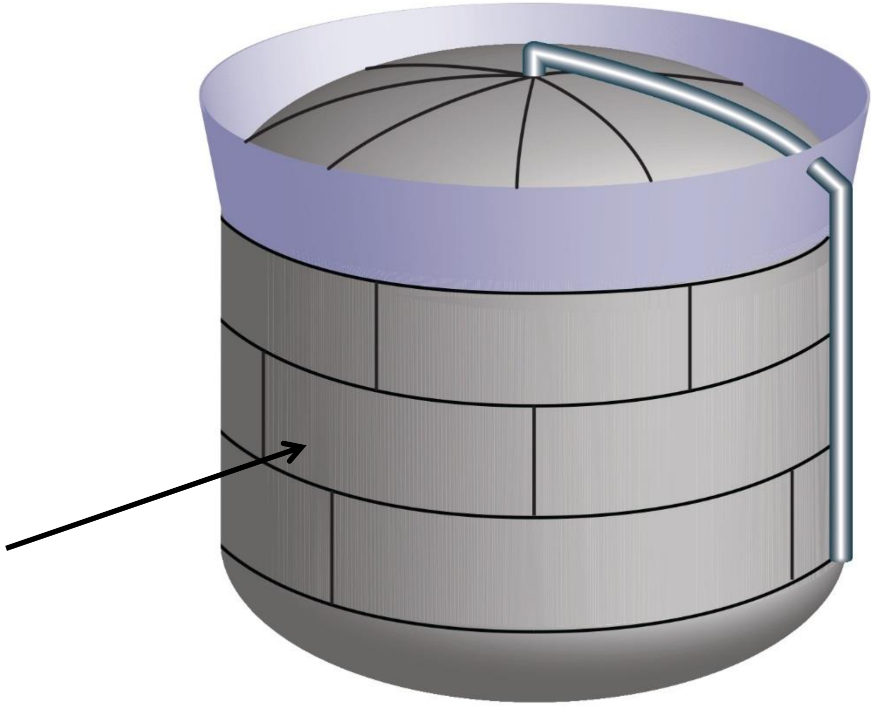
Film Thickness		Typical Emittance	
Mils	Microns	FEP	Polyimide
0.5	12.5	0.41	0.52
1	25	0.52	0.64
2	51	0.65	0.76
5	127	0.79	0.85
10	254	0.86	

Images and data from Sheldahl Red Book

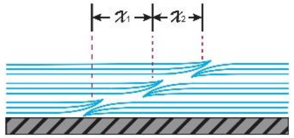
Details to Consider During the Design of Multilayer Blanket Insulation Systems



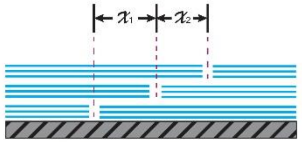
MLI Blankets
- Traditional
- SS-MLI
- IMLI
- Hybrid



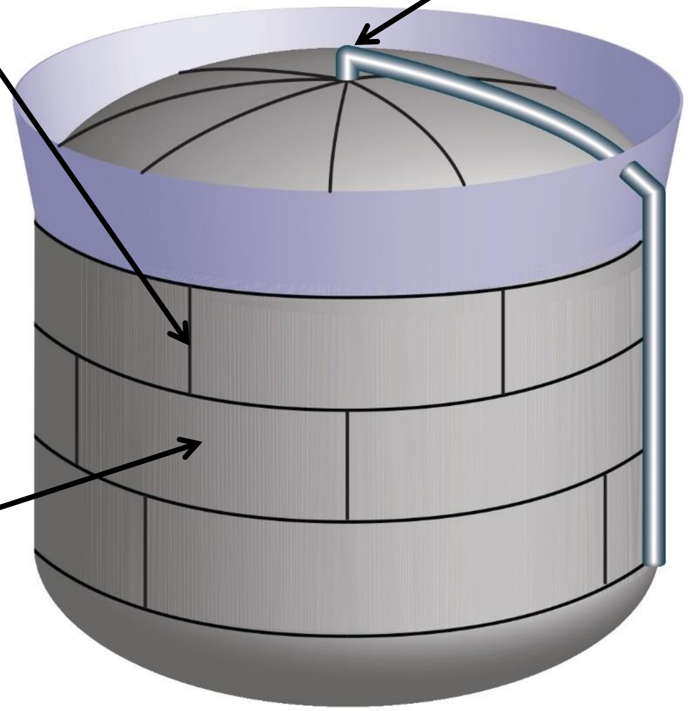
Details to Consider During the Design of Multilayer Blanket Insulation Systems



