Vibro-Acoustic Test Article (VATA) Test Series

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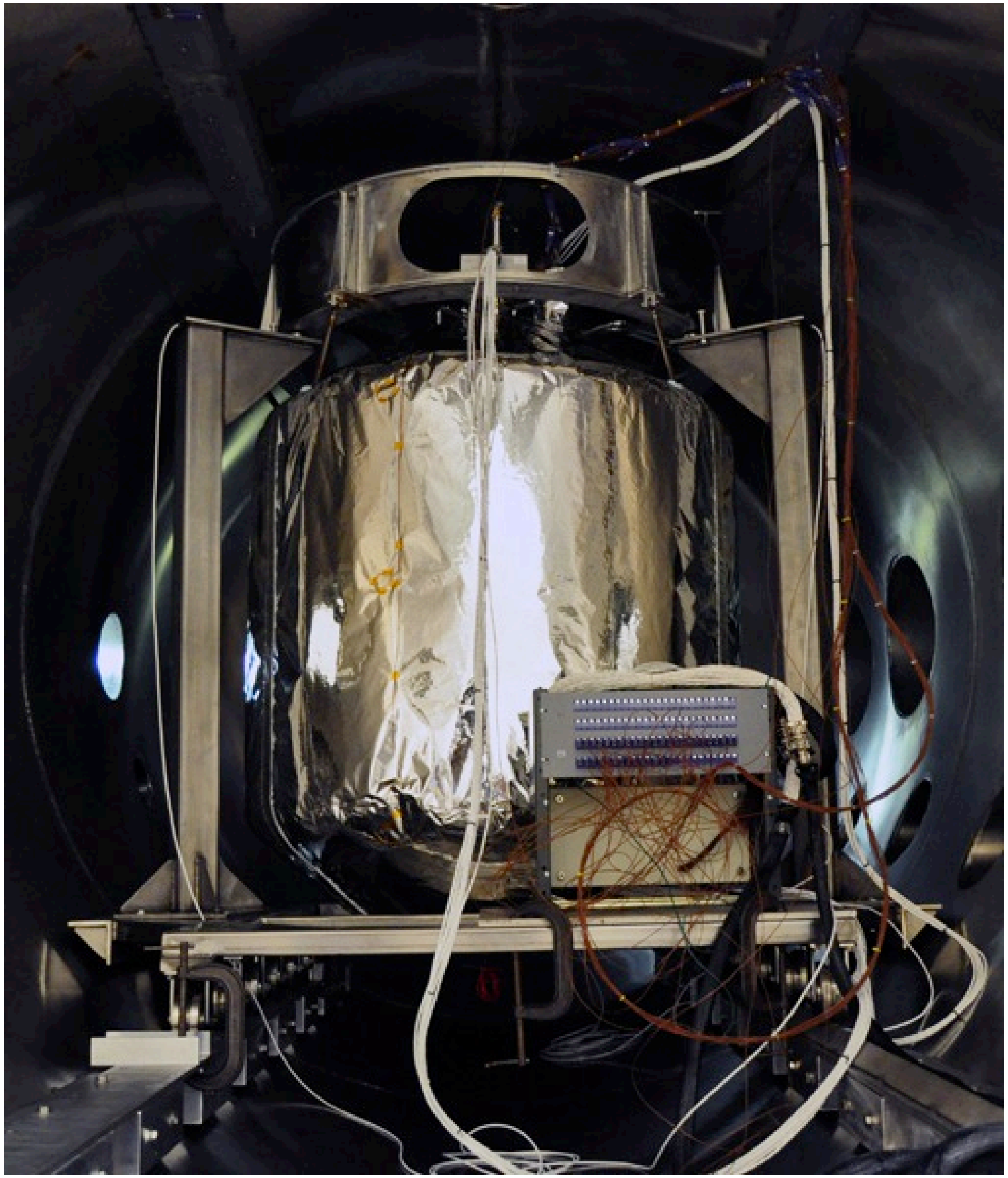
Executive Summary

- **Cryogenic Propellant Storage and Transfer (CPST) Technology Maturation Traditional Multilayer Insulation (tMLI)/Broad Area Cooling (BAC) Shield Thermal and Acoustic Test**
  - Objective: Assess the structural performance of an MLI/BAC shield assembly subjected to launch acoustic loads.
  - Overview:
    - Design, fabricate, and assemble a structurally and thermally acceptable tMLI/BAC shield on the Vibro-Acoustic Test Article (VATA).
    - Install tMLI/BAC shield on tank.
    - Expose tank-applied tMLI/BAC shield assembly to simulated launch acoustic loads.
    - Compare data from the thermal tests conducted before and after the acoustic test to assess possible degradation to the tMLI/BAC shield system.
- **Game-Changing Development LBMLI/BAC Shield Thermal and Acoustic Test**
  - Objective: Assess the structural performance of a Load Bearing (LB) MLI/BAC shield assembly when subject to launch acoustic loads. Compare results to previous configuration.
  - Overview: Repeat CPST Technology Maturation VATA test sequence with LBMLI.
- **VATA Follow-on Testing**
  - Objective: Evaluate the thermal performance of alternative passive and active thermal control system configurations using low-cost LN2 thermal/vac testing.
  - Overview:
    - Passive TCS configurations: compressed-seam tMLI with no BAC shield, Spray-on Foam Insulation (SOFI)-only, LBMLI only, and tMLI with interleaved seams
    - Active TCS configurations: vapor-cooled shield and vapor-cooled struts

Vibro-Acoustic Test Article (VATA) Overview

Test Article Elements

- **Tank:** ASME Stainless Steel Pressure Vessel
  - Same for entire series, SA = 6.45 m^2
- **SOFI:** Stepanfoam S-180 foam
  - Same for entire series
- **MLI:** Reflector and insulator layers
  - Different throughout series:
  - Traditional MLI
    - VATA 1a inner/outer blankets, compressed seams
    - VATA 1b blanket, compressed seams
    - VATA 2a-2c outer blanket, compressed seams
    - VATA 3a-3c varied layer count, interleaved seams
  - Load Bearing MLI
    - VATA 2a-2d inner blanket, interleaved seams
- **Cooling:** Cryo-Cooler Simulator and Vented Vapor
  - Different throughout series:
  - Broad Area Cooling Shield
    - VATA 1a and 2a tube-on-shield configuration using chilled GN2 circulated through an open-loop system to simulate cryo-cooler
  - Vapor Cooling
    - VATA 2b test article vented vapor directed through Vapor Cooled Shield embedded in MLI blanket
    - VATA 2c test article vented vapor directed through tubing for Vapor Cooled Struts
- **Struts:** 6 Tank Support Struts
  - Titanium Struts: VATA 1a – VATA 3c
  - Composite Struts: VATA 4a



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VATA Series Overview

CPST Tech Maturation

- **VATA 1a:** Traditional MLI, BAC shield and support standoffs
  - **Thermal Test 1: 08/14/12 thru 08/29/12**
  - **Acoustic Test: 09/06/12**
  - **Thermal Test 2: 09/12/12 thru 09/25/12**

Follow-On

- **VATA 1b:** Traditional MLI, no BAC shield, no support standoffs, SOFI and MLI blanket with plugs
  - **Thermal Test: 10/23/12 thru 11/05/12**
- **VATA 1c: SOFI only**
  - **Thermal Test: 12/03/12 thru 12/05/12**

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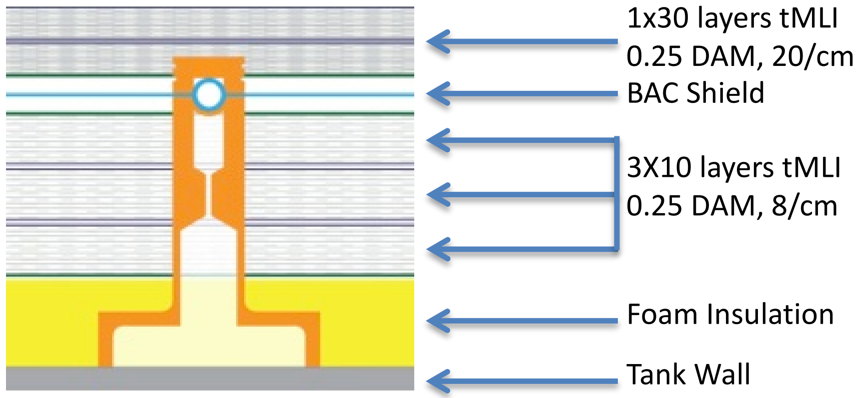
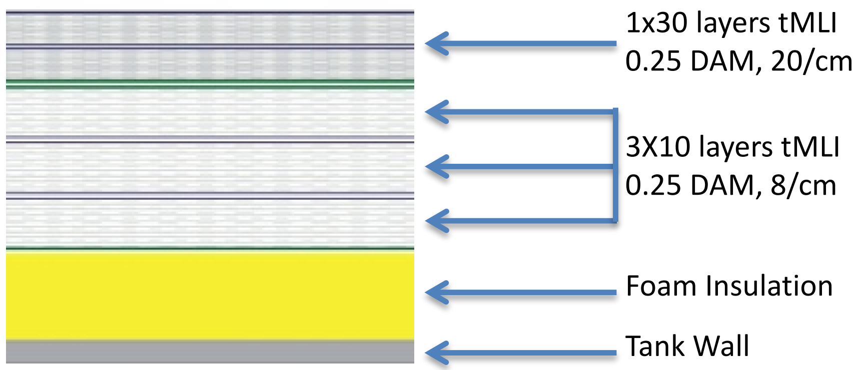
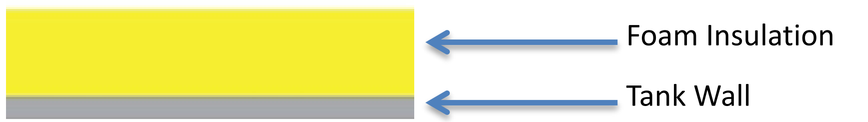
- **VATA 2a:** Inner LBMLI, BAC shield, and Outer Traditional MLI
  - **Thermal Test 1: 01/07/13 thru 01/24/13**
  - **Acoustic Test: 03/22/13**
  - **Thermal Test 2: 03/29/13 thru 04/06/13**

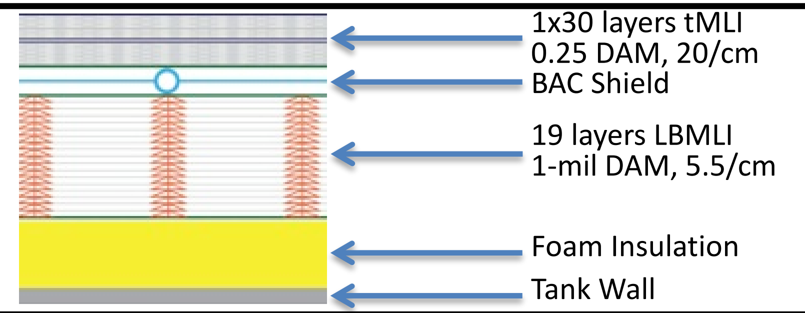
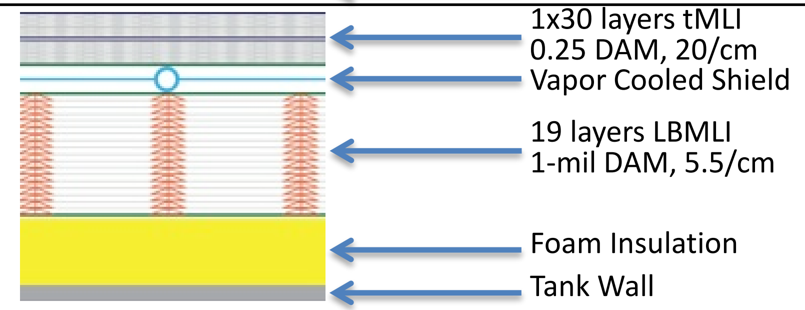
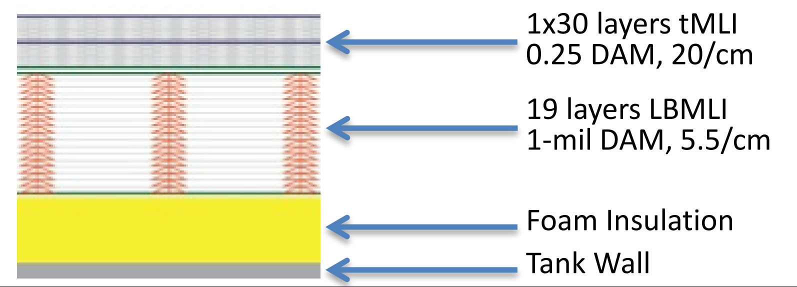
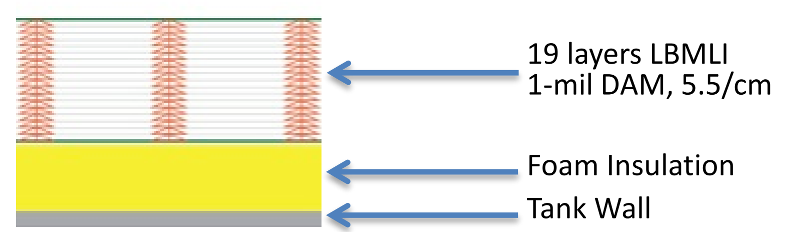
Follow-On