3 Blanket Overlap Staggered



3 Blanket Staggered

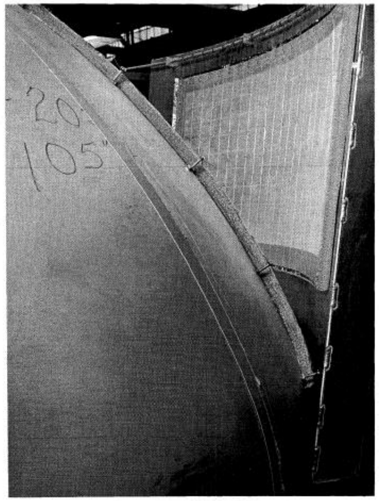


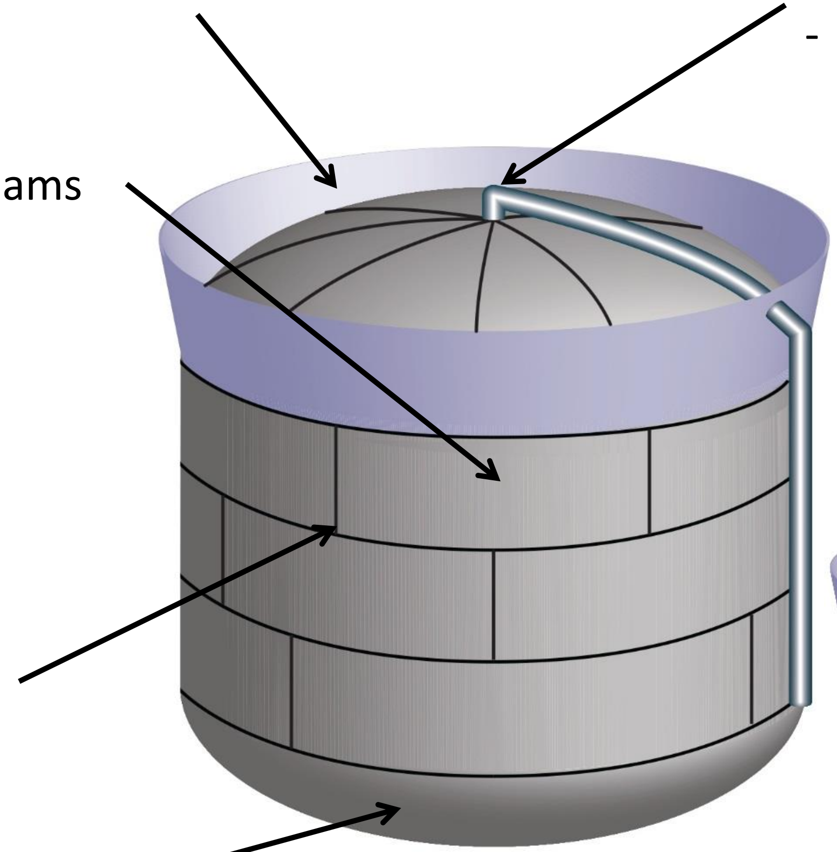
Seams

MLI Blankets
- Traditional
- SS-MLI
- IMLI
- Hybrid

Penetration Integration:
- NASA-TP-2012-216315

Details to Consider During the Design of Multilayer Blanket Insulation Systems





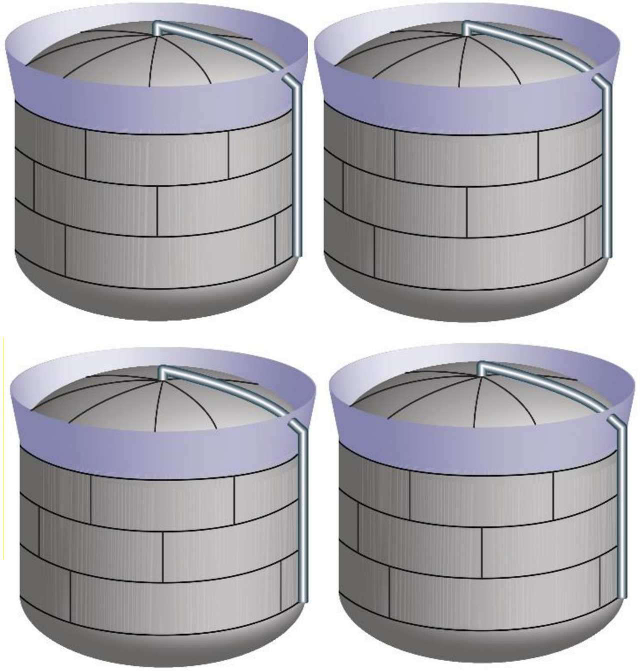
Skirt Integration

Penetration Integration:
- NASA-TP-2012-216315

Seams

MLI Blankets
- Traditional
- SS-MLI
- IMLI
- Hybrid

Tape, Pins & Attachments



Repeatability

Variables in MLI Acreage Performance

- Material Types
  - Reflector: Aluminum foil vs Aluminized plastics
  - Spacer: netting, tissue paper, other
  - Perforations – they hurt performance, help pumping?
  - Emissivity of reflectors
- Layer Density (also whether constant or variable)
  - Can be thought about in terms of pressure on system too
- Thickness (number of layers)
- Interstitial Pressure (and therefore interlayer pressure)
  - Assumed to be 10^{-6} torr in data presented here
  - Assume that there is no pressure gradients within the MLI
  - Interstitial gas (helium, hydrogen, nitrogen, carbon dioxide)
- Warm Boundary Temperature (WBT)
- Cold Boundary Temperature (CBT)
- Application Variable (how applied)
  - Wrapping procedure
  - Connections/penetrations/support
  - Tank geometries

What Insulation Do You Need?

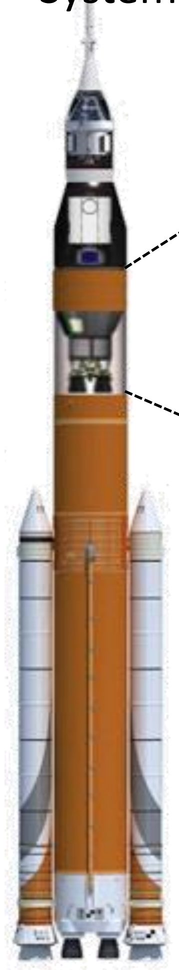
- What type of maintenance do you want to do?
- What type of vacuum does the tank hold?
- How long do you need to store the hydrogen?
- What type of performance do you need?
- What other safety considerations are there?
  - Air liquefaction
  - Handling / touching cold surfaces

Hydrogen Stratification

- Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER)
- Integrated Ground Operations Demonstration Unit – Liquid Hydrogen (IGODU-LH2)
- Integrated Refrigeration and Storage (IRAS)

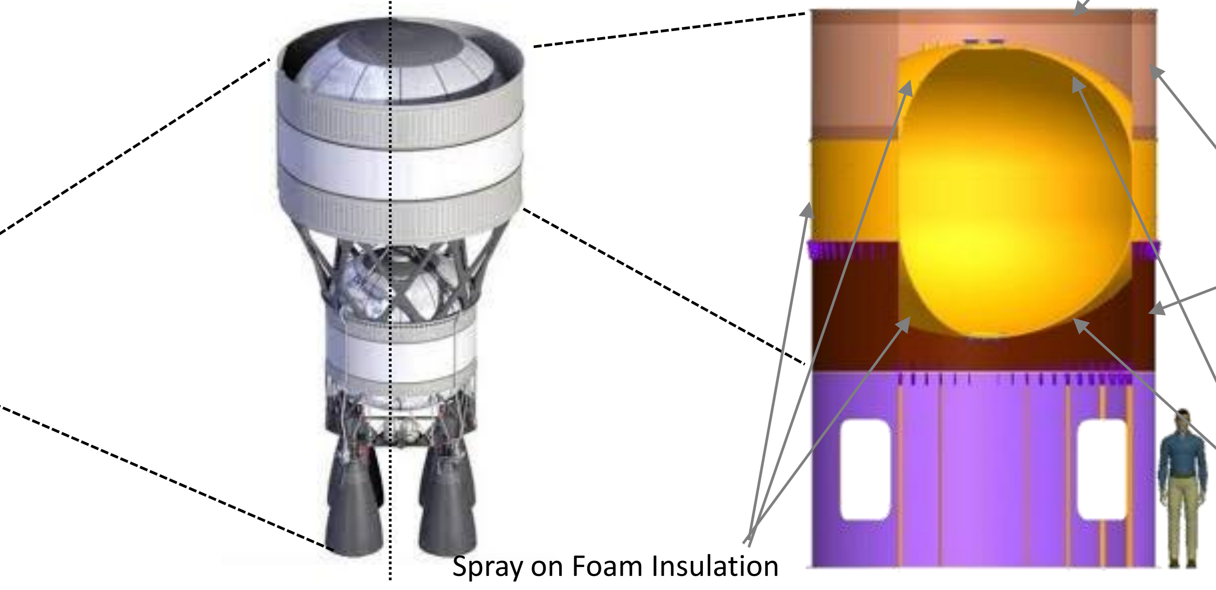
Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) Overview

Space Launch System



Exploration Upper Stage

SHIIVER



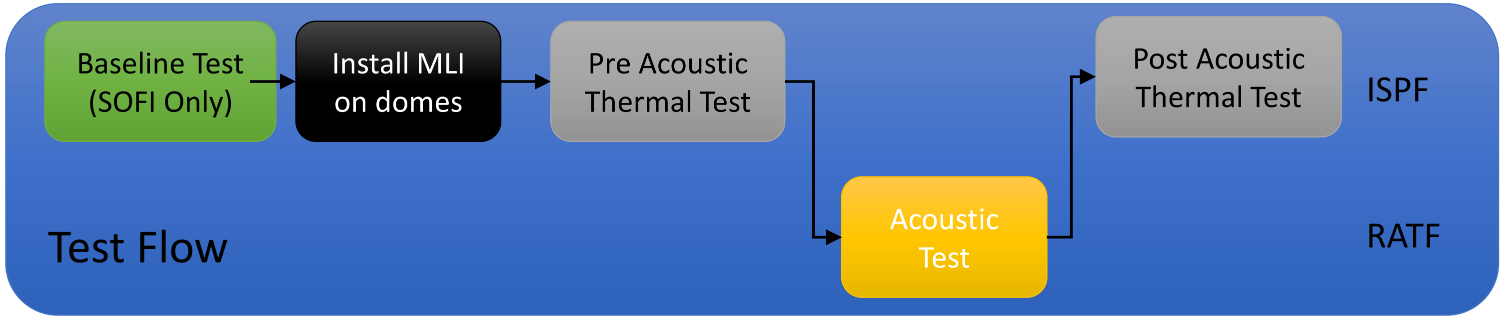
Boil-off vapor cooling on forward skirt

RFMG System inside the Tank

Forward and Aft structural skirts
- Baselined for EUS

Traditional MLI on top and bottom domes

Spray on Foam Insulation on barrel and top and bottom domes
- Baselined for EUS



Test Flow

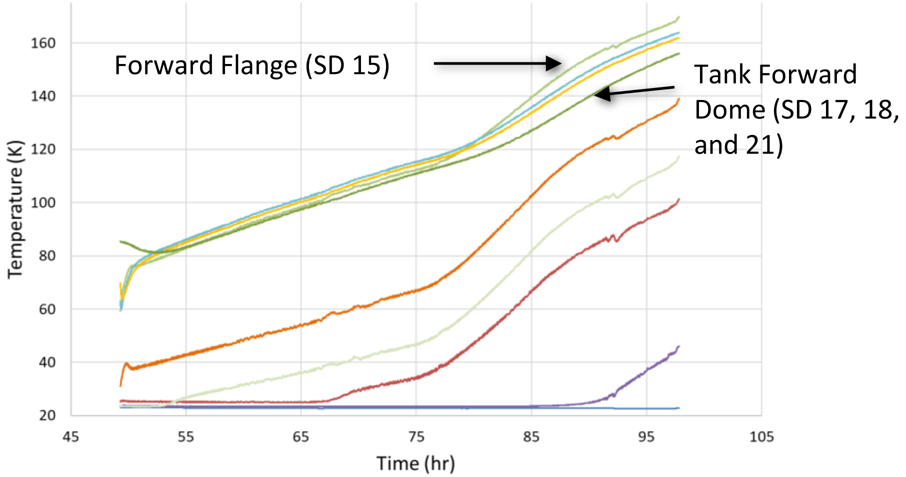
Baseline Test (SOFI Only) → Install MLI on domes → Pre Acoustic Thermal Test → Acoustic Test → Post Acoustic Thermal Test