- **VATA 2b:** Inner LBMLI, Vapor Cooled Shield, and Outer Traditional MLI
  - **Thermal Test: 05/01/13 thru 05/10/13**
- **VATA 2c:** Inner LBMLI, Vapor Cooled Struts, and Outer Traditional MLI
  - **Thermal Test: thru 06/12/13**
- **VATA 2d:** Inner LBMLI
  - **Thermal Test: thru 07/08/13**
- **VATA 3a:** Traditional MLI with Interleaved Seams (Layer Matched to LBMLI)
  - **Thermal Test: 07/19/13 thru 07/26/13**
- **VATA 3b:** Traditional MLI with Interleaved Seams (Mass Matched to LBMLI)
  - **Thermal Test: 08/04/13 thru 08/22/13**
- **VATA 3c:** Traditional MLI with Interleaved Seams (Volume Matched to LBMLI)
  - **Thermal Test: 10/21/13 thru 11/04/13**
- **VATA 3d:** Traditional MLI with Interleaved Seams (Volume Matched to LBMLI) 60% fill
  - **Thermal Test: 01/06/14 thru 01/15/14**
- **VATA 4a:** Traditional MLI with Interleaved Seams (Volume Matched to LBMLI but with composite struts)
  - **Thermal Test: 07/25/14 thru 08/05/14**

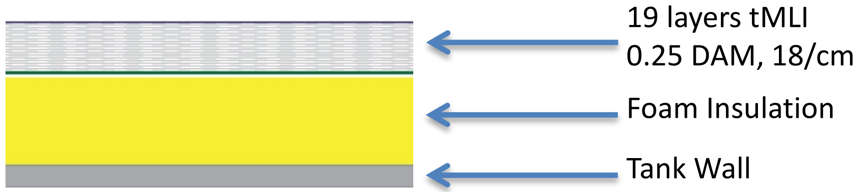
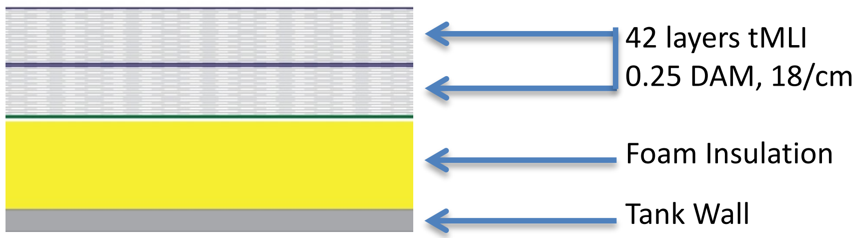
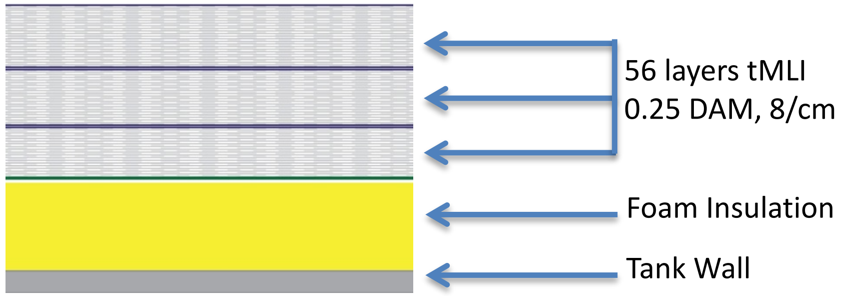
VATA 1 Configuration Overview

Title	**Objective**	
VATA 1a tMLI/BAC Shield Thermal and Acoustic Test	*Assess the structural performance of a tMLI/BAC shield assembly subjected to launch acoustic loads.*	
VATA 1b 60-Layer tMLI Thermal Test	*Evaluate the thermal performance of a tMLI-only configuration in order to determine the thermal degradation associated with the standoffs and BAC shield in VATA 1a.*	
VATA 1c SOFI-Only Thermal Test	*Evaluate the thermal performance of a SOFI-only configuration.*	

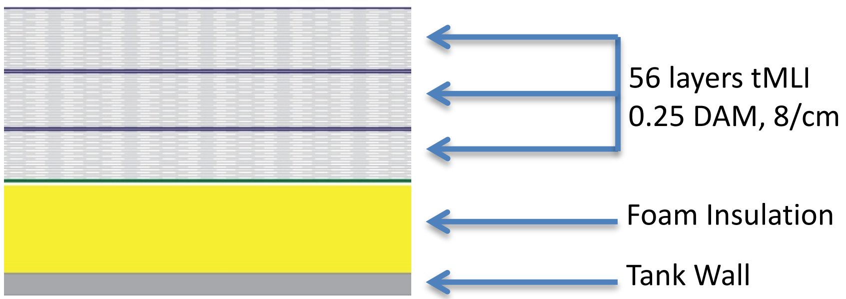
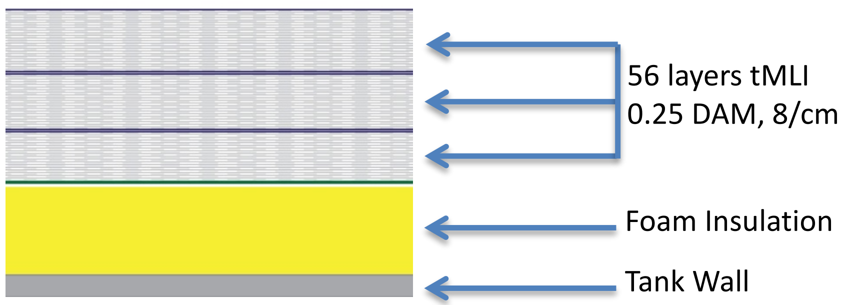
VATA 2 Configuration Overview

Label	Objective	
VATA 2a LBMLI/BAC Shield Thermal and Acoustic Test	*Assess the structural performance of an LBMLI/BAC shield assembly subjected to launch acoustic loads.*	
VATA 2b Vapor Cooled Shield Thermal Test	*Assess the structural performance of an MLI/BAC shield assembly subjected to launch acoustic loads.*	
VATA 2c Vapor Cooled Struts Thermal Test	*Assess the structural performance of an MLI/BAC shield assembly subjected to launch acoustic loads.*	
VATA 2d LBMLI Thermal Test	*Evaluate the thermal performance of an LBMLI-only configuration.*	

VATA 3 Configuration Overview

Title	Objective	
VATA 3a tMLI Layer-Matched to LBMLI Thermal Test	*Evaluate an interleaved-layer MLI blanket with number of layers matched to the VATA 2 series LBMLI blanket.*	
VATA 3b tMLI Mass-Matched to LBMLI Thermal Test	*Evaluate an interleaved-layer MLI blanket with mass matched to that of the VATA 2 series LBMLI blanket.*	
VATA 3c tMLI Volume-Matched to LBMLI Thermal Test	*Evaluate an interleaved-layer MLI blanket with volume matched to that of the VATA 2 series LBMLI blanket.*	

VATA 3d and 4a Configuration Overview

Title	Objective	
VATA 3d tMLI Volume-Matched to LBMLI Thermal Test at 60% fill level	*Evaluate an interleaved-layer MLI blanket with volume matched to that of the VATA 2 series LBMLI blanket but at 60% fill level.*	
VATA 4a tMLI Volume-Matched to LBMLI Thermal Test with composite struts	*Evaluate an interleaved-layer MLI blanket with volume matched to that of the VATA 2 series LBMLI blanket but with composite struts.*	

Summary of Key VATA Tests

Steady State Criteria for all testing:

- MLI temperature changes less than 0.5 Kelvin/6hrs.
- Tank skin temperature changes less than 0.5 Kelvin/6hrs.
- Boundary conditions read constant throughout.
- 6 hour period allotted for final steady state data set.

Table 1 – Overview of Key Parameters

Test	Layers	Spacer Configuration	MLI Mass (kg)	Thickness (cm)	Total Heat Load (W)	MLI Heat Load Only (W)
VATA 2d (LBMLI)	19 LBMLI	Ultem Tripod Posts	**10.88**	**3.81**	8.3	6.0
VATA 3a (Layer Match)	19 tMLI	2 Layers of B4A Netting	**5.16**	**1.02**	9.0	6.6
VATA 3b (Mass Match)	42 tMLI	2 Layers of B4A Netting	**11.09**	**2.29**	7.3	4.9
VATA 3c (Volume Match)	56 tMLI	2 Layers of B4A Netting	**14.5**	**3.81**	6.9	4.8

Table 2 – Test Conditions

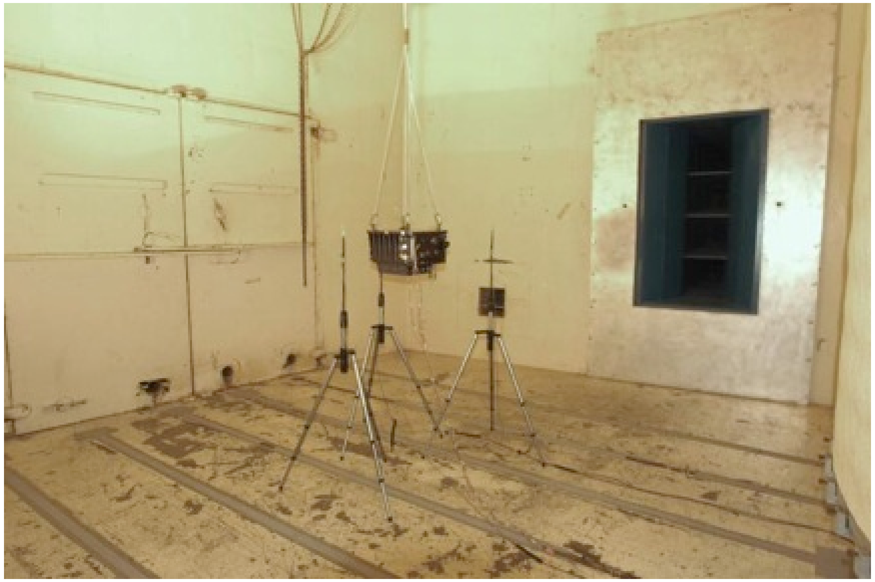
Test	VC Pressure (Torr)	VC Wall Temp (Kelvin)	Ullage Pressure (psia)	Fill Level (%)	Days to Reach Steady State	Layers	Layer Density (layers/cm)	Total Heat Load (W)	MLI Heat Load (W)
VATA 2d (LBMLI)	7.1E-7	290	18	95	10	19	5	8.3	6.0
VATA 3a (Layer Match)	8.1 E-7	290	18	95	6	19	18.6	9.0	6.6
VATA 3b (Mass Match)	5.6 E-7	290	18	94	17*	42	18.3	7.3	4.9
VATA 3c (Volume Match)	7.9 E-7	292	18	94	13	56	14.7**	6.9	4.8

*** For test case 3b, facility issues prolonged time to attain steady state (more information on slide 84).**

**** Actual value for layer density based on set thickness of 19 layers of LBMLI. VATA 3a and 3b are approximate layer densities based on 2 layers of DAM and 1 layer of Mylar.**

VATA Test Facility Overview

- Acoustic Testing: MSFC 4619 Acoustic Chamber
- Thermal Testing: MSFC 4205 Exploration Systems Test Facility (ESTF)



MSFC 4619 Acoustic Chamber

MSFC 4205 Exploration Systems Test Facility

MSFC 4619 Acoustic Chamber

- The Acoustic Test Facility consists of a Reverberation Chamber, which is constructed of reinforced concrete.
  - Encloses 5000 ft^3.
  - Shape is approximately cubic with 17 feet per side.
  - No parallel surfaces in the room to promote a diffuse acoustic environment.
- The acoustic input is generated by four WAS 3000 Modulators with a combined acoustic power of 120 kW.
  - Maximum acoustic level is approximately 160 dB in the room’s center.
- Data acquisition consists of a Precision Filters 28000 for signal conditioning, a TEAC GX for recording, and an m+p vibration control system for analysis.

VATA in MSFC 4619 Acoustic Chamber

- VATA was transported from MSFC b4205 to b4619 for acoustic testing.
- A plastic cover protected VATA from contamination during transportation.

VATA Acoustic Test Configuration

MSFC PRDL Exploration Systems Test Facility

- NASA MSFC Propulsion Research and Development Laboratory (Bld. 4205/Rm. 108)
- 9 ft diameter by 20 ft long vacuum chamber (10^{-8} torr)
- Pumps: 1 roughing (Kinny-CB7230), 2 turbos (TMG2400), 2 cryos (ADPSHD22)
- 240 kW DC power (16 supplies @ 150 V, 100 Amps)
- Control, Data Acquisition via LabVIEW, NI, and Iotech
- Liquid nitrogen (150 psig) / gaseous nitrogen (4500 psig) / Missile grade air (3500 psig)

MSFC PRDL Exploration Systems Test Facility

- Five main transfer systems:
  - Fill (1/2" vacuum jacketed line)
  - Drain (1/2" vacuum jacketed line)
  - Facility GN2 Pressurant (1/4" line)
  - Vent (1" insulated line)
  - Relief (1" insulated line)
- Two supply Dewars and facility hookups:
  - Indoor 240L
  - Outdoor 1000L
  - LN2 trailer hookups are available for large volume test articles
- Pressure certified to 150 psia
- High and low flow boil-off measurement system
- Cryo-cooler Simulator Flow at 2 grams/sec and -150 F

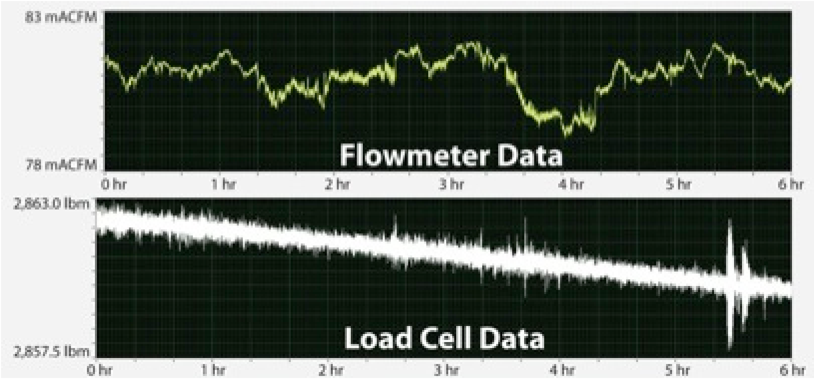
All tests were conducted with a VC pressure ranging between 1.3×10^{-6} and 6.3×10^{-7} Torr and a warm boundary VC wall temperature ranging between 281 and 292 K.

Heat Leak Uncertainty Assessment

- **Heat leak measured in two ways:**
  - Boiloff vapor volumetric flow rate measured with turbine flowmeter
  - Tank mass loss measured by load cells
- **Flowmeter mass boiled away = Volumetric flow rate (Voldot) * density (rho)**
  - Density was obtained from NIST tables using experimental pressure and temperature data
  - $U_{FM} = \{ (U_{VOLDOT})^2 + (U_{PRESSURE})^2 + (U_{TEMPERATURE})^2 \}^{½}$
  - U_{VOLDOT} = 0.63% combined repeatability and accuracy uncertainty of FTI flowmeter
  - $U_{PRESSURE}$ = 0.12% uncertainty of Baratron Pressure Transducer
  - U_{TEMP} = 0.10% uncertainty of E-type thermocouple when calibrated with Omega Model #CL25
  - **$U_{FM} = \{ (0.63\%)^2 + (0.12\%)^2 + (0.10\%)^2 \}^{½} = 0.65\%$**
- **Tank mass loss uncertainty is not well characterized by using the manufacturer's specification**
  - **$U_{LC} = \{ 3*(U_{LINEARITY})^2\}^{½} = \{3*(0.15\%)^2\}^{½} = 0.26\%$ FSO**
  - Using this standard method, the uncertainty would be ± 4 lbm, on order of the mass loss measurement
  - Load cells measured a small change of mass, < 0.1% of total mass (2.6 lbm in 2860 lbm test article)

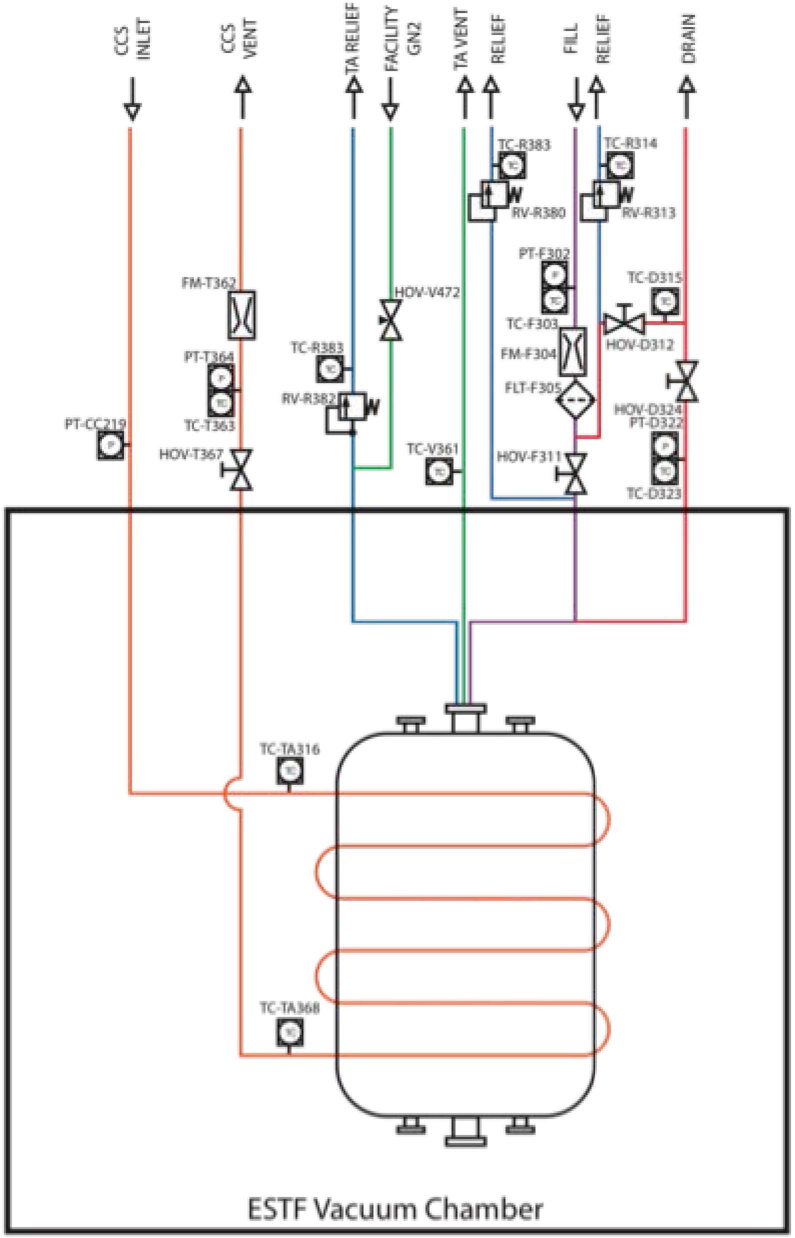
Steady-State Flowmeter Data
6 hour duration

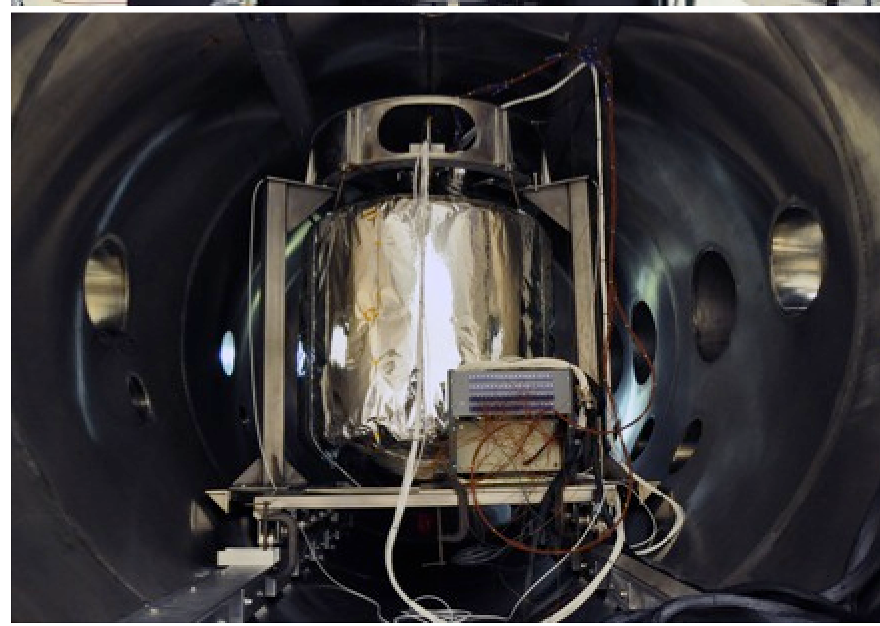
Steady-State Load Cell Data
6 hour duration



Flow-meter method more precise than load cell measurement

VATA in MSFC 4205 ESTF

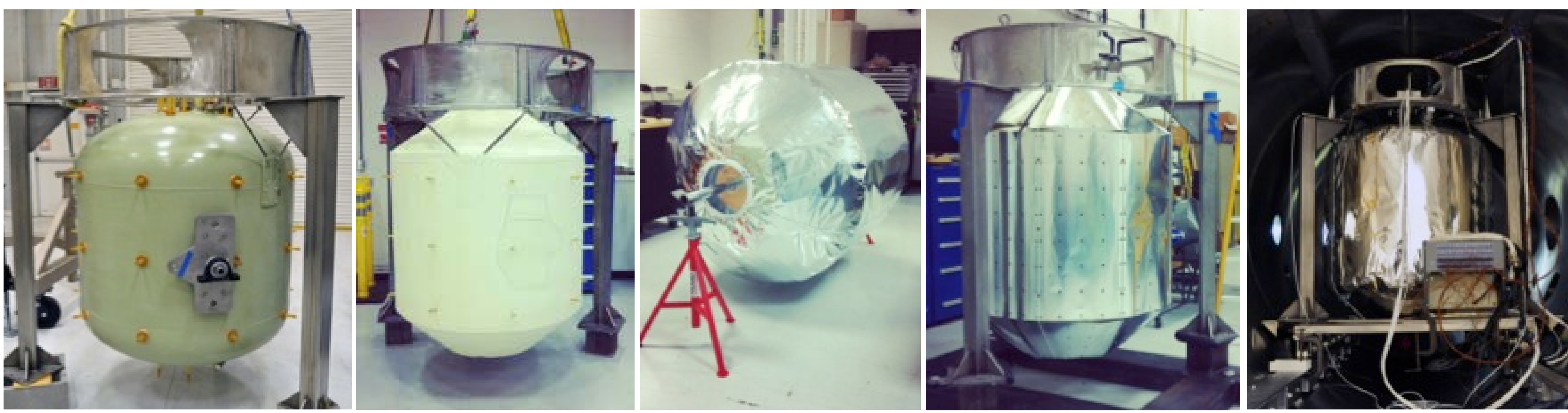




VATA 1a: tMLI/BAC Shield Thermal and Acoustic Test

- CPST Technology Maturation Program

- Objective: Assess the structural performance of a tMLI/BAC shield assembly subjected to launch acoustic loads.



42 Ultem standoffs | 0.5” – 4.5” SOFI | 30-layer, 8/cm inner tMLI | BAC shield | 30-layer, 20/cm outer MLI

VATA 1a Test Approach

- **Structural (acoustic) Test**
  - Worst-case structural load on MLI/BAC shield was desired to best evaluate structural integrity of system design. Falcon 9, Minotaur IV, Delta II and Antares (then called Taurus II) were the launch vehicles under consideration.
  - Acoustic testing was recommended by MSFC structures group for a tank-applied test for the following reasons:
    - An integrated MLI/BAC shield is relatively light weight and has a large surface area, indicating that an acoustic test will prompt a more significant response than a random-vibe test.
    - The MLI/BAC shield system responds directly to acoustic loads in contrast to smaller, heavier components that are subjected to a dynamic load that is the product of the response of the surface to which they are mounted.
- **Thermal (LN2) Test**
  - Vented Fill – top off to 95% at Steady-State
  - Steady State Heat Leak, ~95% full – BAC Shield NOT Operating
  - Steady State Heat Leak ~93% full – BAC Shield Operating at 160K +/- 10K
  - Drain Tank

The thermal test series was completed before and after the acoustic test to assess any performance degradation.