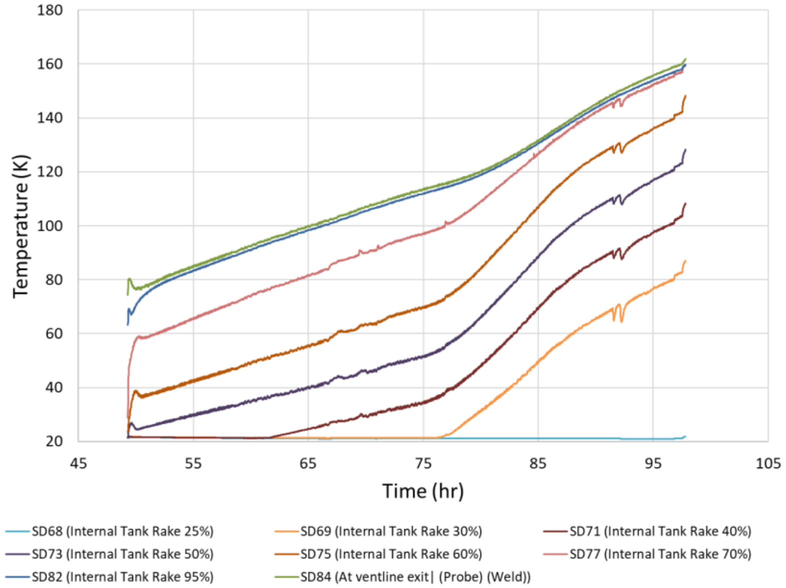
ISPF

RATF

SHIIVER Testing – Impacts of Heat Load Distribution

- The top plot shows an example of temperature on the tank walls where the structural heat load was driving heat into the tank.
    - The top of the forward dome was lower temperature than the skirt flange and temperatures along the forward dome.
- The lower plot shows the same test, but internal tank temperature stratification in the ullage gas during testing at low fill levels.
    - Inflections in temperature gradients when liquid crossed bottom dome flange.
    - Temperature of vapor in upper dome has very little stratification compared to in the barrel section.

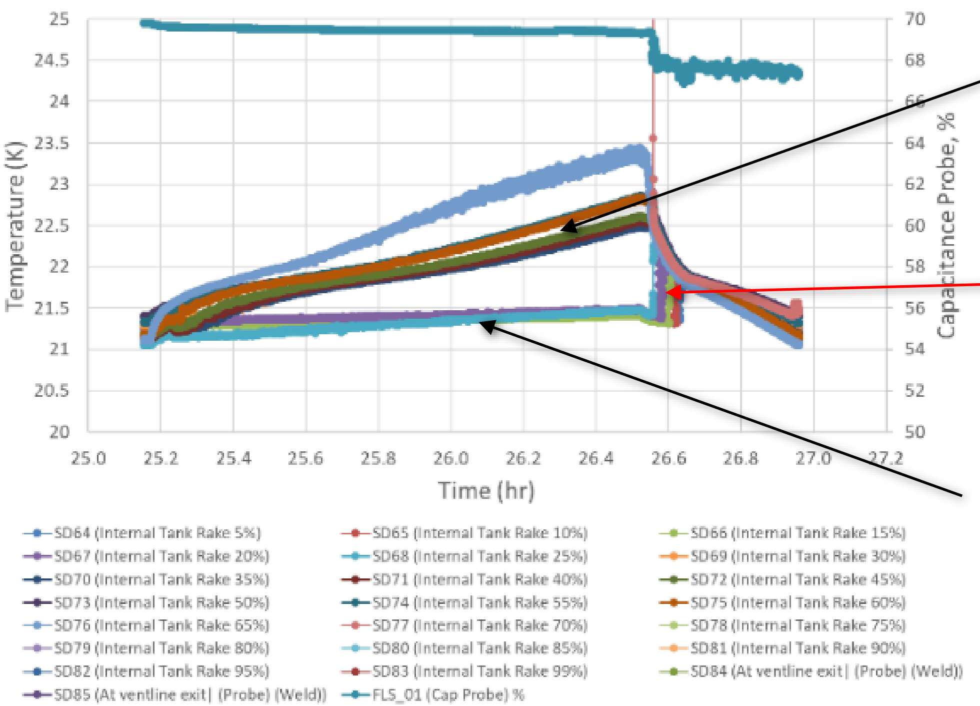




SHIIVER Liquid Stratification

Once MLI installed on bottom dome, during self-pressurization an interesting form of stratification occurred.

- The liquid in the bottom dome did not warm up with the liquid above the flange.
- The liquid above the aft skirt flange warmed up uniformly
- Caused by buoyancy driven flows: nothing to cause the cold liquid in the dome to rise, warm up, or otherwise participate in the heat transfer phenomena.



Liquid temperatures above aft skirt flange

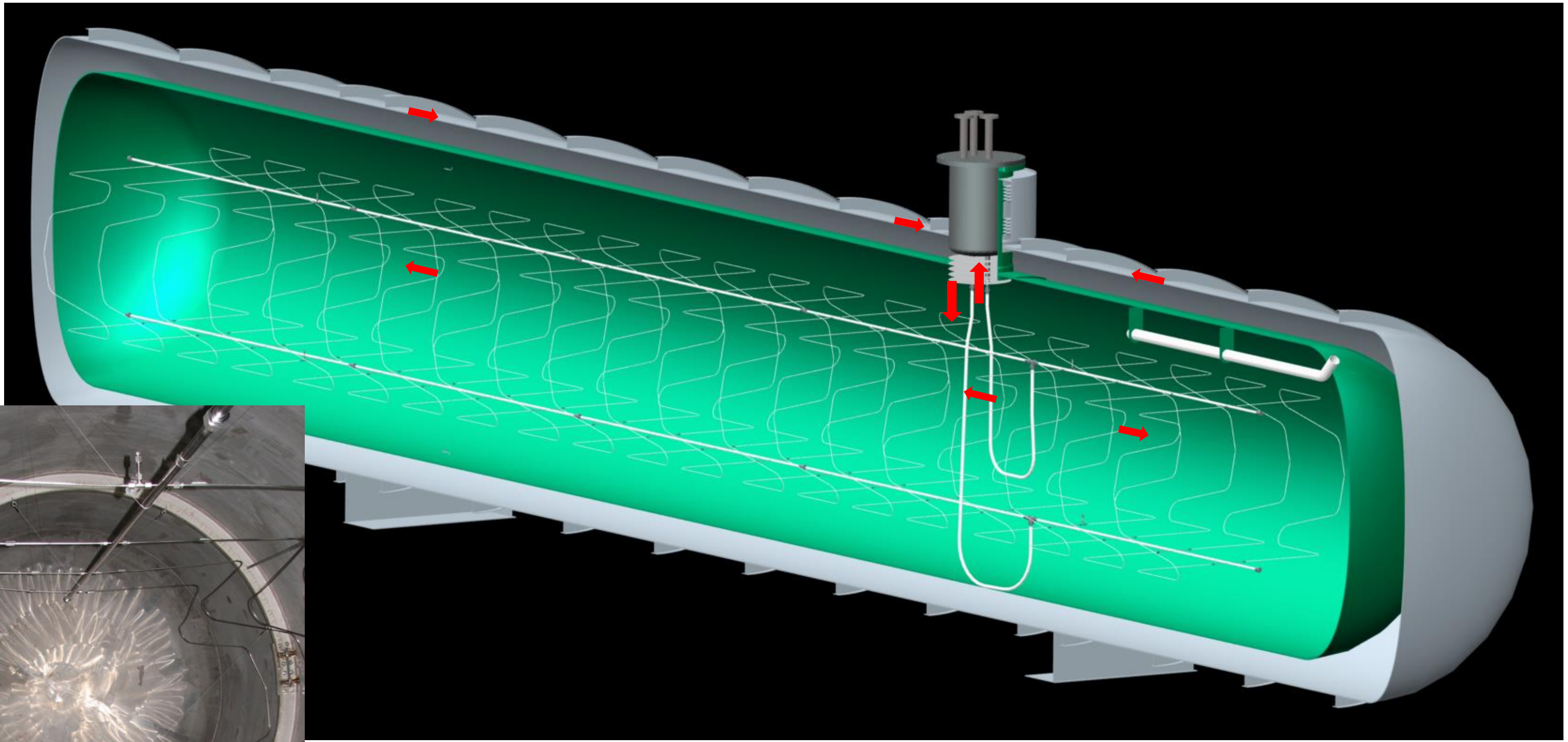
Mixing caused by venting

Liquid temperatures below aft skirt flange

IGODU-LH2 IRAS Tank Design

HX Details

- Roughly 800’ of 1/4” SS tubing (lobes) & 120’ of 1” SS tubing (headers)
- Headers interface to manway with 1” braided SS flex hoses.
- All tubing is connected using Swagelok VCR fittings with silver plated nickel gaskets.