VATA 1a Evaluation Criteria

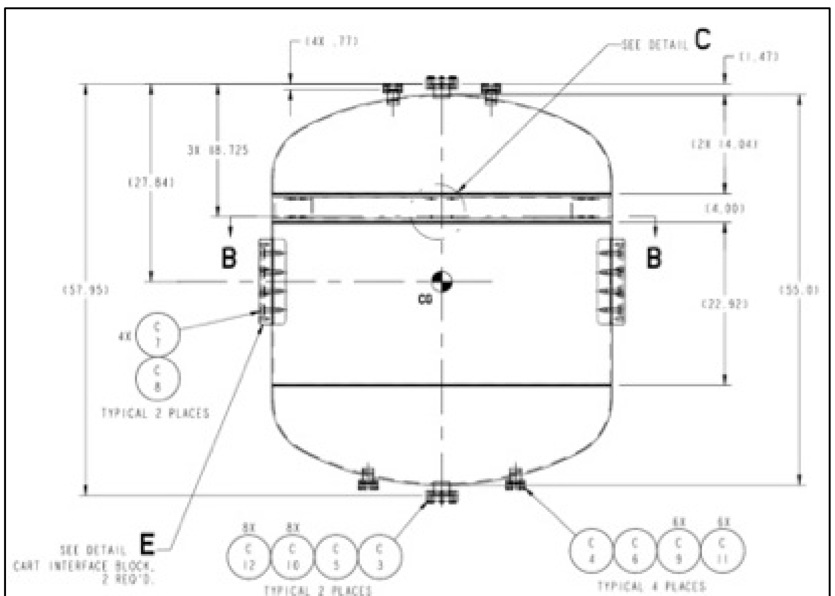
- Visual inspection of VATA exterior after acoustic test
- BAC shield leak check
  - Before and after the acoustic test
- Acoustic test data analysis
  - Verify required SPL requirements were met
  - Measure accelerations on key positions of test article
- Pre- and post-acoustic test LN2 thermal test data comparison
  - Determine if VATA exposure to the simulated launch acoustic load affects the thermal performance of the MLI/BAC shield system
- Visual inspection of VATA thermal protection system during disassembly after test completion
  - Determine if any element of the MLI/BAC shield system was physically damaged during the test process

VATA 1a Element Overview

- **Tank**: ASME Stainless Steel Pressure Vessel
  (4 ft dia, 4.6 ft high, 48.5 ft^3, 644 lbs, 66.5 ft^2, 3/16" wall thickness)
- **Tank Struts:** 6 Titanium tank support struts (~1" dia.)
- **SOFI**: Formed in faceted shape to accommodate LBMLI follow-on test, thickness ranges from 0.5" – 4.5"
- **Integrated MLI/BAC shield system:**
  - Inner tMLI blanket: 30-layer, 8 layer/cm
  - BAC shield
    - 0.25" tube bonded to 5 mil aluminum foil with Scotch-Weld 2216 epoxy
    - Chilled GN2 (~ 160K) circulated through tube loops to simulate active cooling
    - Supported off of tank by Ultem standoffs
  - Outer tMLI blanket: 30-layer, 20 layer/cm
- **Instrumentation**: Relied primarily on existing instrumentation in ESTF
  - Temperature (Silicon Diodes and Thermocouples)
  - Pressure (Pressure Transducers and Barometer)
  - Flow (Manifold of Turbine Flow Meters, in series)
  - Mass (Load Cells)

VATA Tank

- Rated pressure: 120 psid to -15 psid
- Diameter/Height: 48inches/55inches
- Wall thickness: 3/16 inches
- Surface area: 66.5 square feet
- Material: Stainless Steel
- Weight: 644 lbs empty
- ASME Section VIII Division I pressure vessel



VATA SOFI

- Material: Stepanfoam S-180 foam
- Shape: Faceted shape on domes to accommodate Load-Bearing MLI in VATA 2 testing.
- Thickness:
  - Minimum: ½-inch on barrel section
  - Maximum: 4.5-inches on bottom dome
- Tolerance: ¼-inch tolerance over the minimum OML specified in design
- Application Process:
  - Hand-spray
  - Sanded to shape using SOFI trimmer and hand sanding
  - Closeouts made using Utah Foam pour foam product.

VATA SOFI: MSFC TPS Development Facility

- $10M investment in the 4765 TPS Development Facility

- State-of-the art features/capabilities:
  - 30'x30'x85' Class I Div I* temperature and humidity controlled spray booth with associated HVAC equipment. Provides:
    - 20'x27'x70' hardware capability
    - Temperature limits of 65ºF to 130ºF and temperature dependent relative humidity ranges of 5% to 75%
    - Ability to spray both cryoinsulation and primer material systems (first time capabilities have been combined at MSFC)
  - 2-part foam dispense system along with a nitrogen drum pressurization capability
  - 9-axis robotic application system with tower and track
  - Data acquisition and remote viewing capability
  - Cold-storage coolers required for processing of HFC-245fa based materials

4765 Robot, Track, and Tower

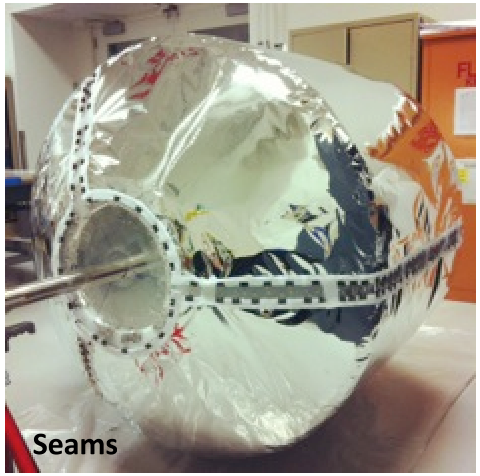
4765 Spray Booth

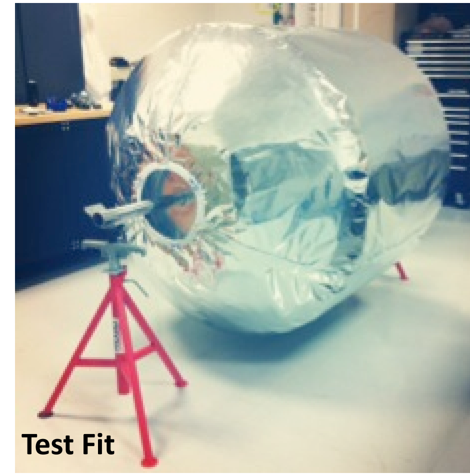
4765 Foam Dispense Unit

* Class I Div I rating allows use of flammable materials. Significantly increases cost of facility

VATA 1a tMLI

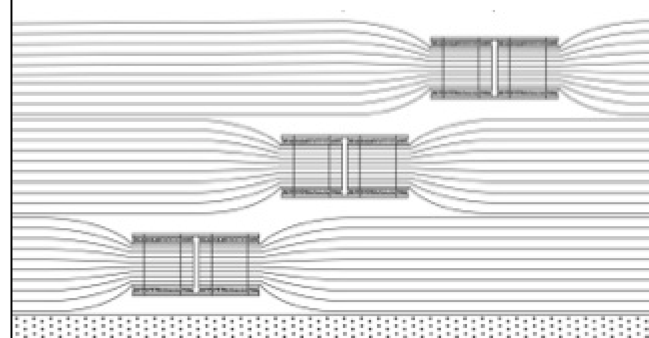
tMLI Assembly





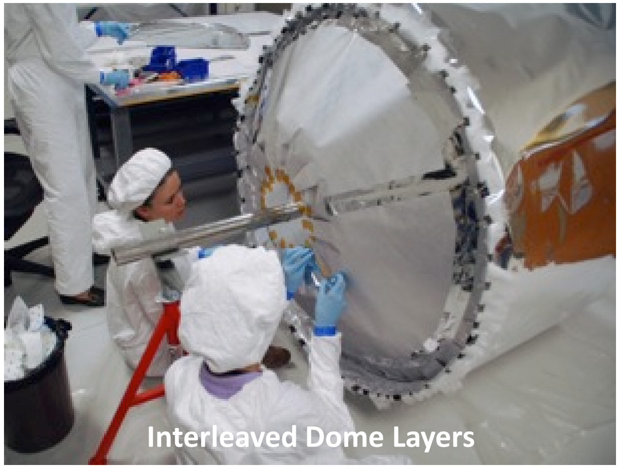
- Thermal Design
  - 30 layer, 8 layer/cm density tMLI blanket between SOFI and BAC shield
  - 30 layer, 20 layer/cm density tMLI blanket outside BAC shield
- Materials
  - ¼ mil Double Aluminized Mylar (DAM)
  - B4A Dacron netting spacers for surface area
  - B2A Dacron netting spacers for bumper strips
  - Nomex reinforced and 2-mil Kapton cover layers

- Seam Treatment
  - Velcro sewn on both sides of seam
  - Reflector patches on either side of seam

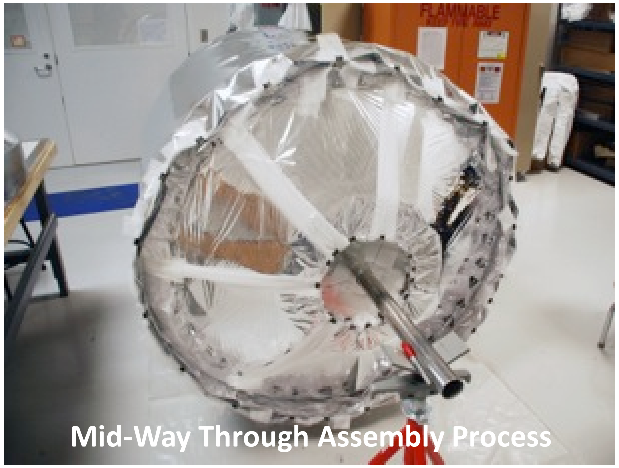


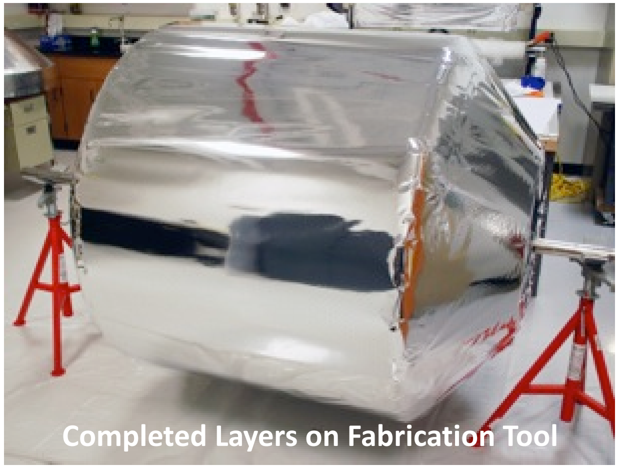
VATA 1a tMLI


Roll-Wrap Cylinder on Fabrication Tool


Interleaved Dome Layers


Dacron Netting Bumper Strips

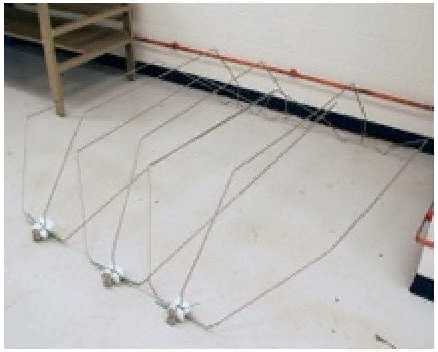

Mid-Way Through Assembly Process


Completed Layers on Fabrication Tool

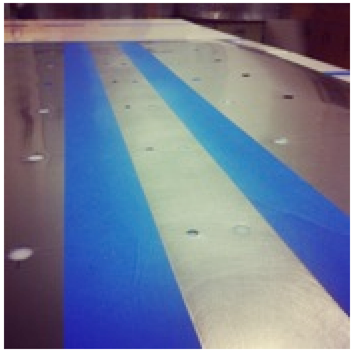

Velcro Seam Installation

VATA 1a BAC Shield

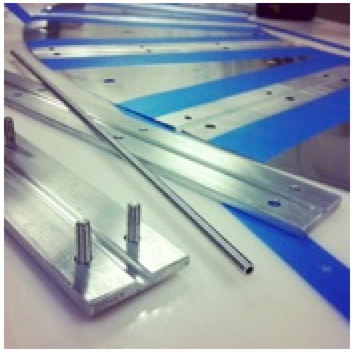
BAC Shield Assembly



Tube Bend/Cryo Shock/Leak Check



Foil Prep/Forming



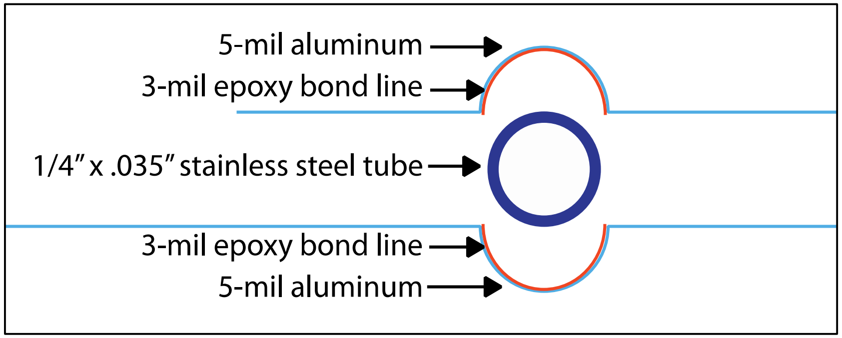
Tube-to-Shield Bonding Set Up

Epoxy Application

Velcro Installation

- ¼" x 0.035" wall stainless steel tube
- 5-mil aluminum foil
- Isothermal criteria: Less than 1-meter spacing between tubes (design of ~18" between tubes)

- Scotch-Weld 2216 epoxy was used to bond shield to tube



BAC Shield on VATA

VATA 1a Ultem Standoffs

- 42 Ultem standoffs were epoxied to the surface of the VATA tank to structurally support the BAC shield.
- 4 different standoffs were designed to support the shield on different locations on the tank.
- Standoff designs focused on minimizing conductive heat leak from the BAC shield to the tank.

VATA Ultem Standoff Spacing

BAC Standoff Spacing - Estimated Flight Level Stresses

$$\sigma_{Flight} \approx 22ksi = \frac{Mc}{I} = \frac{wl^2c}{12I}$$

$$w = 16g \cdot (0.0068\frac{lb}{in} + 0.0078\frac{lb}{in})$$

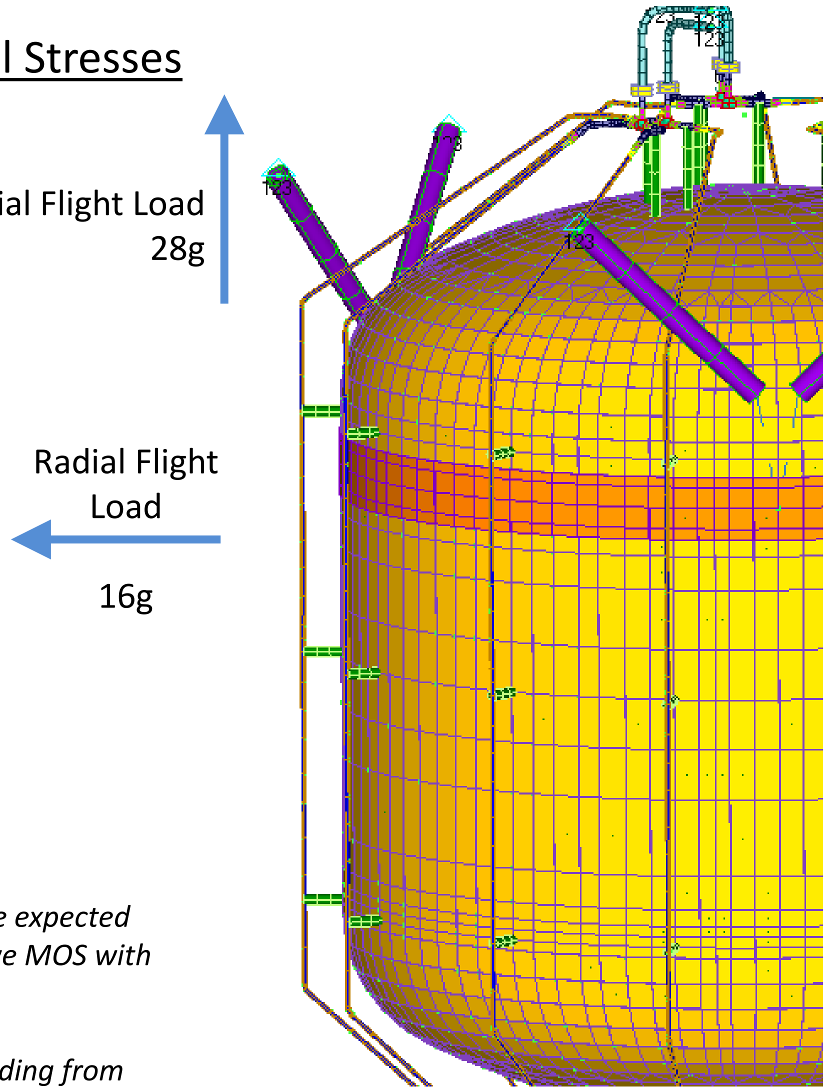
$$w = 16g \cdot (0.0146\frac{lb}{in}) = 0.23\frac{lb}{in}$$

$$\sigma_{Flight} \approx 22ksi \geq \frac{0.23\frac{lb}{in} \cdot (0.125in) \cdot l^2}{12(0.00014in^4)}$$

$$l_{Max} \approx 36in$$

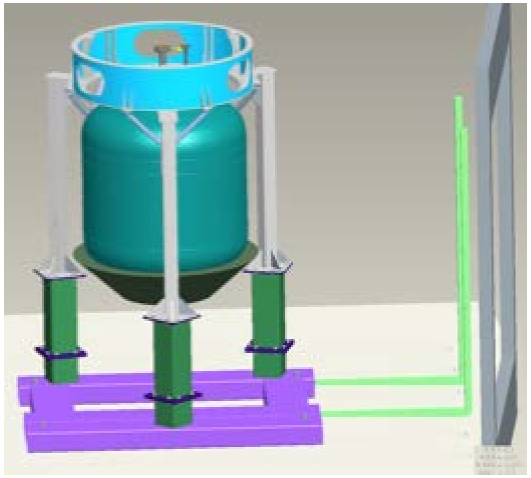
Maximum unsupported line length for the expected flight environment. Maintaining a positive MOS with a FS of 1.0 on yield.

This does not allow for additional line loading from MLI pressure differential.

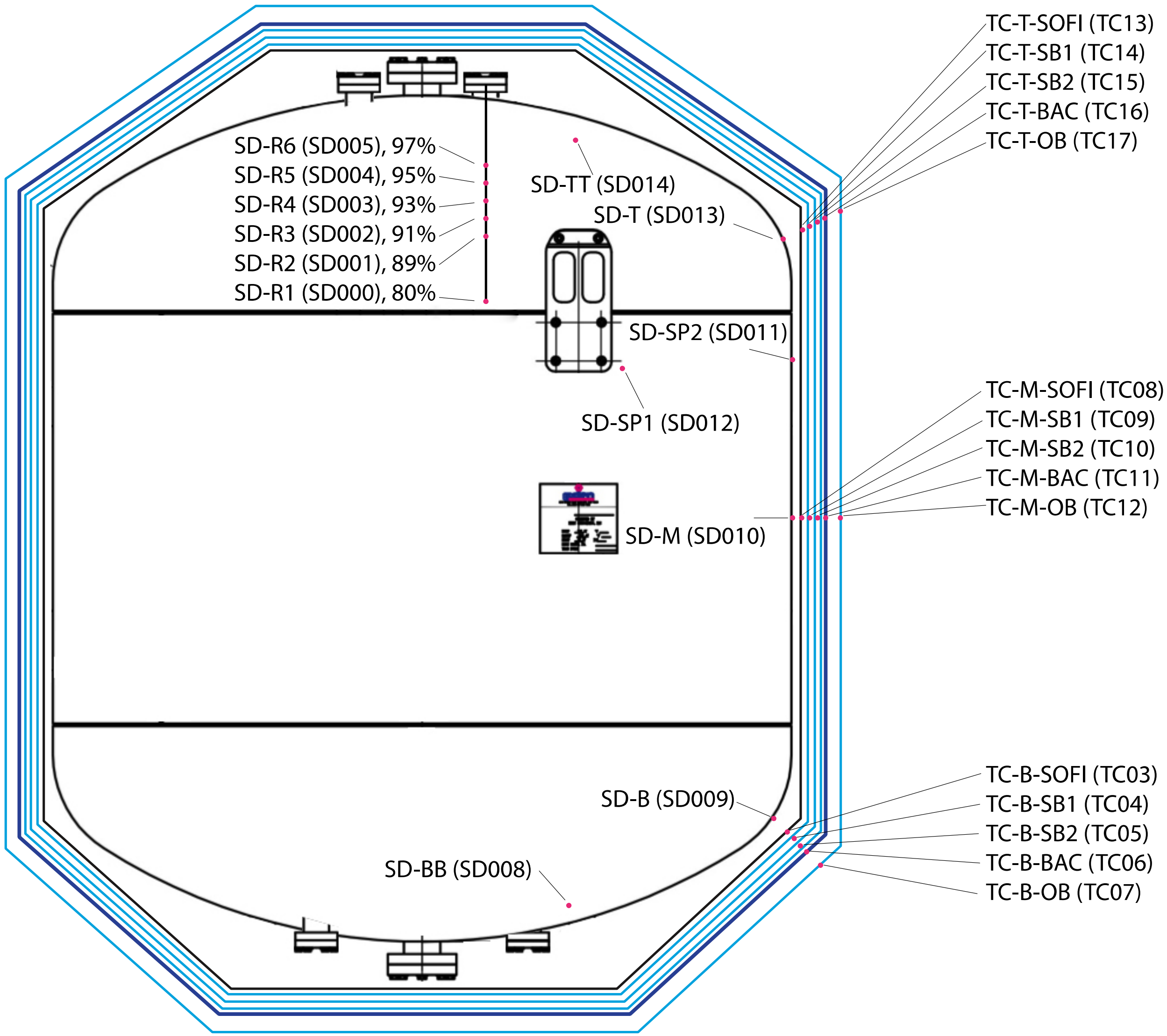


VATA Support Structure

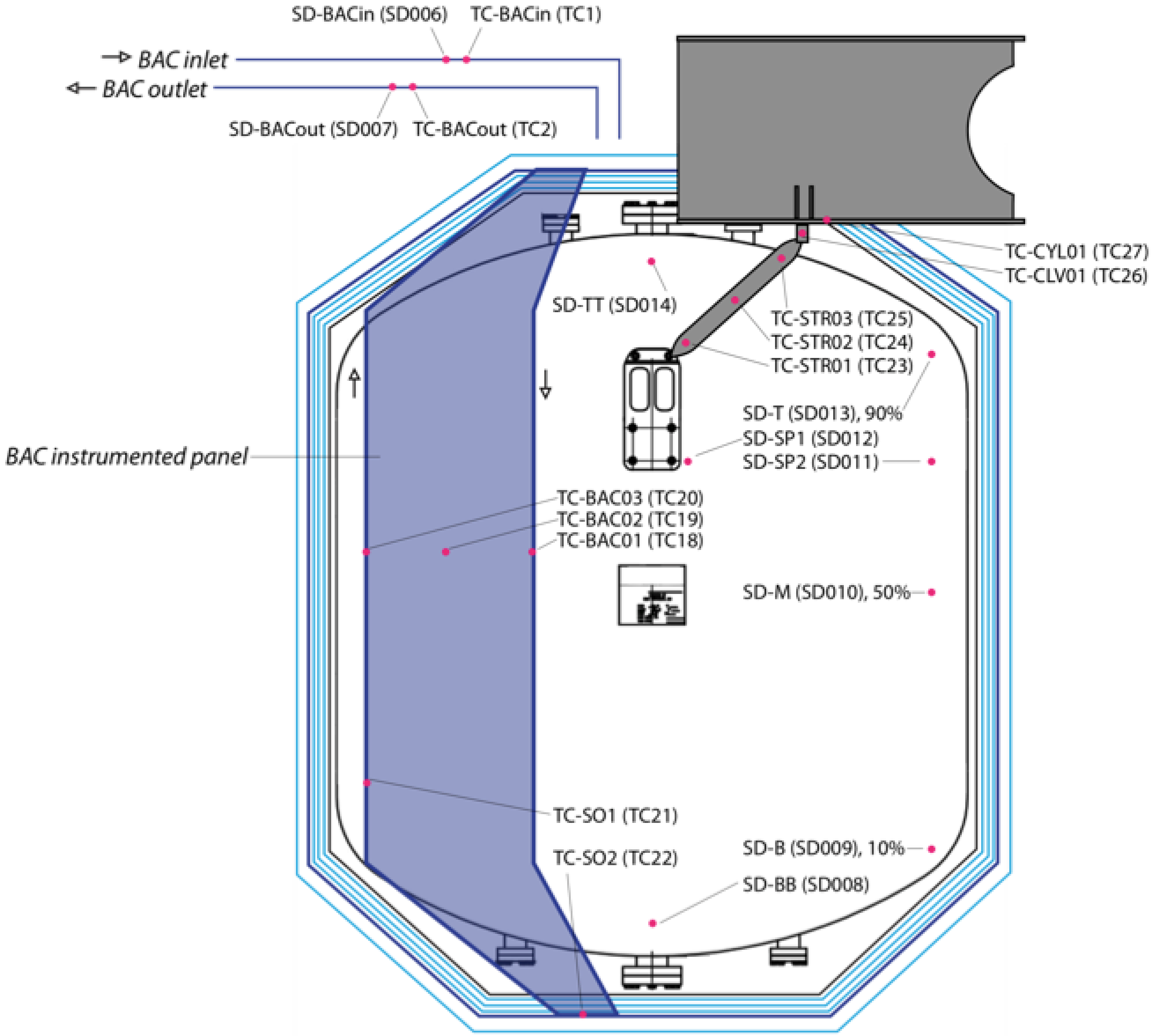
- VATA tank is suspended from 6 titanium struts.
- Struts interface with a cylinder identical to the one used for the GRC RBO tank.
- Three legs support the tank/strut/cylinder assembly off the ground.
- Trolley was designed and built to carry VATA in the ESTF vacuum chamber.
- Forklift fixture was design to transport VATA from PRDL/ESTF to the 4619 Acoustic Chamber.