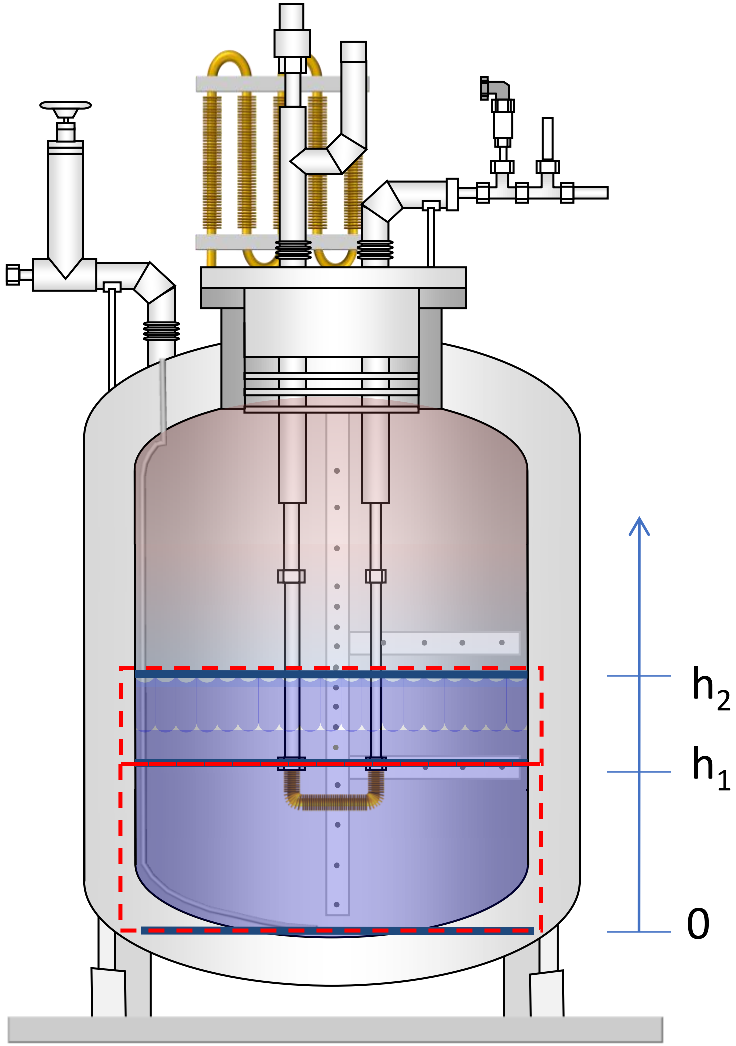


- Headers are located at the 25% and 75% fill levels.
- Generally controlled both liquid and vapor temperature

Heat Exchanger Below the Liquid Vapor Interface

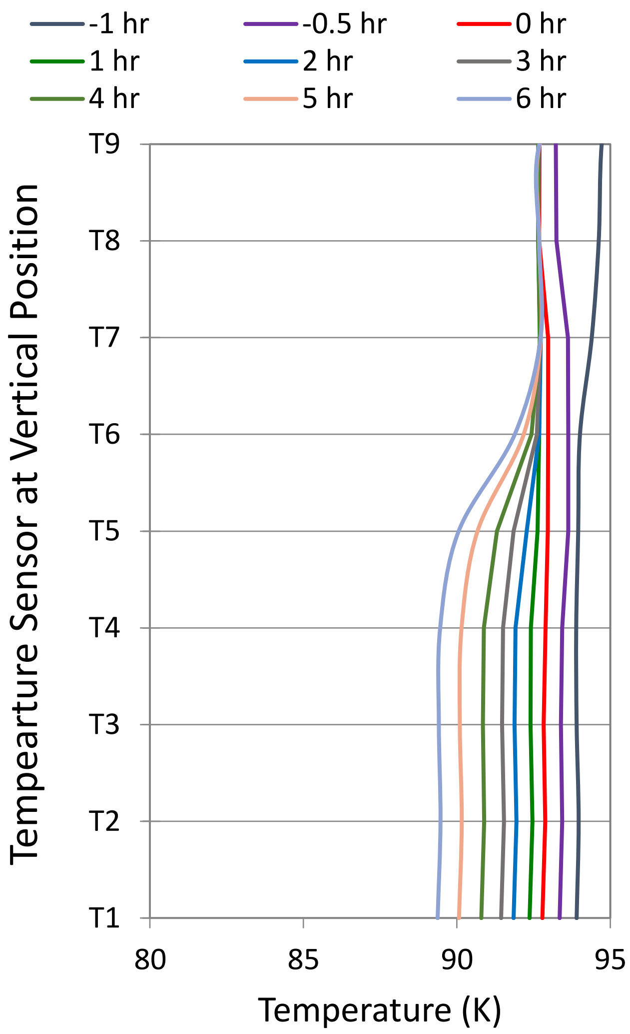
- Partridge did a study of densification with the heat exchanger only in the liquid
  - Varied the relative height of the heat exchanger (h_1) relative to surface (h_2).
- Provided cooling at the heat exchanger height.

J.K. Partridge, J.W. Tuttle, W.U. Notardonato, W.L. Johnson, **Mathematical model and experimental results for cryogenic densification and sub-cooling using a submerged cooling source**, *Cryogenics*, Volume 52, Issues 4–6, April–June 2012, Pages 262-267.



Results from Partridge

- Liquid vapor interface around T7, heat exchanger around T4.
- Cold liquid settled to the bottom of the tank and got progressively colder over time.
- Liquid Vapor Interface did not get substantially colder (i.e. tank pressure did not decrease much).
- Similar results seen in GODU LH2 tank at 90% full.



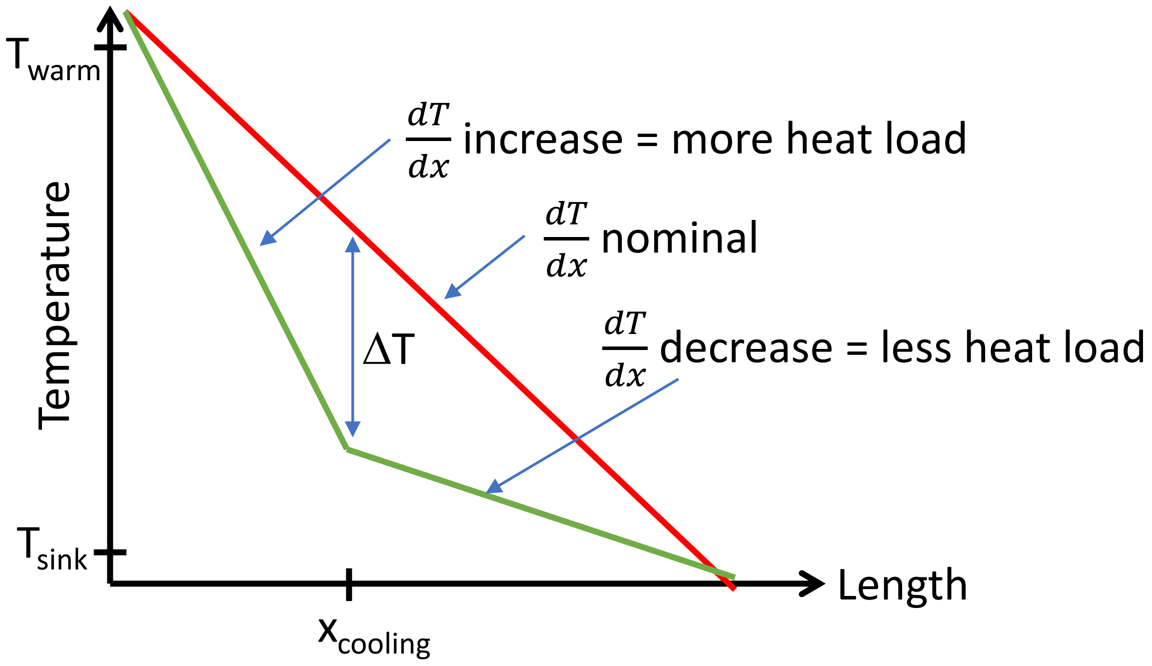
General Conclusions on Controlling Temp / Press

- If you want to control liquid temperature, but not ullage pressure, keep a refrigerated heat exchanger submerged.
- If you want to control liquid temperature and vapor pressure, need the refrigerated heat exchanger exposed to both phases.
  - In hydrogen, need to determine appropriate surface area to effectively remove heat. It will probably be larger than you think.
  - Liquid hydrogen will stay saturated unless you intentionally drive it via ullage pressure.
- For effectively heating liquid within a tank – heaters need to be as low on tank as possible.
  - Otherwise will have a section of the liquid below heater that is not easily heated with rest of liquid.

Heat Load Reduction Via “Heat Intercept”

- One method that is often used for heat load reduction is heat interception at an intermediate temperature.
  - Cryocoolers get better performance at higher temperatures.
  - Allows for any boil-off vapor to be used as forced convection coolant
  - Either reduces boil-off or reduces heat load removal requirements at lower temperatures (ultimately saving energy)
- A key mistake often made in design and evaluation of such systems is to assume that the passive heat load and the load being reduced from are the same.
  - This is exacerbated by the general Key Parameter of heat load reduction from passive to heat intercept case.
  - Severely complicates the testing approach in certain configurations.
  - Has caused multiple PIs to overstate the predicted performance.
  - You must reanalyze both sides of the cooling location to solve the energy conservation in the heat intercept case.
- That being said, “Heat Intercept” does work!

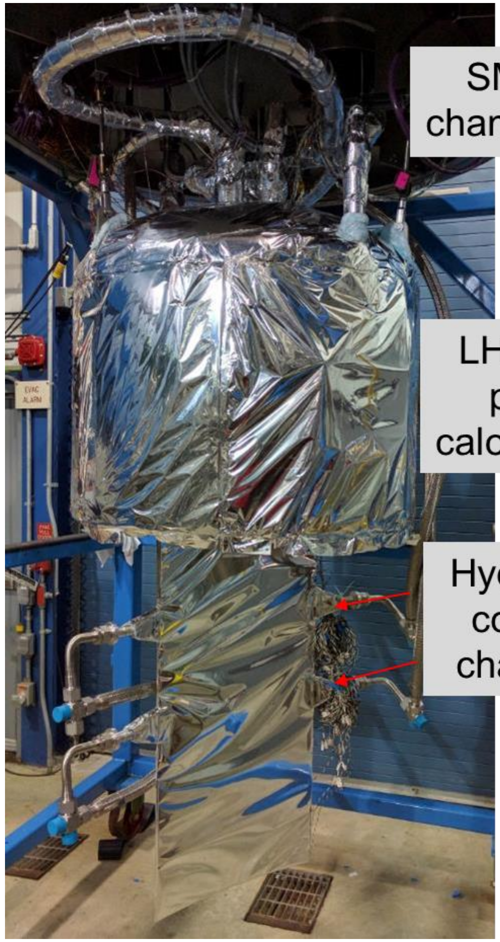
General Theory



Two Testing Examples

- With a cryocooler
  - Reduced Boil-off (RBO) 1 and 2 testing (2012 and 2013)
- Using “boil-off” vapor
  - Subscale Investigation of Cooling Enhancements (SLICE) testing (2017 – 2019)