VATA Thermal Instrumentation



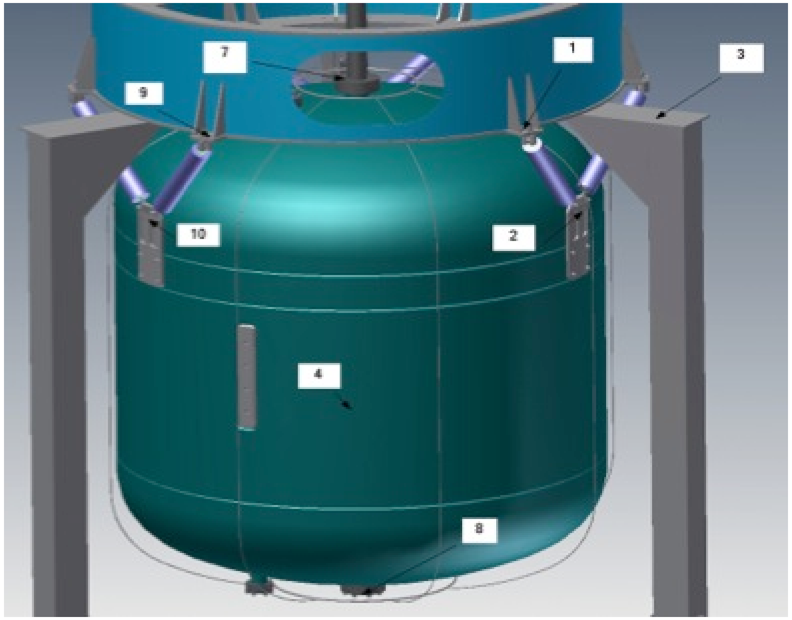
VATA Thermal Instrumentation

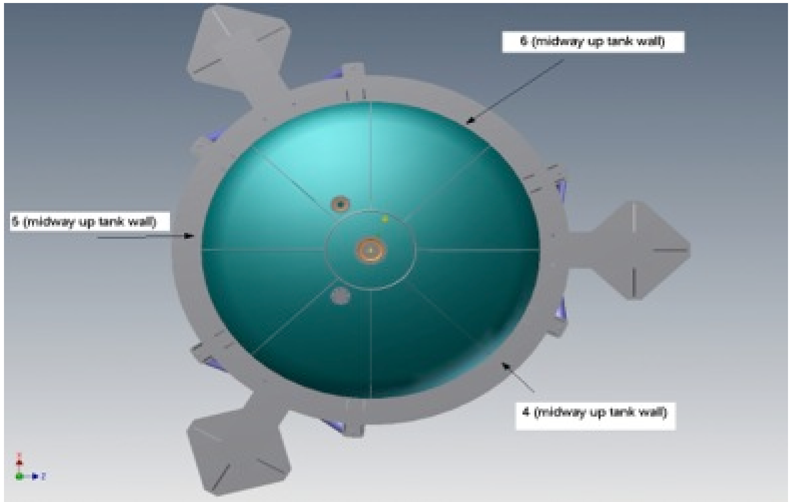


VATA Acoustic Instrumentation

Accelerometers:

- 01 – On gusset, near strut attach point
- 02 – On tank, near strut attach point
- 03 – On support column, top surface
- 04 – On tank surface, mid-barrel section
- 05 – Same as #4, clocked 120 degrees around tank
- 06 – Same as #4, clocked 240 degrees around tank
- 07 – On top of tank
- 08 – On bottom of tank
- 09 – On gusset, near strut attach point
- 10 – On tank, near strut attach point





VATA 1a Series Test Matrix Highlights

- **VATA 1a:** Traditional MLI, BAC shield and support standoffs
  - **Thermal Test 1**
    - Fill: completed 08/14/12
    - Passive Steady State (SS) Heat Leak: completed 08/19/12
    - Active SS Heat Leak: completed 08/29/12
  - **Acoustic Test**
    - Maximum Predicted CPST Payload Acoustic Environment: completed 09/06/12
  - **Thermal Test 2**
    - Fill: completed 09/12/12
    - Passive SS Heat Leak: completed 09/20/12
    - Active SS Heat Leak: completed 09/25/12

All tests completed on-time and within budget.

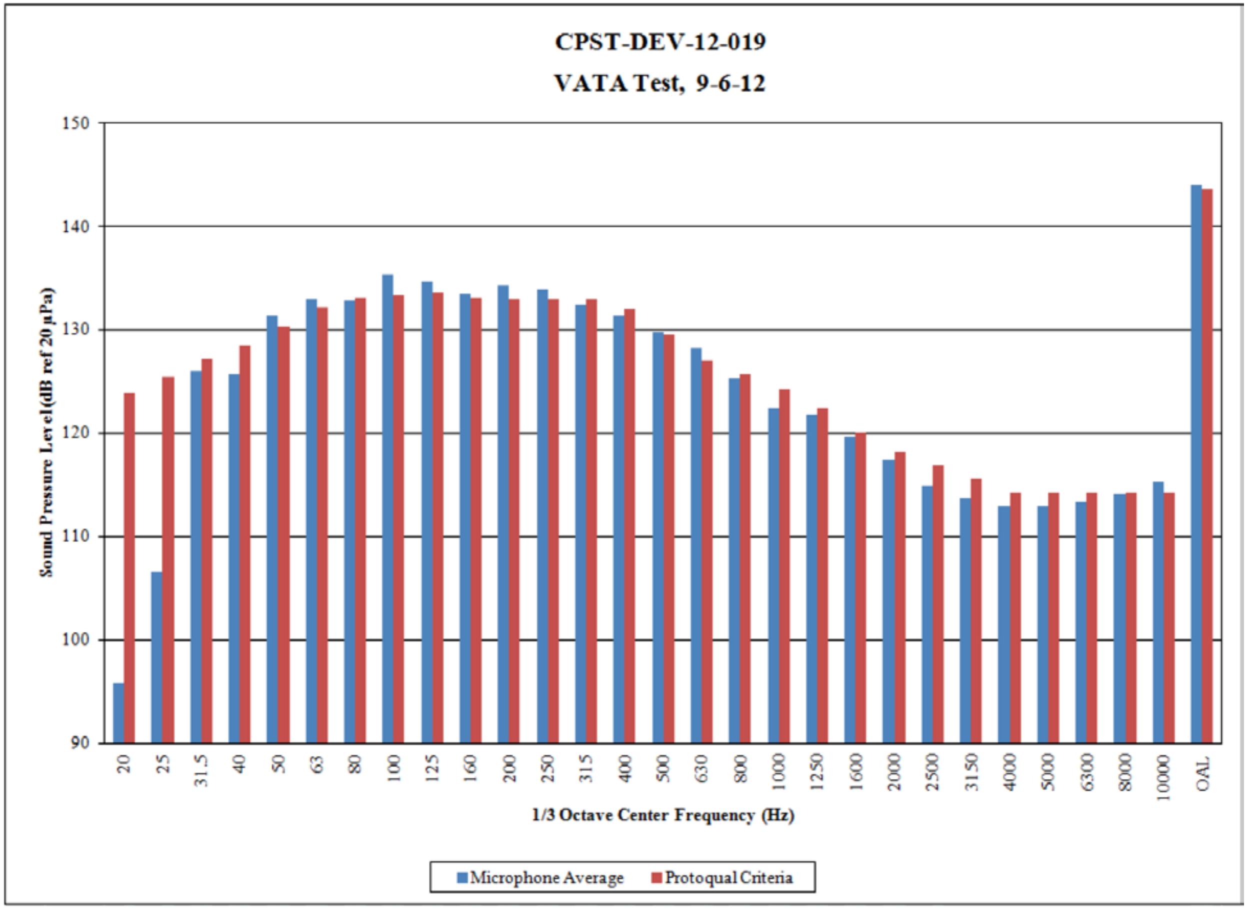
Results Summary: VATA 1a
Pre-Acoustic Thermal Test Data

HEAT LEAK TYPE	PRE-ACOUSTIC TEST PASSIVE DATA	PRE-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	10.67 W	6.84 W
All 6 Struts	1.041 W	1.068 W
Vent Line	0.009 W	0.012 W
Fill/Drain Line	0.018 W	0.018 W
BAC inlet	0.005 W	0.00009 W
BAC outlet	0.0004 W	0.0003 W
6 Bottom Standoffs	0.184 W	0.094 W
27 Side Standoffs	1.786 W	0.711 W
6 BAC inlet ullage standoffs	0.177 W	0.088 W
3 BAC outlet ullage standoffs	0.088 W	0.044 W
Silicon Diode Rake	1.283 W	1.273 W
Total Heat Leak from Penetrations	4.59 W	3.08 W
Total Heat Leak through MLI, Surface-Mounted Instr.	6.08 W	3.76 W
Heat Removed from BAC Shield	-	12.33 W

VC Pressure: 7.4E-07 Torr	**Warm Boundary: 290 K**	**Cold Boundary: 79 K**	**Fill Level: 95%-93%**

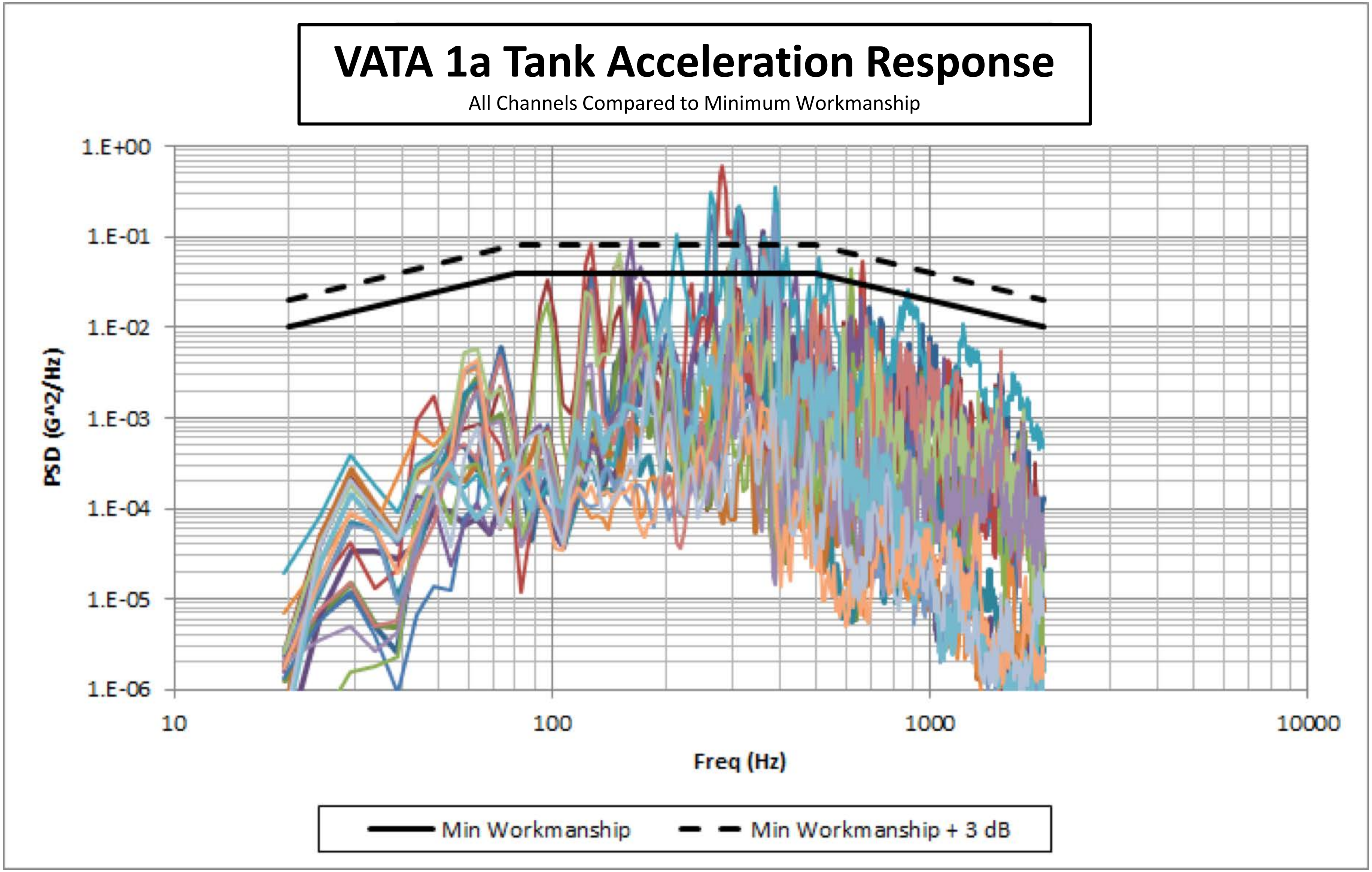
Results Summary: VATA 1a Acoustic Test Data

- Desired acoustic environment was successfully produced for test.
  - Based on NASA-STD-7001A and MLI-STD-1540
- Out-of-plane responses occurred between 1.28 and 4.81 GRMS.
- Overall highest response occurred on Accelerometer #05, positioned on the BAC shield standoff at the VATA tank equator.
- Acceleration levels and overall profiles recorded during testing were appropriate for the applied acoustic environment.