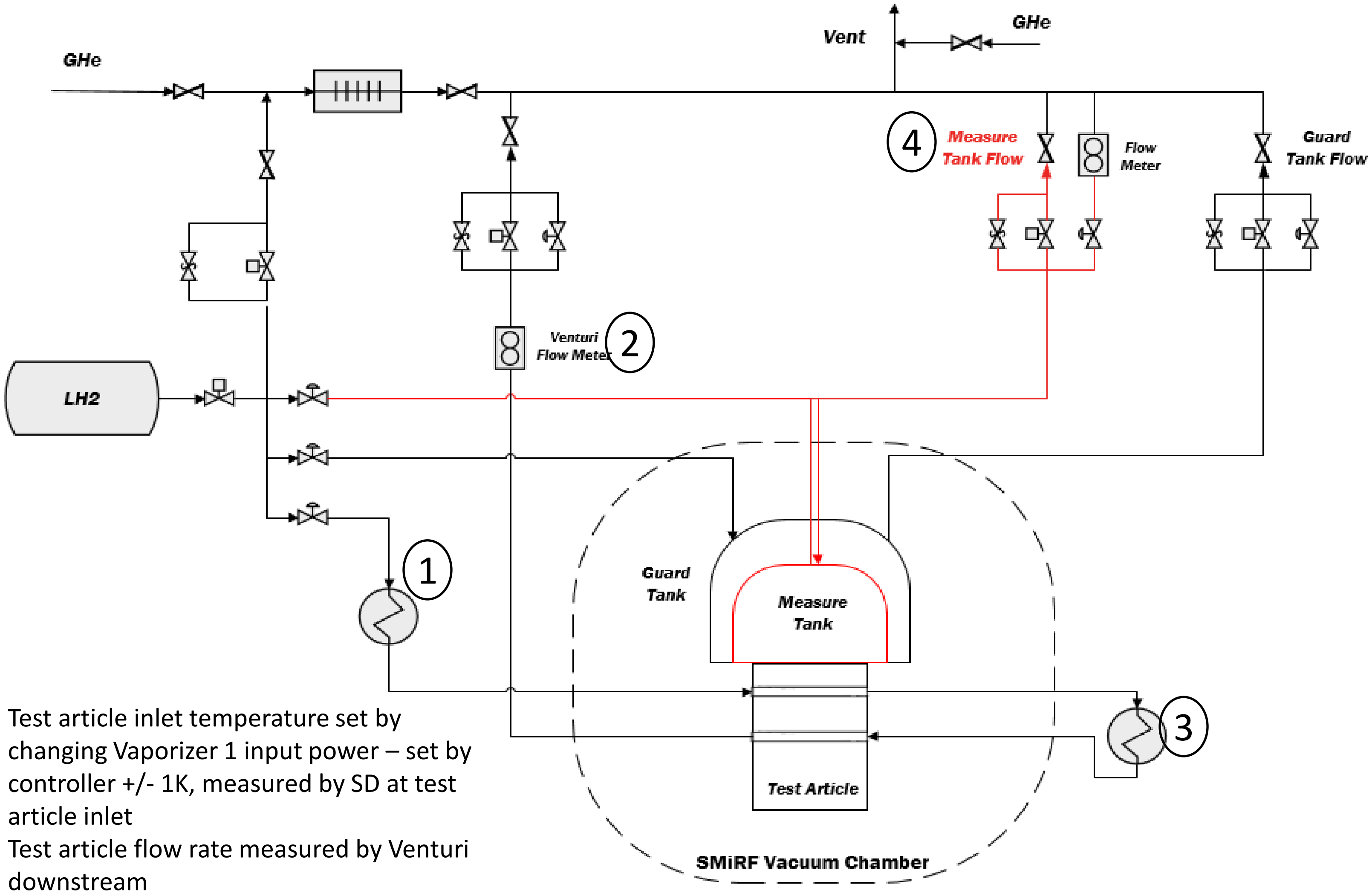
SLICE Testing



SMiRF chamber lid

LH2 Flat plate calorimeter

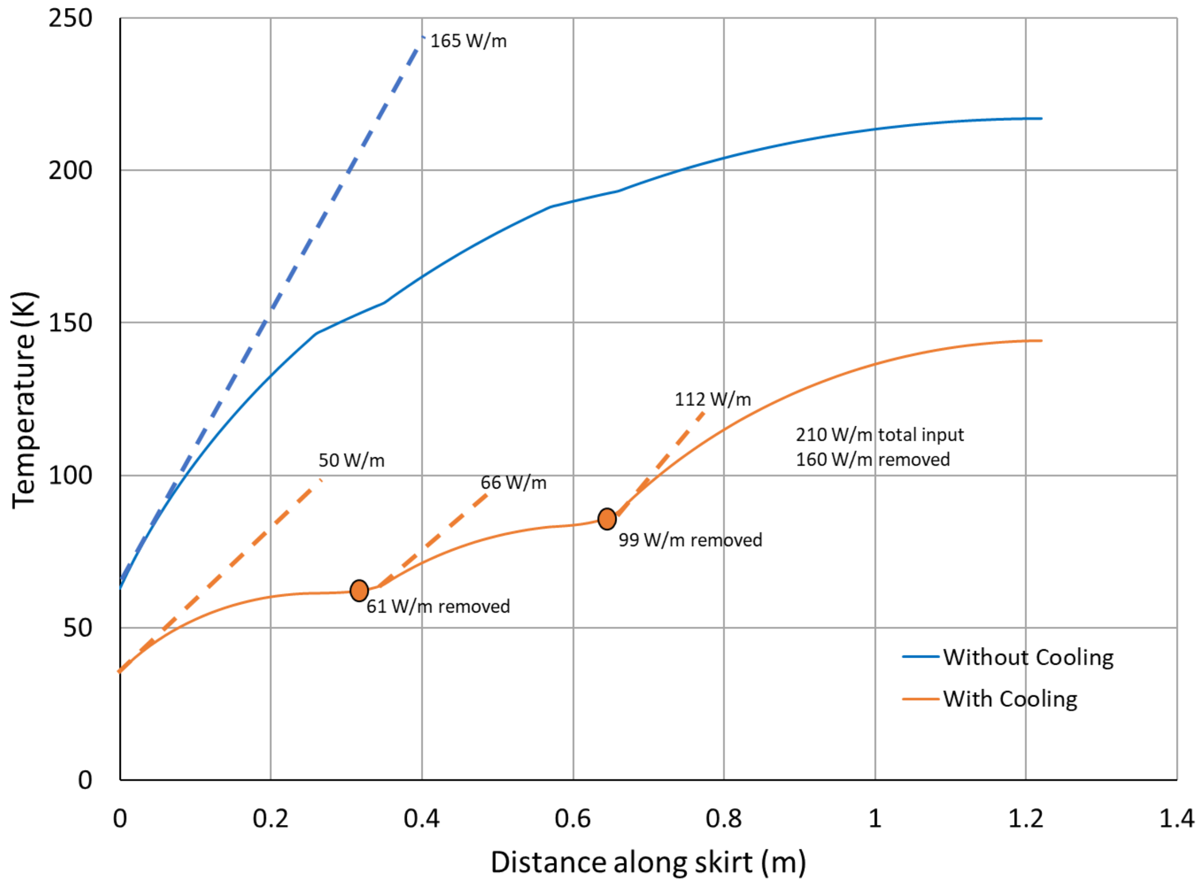
Hydrogen cooling channels



1. Test article inlet temperature set by changing Vaporizer 1 input power – set by controller +/- 1K, measured by SD at test article inlet
2. Test article flow rate measured by Venturi downstream
3. Vaporizer 2 set to constant power to mimic circumferential heat pickup by fluid as it travels around skirt
4. Calorimeter boil-off measured by Coriolis flow meter (FH125)

Ameen, L.M., Zoeckler, J.G., Wendell, J.C., and Johnson, W.L., **Testing of Hydrogen Vapor Cooling for Large Scale Structural Applications**, presented at the 2019 Space Cryogenics Workshop, Southbury, CT, 2019.

SLICE Test Results - Sample



Initial heat load: 165 W/m

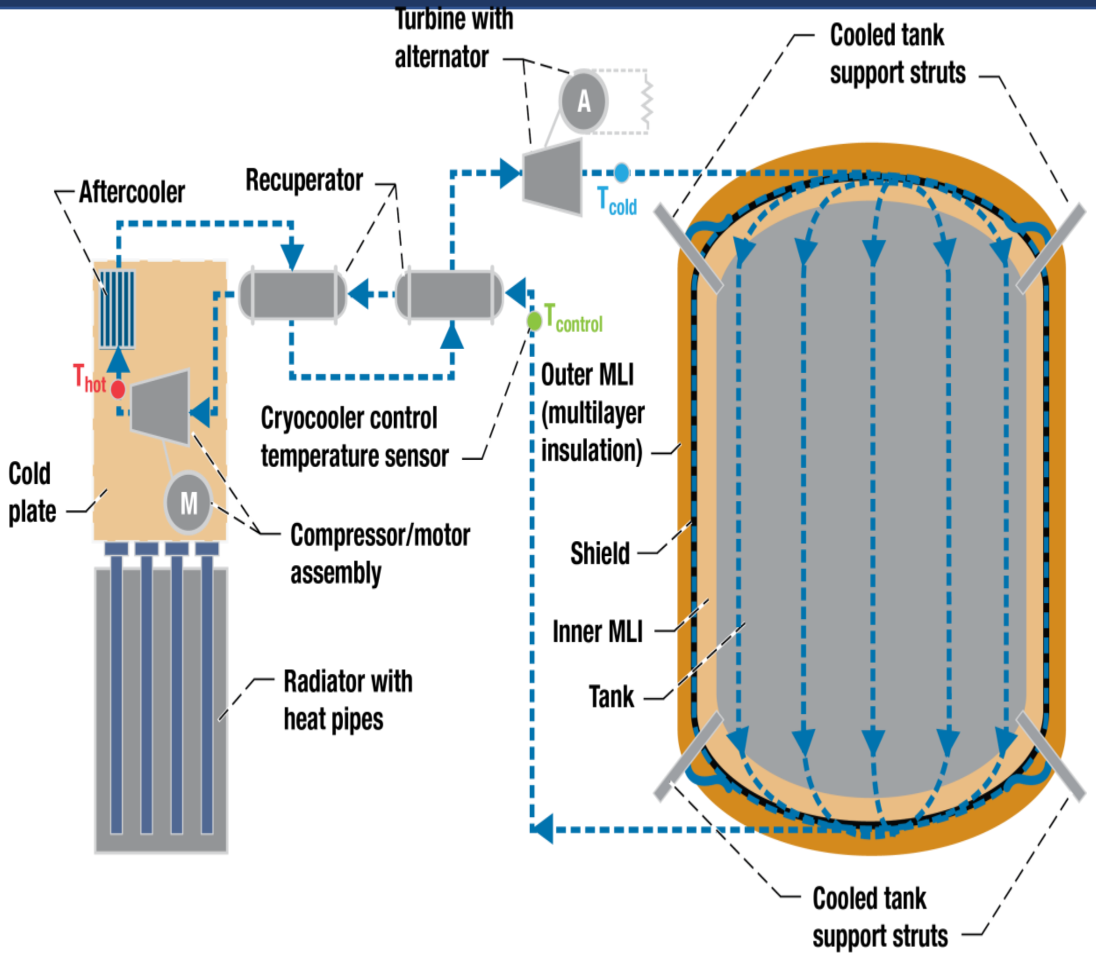
With hydrogen vapor cooling, 160 W/m Removed

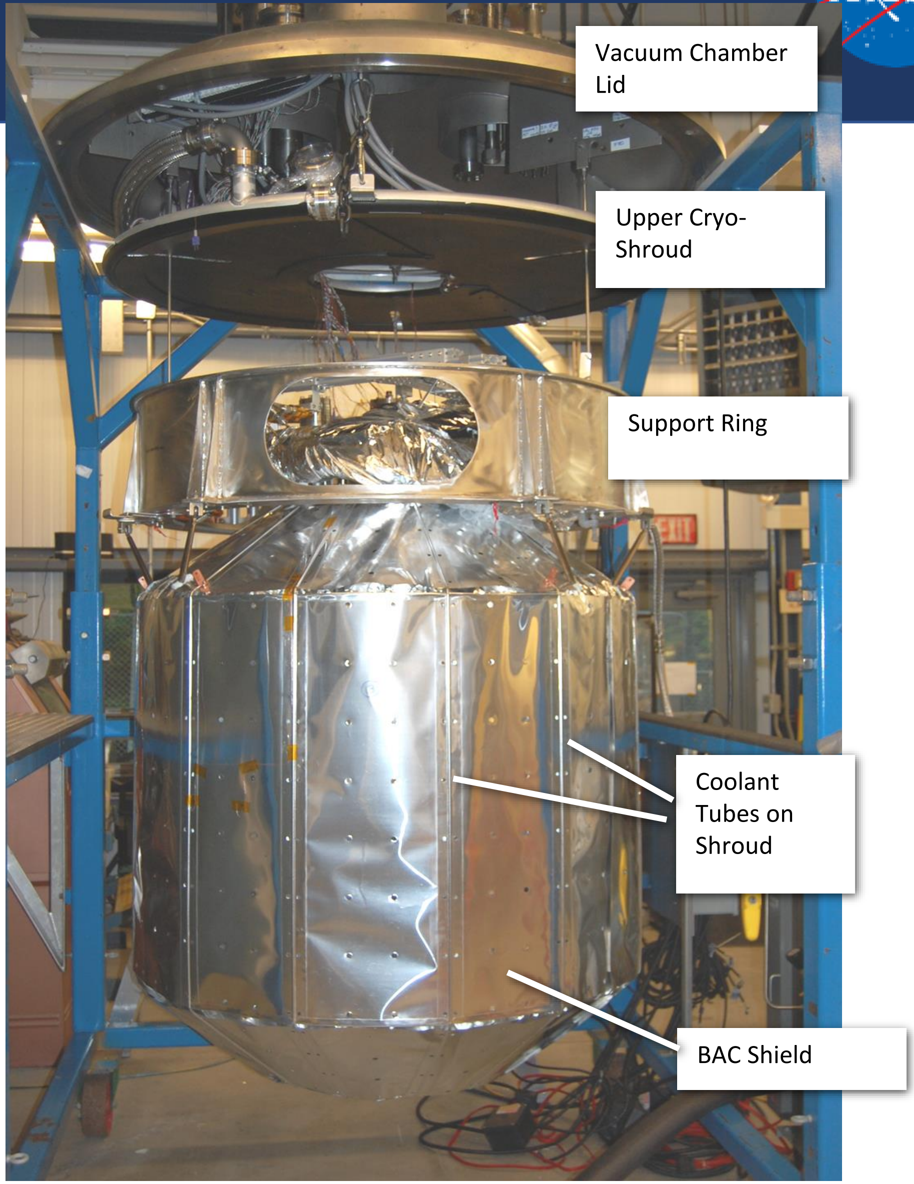
- Still has heat load of 50 W/m

Heat Load reduction of ~70%

- Removed same amount of heat as initial heat load at two different cooling locations

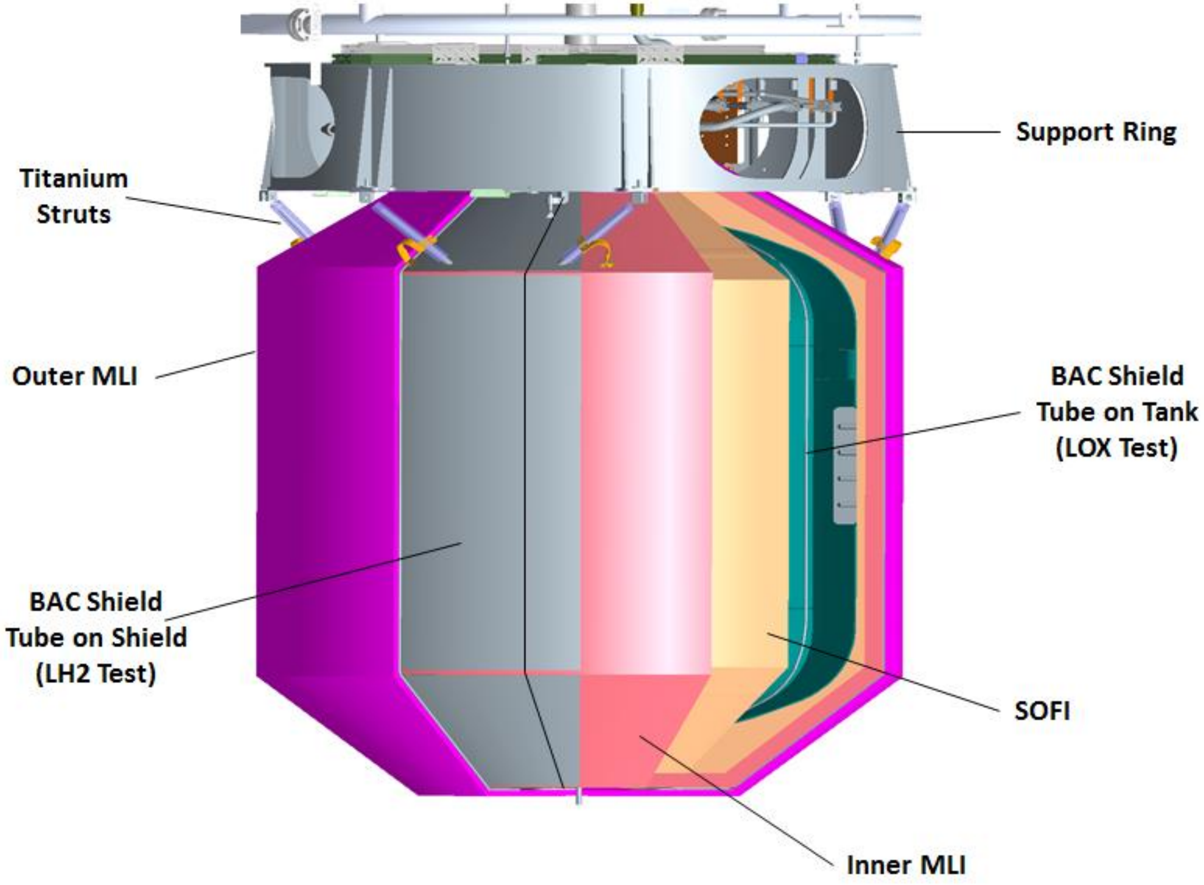
RBO Testing Overview



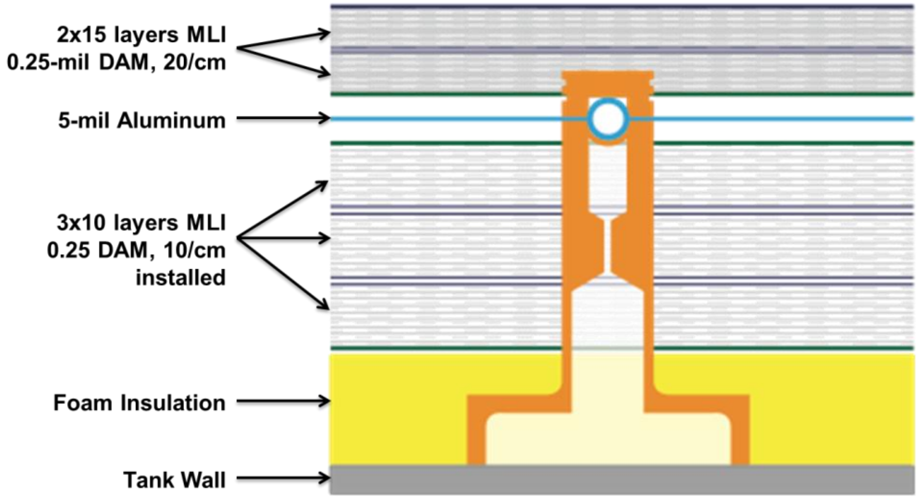


Plachta, D.W., Christie, R.J., et.al. “**Cryogenic Boil-off Reduction System Testing**”, presented at the 2014 AIAA Propulsion and Energy Forum, Cleveland, OH, AIAA paper 2014-3579, 2014.