Accelerometer	GRMS
R1R	1.941
R1L	1.82
R1T	0.904
R2R	2.695
R2L	0.772
R2T	0.48
R3R	1.278
R3L	3.55
R3T	1.178
R4R	3.359
R5R	4.806
R7L	0.911
R8L	1.648
R9R	1.928
R9L	1.774
R9T	0.847
R10R	2.142
R10L	0.49
R10T	0.477

Results Summary: VATA 1a Acoustic Test Data



Results Summary: VATA 1a Post-Acoustic Thermal Test Data

HEAT LEAK TYPE	POST-ACOUSTIC TEST PASSIVE DATA	POST-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	**10.78 W**	**6.81 W**
All 6 Struts	1.020 W	1.053 W
Vent Line	0.008 W	0.011 W
Fill/Drain Line	0.018 W	0.018 W
BAC inlet	0.005 W	0.0001 W
BAC outlet	0.0005 W	0.0005 W
6 Bottom Standoffs	0.185 W	0.095 W
27 Side Standoffs	1.797 W	0.699 W
6 BAC inlet ullage standoffs	0.178 W	0.088 W
3 BAC outlet ullage standoffs	0.089 W	0.044 W
Silicon Diode Rake	1.348 W	1.337 W
Total Heat Leak from Penetrations	4.65 W	3.35 W
Total Heat Leak through MLI, Surface-Mounted Instr.	6.13 W	3.47 W
Heat Removed from BAC Shield	-	12.42 W

VC Pressure: 8.4E-07 Torr	**Warm Boundary: 290 K**	**Cold Boundary: 79 K**	**Fill Level: 95%-93%**

Results Summary: VATA 1a Passive Thermal Test Comparison

HEAT LEAK TYPE	PRE-ACOUSTIC TEST PASSIVE DATA	POST-ACOUSTIC TEST PASSIVE DATA
Total Heat Leak from Flow Meter Calculation	**10.67 W**	**10.78 W**
All 6 Struts	1.041 W	1.02 W
Vent Line	0.009 W	0.008 W
Fill/Drain Line	0.018 W	0.018 W
BAC inlet	0.005 W	0.005 W
BAC outlet	0.0004 W	0.0005 W
6 Bottom Standoffs	0.184 W	0.185 W
27 Side Standoffs	1.786 W	1.797 W
6 BAC inlet ullage standoffs	0.177 W	0.178 W
3 BAC outlet ullage standoffs	0.088 W	0.089 W
Silicon Diode Rake	1.283 W	1.348 W
Total Heat Leak through Penetrations	4.59 W	4.65 W
Total Heat Leak through MLI + Surf-Mounted Instr.	6.08 W	6.31 W

Results Summary: VATA 1a Active Thermal Test Comparison

HEAT LEAK TYPE	PRE-ACOUSTIC TEST ACTIVE DATA	POST-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	6.84 W	6.81 W
All 6 Struts	1.068 W	1.053 W
Vent Line	0.012 W	0.011 W
Fill/Drain Line	0.018 W	0.018 W
BAC inlet	0.00009 W	0.0001 W
BAC outlet	0.0003 W	0.0005 W
6 Bottom Standoffs	0.094 W	0.095 W
27 Side Standoffs	0.711 W	0.699 W
6 BAC inlet ullage standoffs	0.088 W	0.088 W
3 BAC outlet ullage standoffs	0.044 W	0.044 W
Silicon Diode Rake	1.273 W	1.337 W
Total Heat Leak from Penetrations	3.08 W	3.35 W
Total Heat Leak through MLI, Surface-Mounted Instr.	3.76 W	3.47 W
Heat Removed from BAC Shield	12.33 W	12.42 W

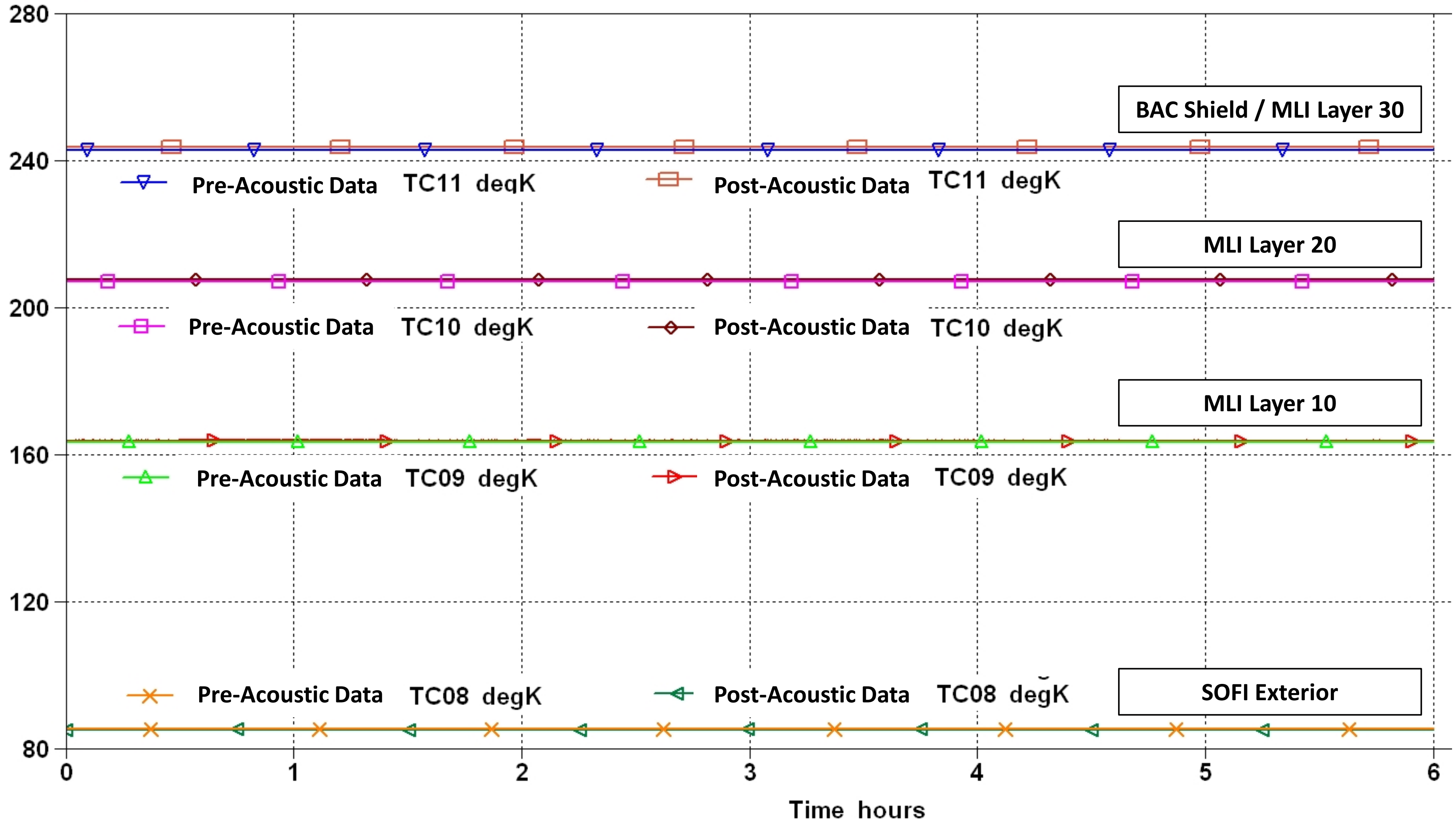
Results Summary: VATA 1a
Passive Thermal Test Fill Level Comparison

HEAT LEAK TYPE	90% Full	50% Full	25% Full
Total Heat Leak from Flow Meter Calculation	**10.67 W**	**9.64 W**	**9.46 W**
All 6 Struts	1.041 W	0.990 W	0.963 W
Vent Line	0.009 W	0.009 W	0.009 W
Fill/Drain Line	0.018 W	0.014 W	0.013 W
BAC inlet	0.005 W	0.0047 W	0.005 W
BAC outlet	0.0004 W	0.0004 W	0.0003 W
6 Bottom Standoffs	0.184 W	0.181 W	0.094 W
27 Side Standoffs	1.786 W	1.713 W	1.624 W
6 BAC inlet ullage standoffs	0.177 W	0.168 W	0.162 W
3 BAC outlet ullage standoffs	0.088 W	0.084 W	0.081 W
Silicon Diode Rake	1.283 W	1.285 W	1.245 W
Total Heat Leak from Penetrations	4.59 W	4.45 W	4.20 W
Total Heat Leak through MLI, Surface-Mounted Instr.	6.08 W	5.19 W	5.27 W

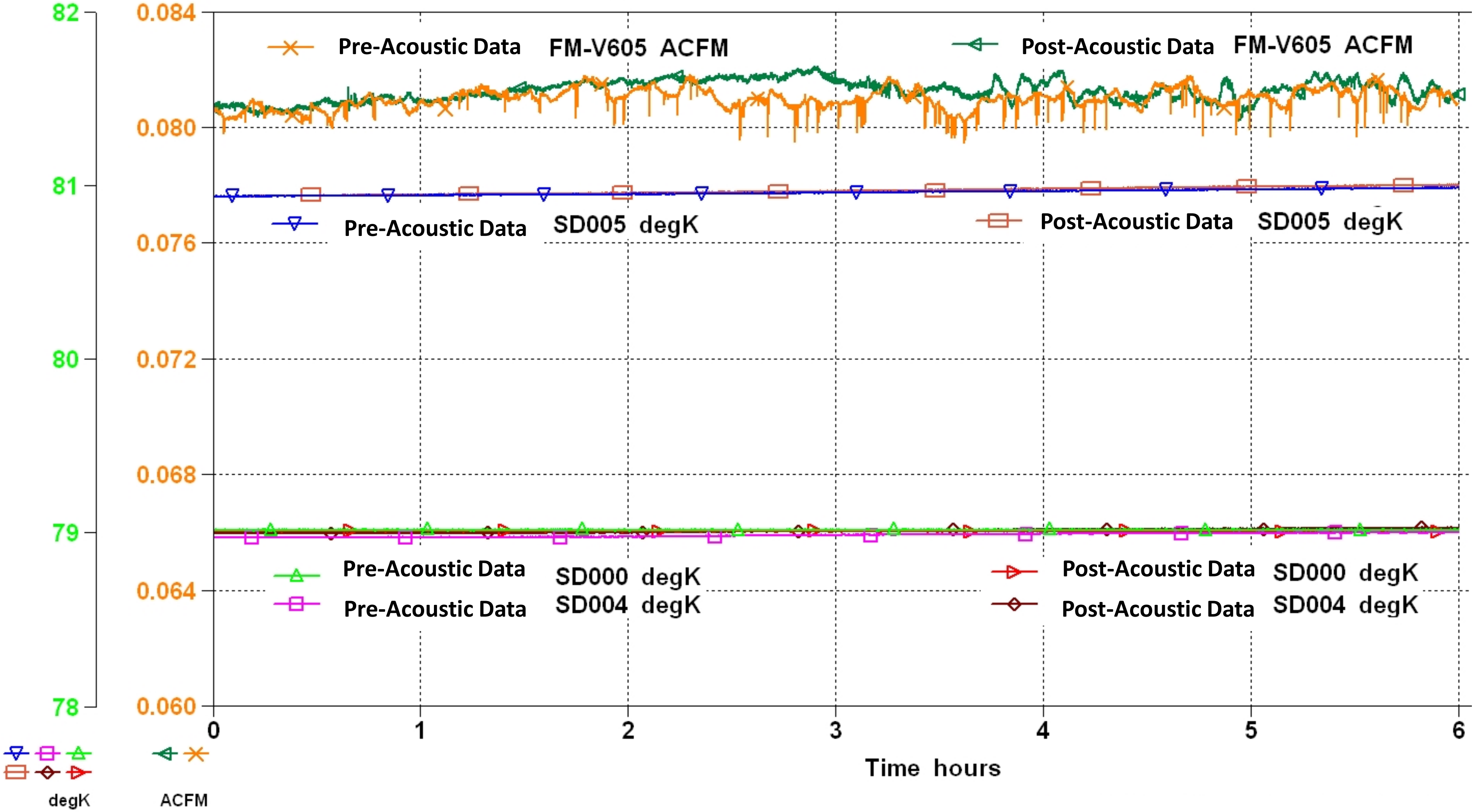
VC Pressure: 9.0E-07 Torr	**Warm Boundary: 290 K**	**Cold Boundary: 79.2 K**	**Fill Level: 90%, 50%, 25%**

*Only relevant to settled propellant and also a function of the tank material and wall thickness.