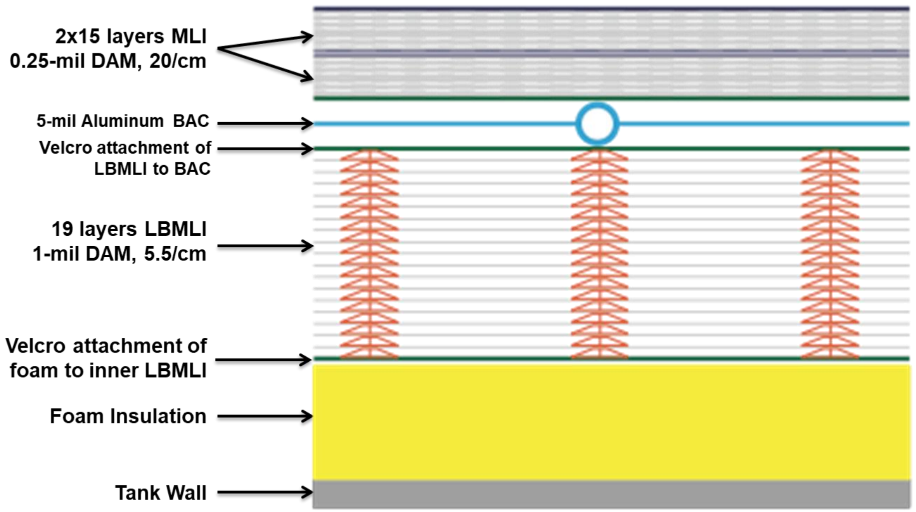
RBO Testing, cont



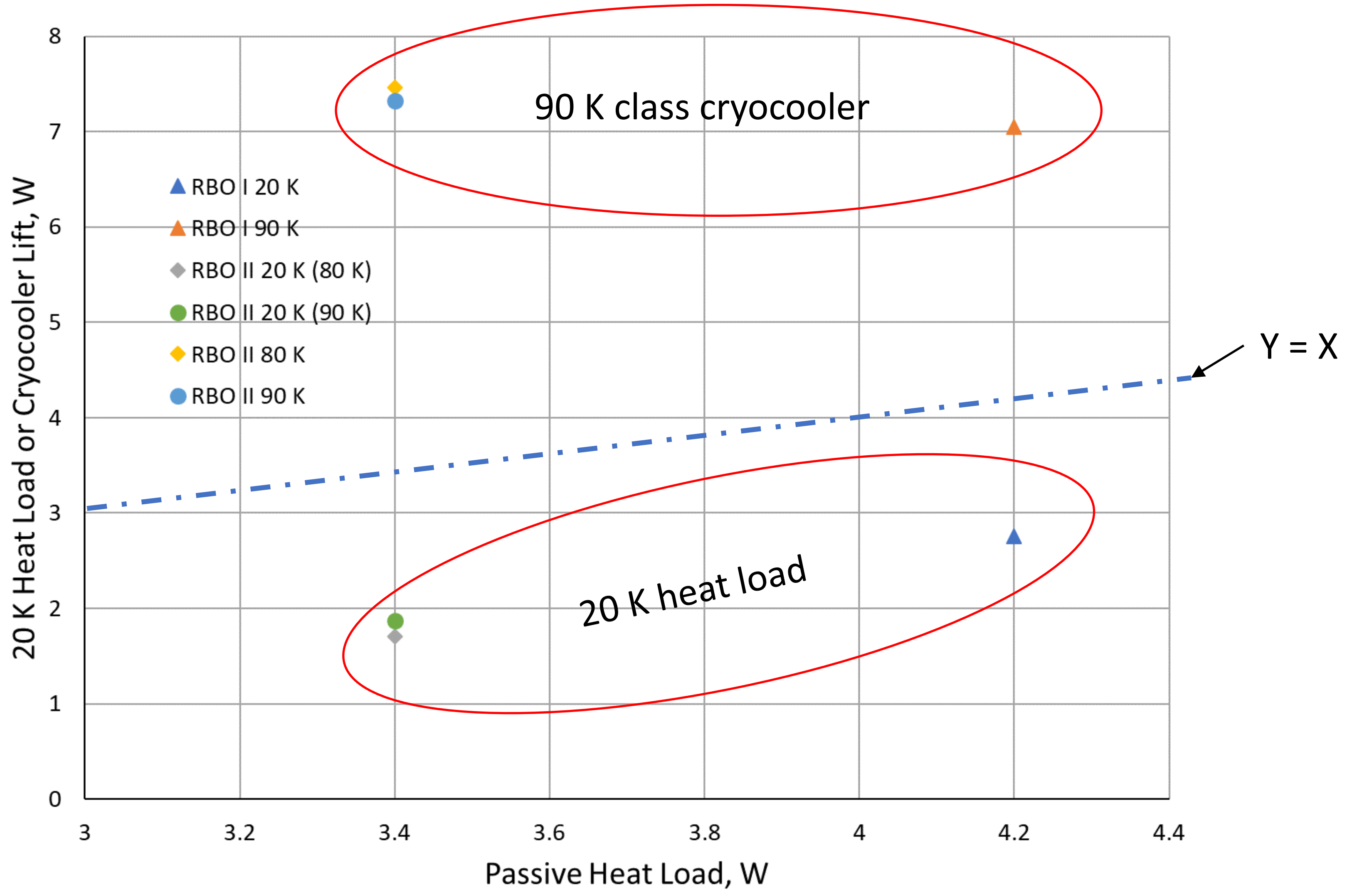
RBO I



RBO II



RBO Test Results (Sample)



Heat Reduction of ~ 50% for both tests.

Removed ~2x the original heat load at intermediate cooling temperature.

If cost of heat removal is 10 Welec/Wcooling at 90 K and 90 Welec/Wcooling at 20 K:

- 3.4 W case:
  - Passive: 306 W
  - Active: 228 W
  - 25% input power reduction
- 4.2 W case:
  - Passive: 378 W
  - Active: 304 W
  - 20% input power reduction

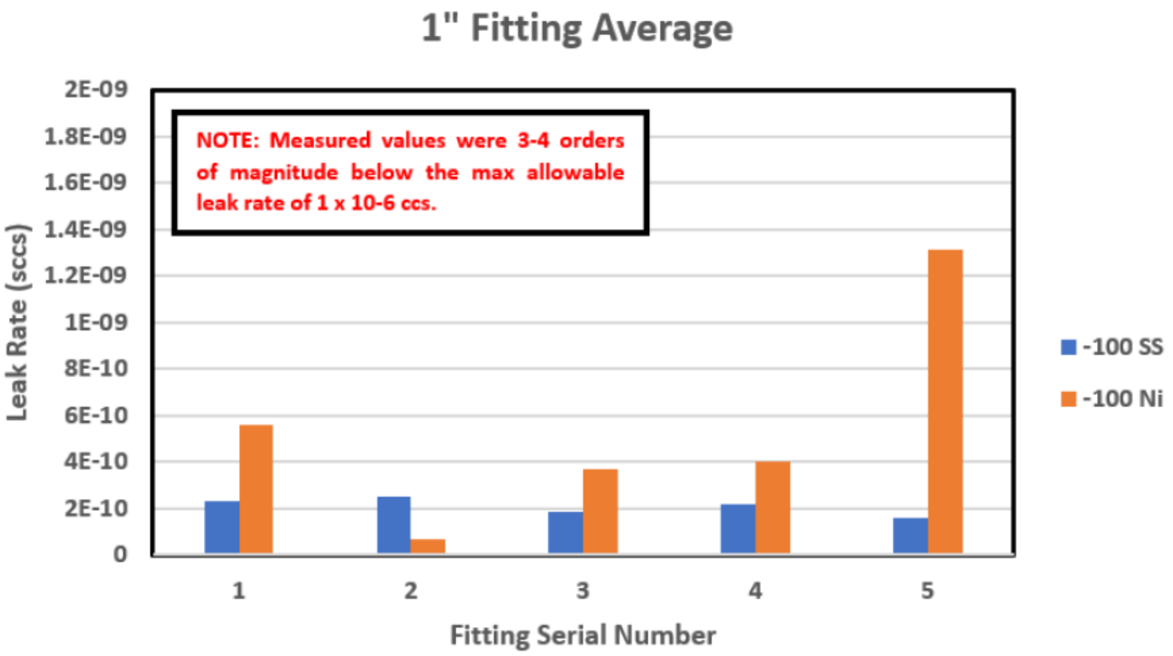
Fitting Testing

- Recent testing of Swagelok VCR fittings down to 20 K showed very little leakage.
  1. Testing of three (3) different VCR fitting sizes: 1/4, 1/2, and 1 inch.
  2. Five (5) samples of each fitting size
  3. Two (2) different seal material types: SST and Ni. These materials were selected because they are the most compatible with the cryogenic space flight fluids.
  4. Four (4) complete ambient (300K) to cryogenic (20-30K) thermal cycles in TVAC for each fitting size and seal material combination. Two (2) thermal cycles were performed before and two (2) cycles after vibration testing.
  5. Vibration testing to relevant launch dynamic profile, see Section 9.1 Test Method.
  6. Leak checking of fittings throughout the TVAC test sequence by pressurizing to 400-420 psi (27.5-29 bar) with GHe and monitoring the chamber background with a GHe mass spectrometer leak detector.

https://ntrs.nasa.gov/citations/20230009184

Fitting Testing Results

- The results of this testing programs showed that the fittings remain leak tight at cryogenic temperature (20K- 30K).
  - All fittings passed the requirement that a measured leak rate not exceed 10^{-6} sccs.
  - Measured leak rates for the 30 fitting/seal pairs were typically in the range of 10^{-9} -10^{-10} sccs during both Pre-Vibe and Post-Vibe thermal vacuum cycles.



Typical Results

Questions?

References

1. Columbia Accident Investigation Board, Report Volume 1, August 2003.
2. Johnson W L, Valenzuela J G, Feller J R, and Plachta D W, “Tank Applied Testing of Load-Bearing Multilayer Insulation (LB-MLI)”, AIAA-2014-3581, 2014.
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5. Johnson W L, Demko J A, and Fesmire J E, “Analysis and Testing of Multilayer and Aerogel Insulation Configurations,” Advances in Cryogenic Engineering, Vol. 55A, American Institute of Physics, Melville, NY, 2010. Pg. 780-787.
6. Parmley R T and Cunnington G R, “Evacuated Load-Bearing High-Performance Insulation Study”, NASA CR-135342, 1977.
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