VATA 1a MLI Profile
Passive SS for Pre- and Post-Acoustic Thermal Tests

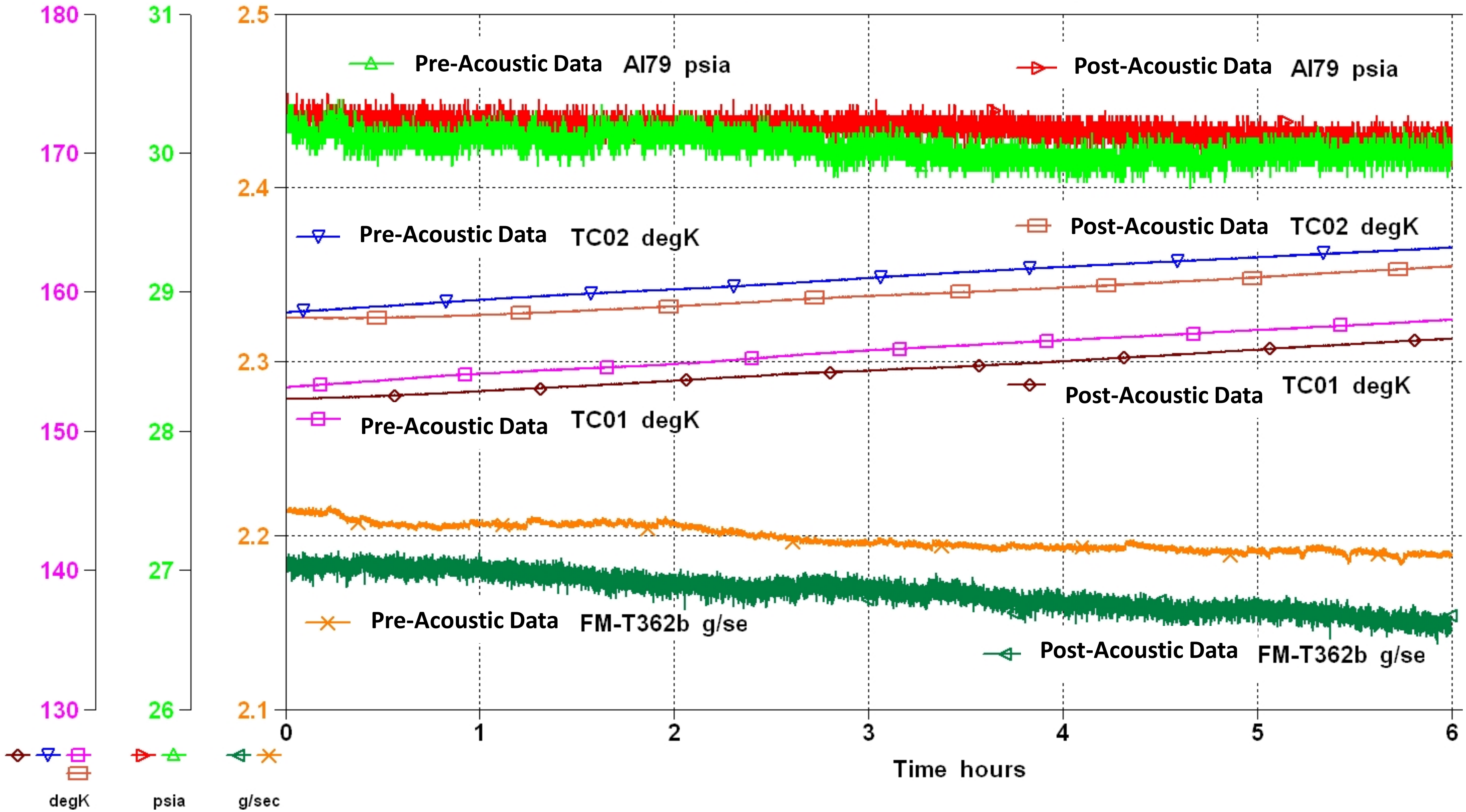


VATA 1a Boil-Off and Ullage Vapor Temperatures Passive SS for Pre- and Post-Acoustic Thermal Tests



Boil-off vapor production measured by flowmeter FM-V605 is identical between the Pre- and Post-Acoustic Thermal Tests. Ullage Vapor at 97% fill (SD005) and all liquid submerged temperature measurements are identical.

VATA 1a BAC Shield Operations
Active SS for Pre- and Post-Acoustic Thermal Tests



BAC Shield tube pressure (AI79), Temp in (TC01), Temp out (TC02), and mass flow rate (FM-T362b) are very close between the two thermal tests. Reliable and repeatable BAC shield operation is shown.

VATA 1a Thermal Test Summary

- **Pre- and Post-Acoustic Passive Thermal SS Tests compared:**
  - MLI temperature profiles essentially identical (Δ_{max} = 0.9K)
  - Boiloff flowmeter data essentially identical (Δ_{max} = 0.0003 ACFM)
  - Ullage stratification essentially identical (Δ_{max} = 0.01K)
  - Heat leak ~10.5 Watts
- **Pre- and Post-Acoustic Active Thermal SS Tests compared:**
  - BAC shield operations repeatable and reliable
  - MLI temperatures identical, cooler than for passive case (Δ_{max} = 1.7K)
  - Boil-off flow-meter data essentially identical (Δ_{max} = 0.0002 ACFM)
  - Ullage stratification nearly identical, 0.5 K shift is due to slightly different liquid level height between active thermal tests
  - Heat leak with BAC shield operating ~6.5 Watts
  - BAC shield draws ~12.5 Watts during operation
- **Thermal test series proves:**
  - Launch acoustic loads do not degrade thermal performance of MLI and BAC shield in current VATA1a configuration.
  - Thermal tests can be highly repeatable, even with test article removal and transport between two thermal tests.

VATA 1a Post-Test Visual Inspection

- VATA insulation system was disassembled after the conclusion of Thermal Test 2.
- Thorough visual examination and documentation occurred during disassembly process:
  - Outer MLI blanket: No damage.
  - BAC shield: Denting, as seen in the photos to the right. Causing of denting is unknown. Turbulence during transportation, vacuum chamber repressurization, and acoustic test loads are possible causes.
  - Inner MLI blanket: A few tears in the innermost blanket were observed. The inner blanket did not have a thick cover; tears were likely caused as a result of blanket handling.

VATA 1a Key Performance Parameters

- **Visual inspection of VATA exterior after acoustic test**
  - No damage or change was evident on the VATA exterior after the acoustic test. During the acoustic test, the only movement observed was a slight vibration of the outer MLI blanket.
- **BAC shield leak check**
  - Two BAC shield leak checks were conducted; no leaks were found:
    - Leak checker was attached to BAC tube loop, tube loop was evacuated, and helium was sprayed around exposed fittings.
    - VATA was installed in vacuum chamber, vacuum chamber was evacuated, BAC tube loop was filled with helium, and leak checker was attached to turbo pumps.
- **Acoustic test data analysis**
  - Test SPL consistent with test requirements
  - Accelerometer data reasonable for test
- **Pre- and post-acoustic test LN2 thermal test data comparison**
  - Thermal test matrix was successfully conducted before and repeated after the acoustic test
  - No difference in either passive or active tests was observed between the two test iterations
- **Visual inspection of VATA thermal protection system during disassembly**
  - Minor denting observed in BAC shield; did not require repair for VATA 2

There were no departures from the original VATA test plan.

VATA 1a Key Performance Parameters

KPP	Description	Performance Target Full Success	Performance Target Minimal Success	Measured
Survive acoustic load	Does shield survive acoustic load intact with no damage to tubing?	10% increase in boil off rate after acoustic test	20% increase in boil off rate after acoustic test	0% increase in boil off rate after acoustic test
Leak check	Does shield survive acoustic load intact with no damage to tubing	No leaks detected.	Leak detected. Visual inspection reveals location of leak.	No leaks detected
MLI robustness	Does MLI survive launch loads when near a BAC	Visual inspection reveals no damage to MLI due to BAC	Visual inspection reveals minimal damage to MLI due to BAC	Visual inspection revealed slight deformation to BAC shield; did not affect thermal or structural performance of integrated system

VATA 1a TRL Assessment

- **Passive Thermal Control:** (TRL 5)
  - Baseline: Foam/MLI, Low-conductivity tank support structure
  - S-glass and Titanium struts are acceptable options.
  - Options below TRL 5:
    - GHe purged MLI for ground hold
    - Carbon fiber struts have not been thoroughly tested at LH2 temperatures.
    - Load-Bearing MLI (LBMLI)
- **Active Thermal Control:** (TRL: BAC Shield 4 / Strut Cooling 7)
  - Distributed cooling of support structure: TRL 9
  - Turbo-Brayton Cryo-cooler: TRL 7
  - Baseline (prior to reformulation)
    - Turbo-Brayton Cryo-cooler with BAC
  - Options below TRL 5:
    - Distributed cooling w/ BAC shield: TRL 4 (different configurations were tested between the VATA and CBRS during Tech Maturation)
    - LBMLI

VATA 1a TRL Assessment – Active Thermal Control

Red	Red = Below TRL 3
Yellow	Yellow = TRL 3,4, & 5
Green	Green = TRL 6 and above
	White = Unknown
x	Exists
Y	Yes
N	No
?	Uncertain

Fluid: LH2

	Demonstration Unit			Environment								
	Breadboard	Prototype	Flight Qualified	Laboratory Environment	Relevant Environment	Space Environment	Operational Environment (Space/Launch)	Analytical Scalability	Manufacturing Scalability	T-DOG Recommended	Overall TRL	Rationale
2.3.1 Active Thermal Control											5	
2.3.1.1 Cryocooler											6	
2.3.1.1.1 20 K Turbo-Brayton Cryocooler (20 W)	x			x				Y	Y		4	Various components (turbo-alternator & compressor) developed by Creare under various contracts, but not integrated system
2.3.1.1.2. 90 K Turbo Brayton Cryocooler (20 W)		x			x			Y	Y	x	7	NICMOS cooler flown on Hubble Telescope with slightly less power
2.3.1.1.3. 90 K Pulse Tube Cryocooler (20 W)		x			x			Y	?		6	Raab, J., and Tward, E. "Northrop Grumman Aerospace Systems Cryocooler Overview", Cryogenics vol. 50, pg. 572-581 (2010)
2.3.1.1.4. 90 K Stirling Cryocooler (20 W)		x			x			Y	?		6	Launched on LCDM
2.3.1.2. Distributed Cooling											5	
2.3.1.2.1. Structure Cooling											9	
2.3.1.2.1.1. Thermal Straps			x				x	Y	Y	x	9	Flown on multiple missions
2.3.1.2.2 Broad Area Cooling (BAC)											5	
2.3.1.2.2.1. Tube on Shield											5	
2.3.1.2.2.1.1. Shield/Tubing Attachment	x				x			?	?	x	5	CPST-DOC-0065 CPST-DOC-0068
2.3.1.2.2.1.2. Standoffs	x			x				?	Y		4	VATA I & CBRS I were different
2.3.1.2.2.1.3. Load-Bearing MLI	x				x			Y	?	x	5	see passive thermal chart
2.3.1.2.2.1.4. Valving Manifolds		x			x			Y	Y	x	6	CPST-DOC-0065 CPST-DOC-0068
2.3.1.3. Radiator											9	
2.3.1.3.1. Heat Pipes			x				x	Y	Y	x	9	Flown on multiple missions

VATA 1b: tMLI Blanket Thermal Test

- MSFC/ER24 Initiated Test

- Objective: Evaluate the thermal performance of a tMLI-only configuration in order to determine the thermal degradation associated with the standoffs and BAC shield in VATA 1a.

- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

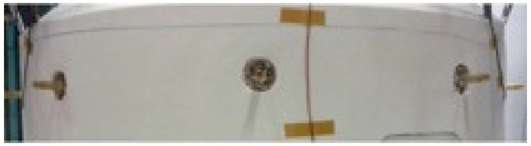
Standoffs Removed	SOFI Patched	30-layer, 8/cm inner tMLI	30-layer, 20/cm outer MLI

VATA 1b Configuration Change

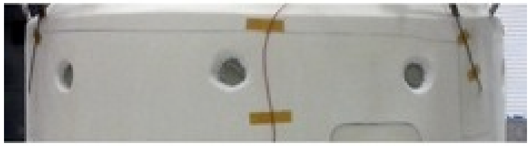
- Background: Determine MLI passive performance with no BAC shield, standoffs
- Configuration: 60 layers of traditional MLI, no BAC shield, no support standoffs
- Test: 93% full passive steady-state thermal test, completed

Standoffs on VATA tank

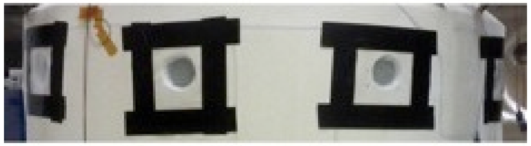
SOFI and standoff VATA 1a configuration



SOFI removed from standoff bases



Standoffs removed from VATA



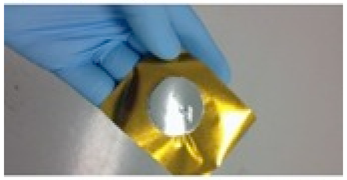
Standoff cavities masked for foam fill

Cavities filled and sanded for VATA 1b

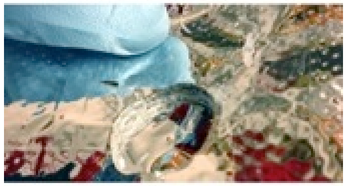
SOFI/Standoff Modifications

MLI plugs are made by punching through layers, connected with plastic tag

Plugs are secured to blanket with aluminized Kapton tape



MLI blanket holes are the same diameter as the plugs



MLI plug fits into the hole in the blanket

Aluminized Kapton tape secures the plug in place on both sides of the blanket

MLI Plugs

Results Summary: VATA 1b Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEAD-STATE DATA
Total Heat Leak from Flow Meter Calculation	**9.65 W**
All 6 Struts	0.996 W
Vent Line	0.01 W
Fill/Drain Line	0.018 W
Silicon Diode Rake	1.37 W
Total Heat Leak through Penetrations	2.39 W
Total Heat Leak through MLI + Surf-Mounted Instr.	7.26 W

VC Pressure: not recorded (likely in the E-07 Torr range)	**Warm Boundary: 291 K**	**Cold Boundary: 79 K**	**Fill Level: 95%**

VATA 1c: SOFI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the thermal performance of a SOFI-only configuration.
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at a Rapidly Reducing Fill Level Due to High Heat Load, Drain

SOFI-only

VATA 1c Test Results

HEAT LEAK TYPE	PASSIVE STEAD-STATE DATA
Total Heat Leak from Flow Meter Calculation	**327 W**
All 6 Struts	0.278 W
Vent Line	0.0004 W
Fill/Drain Line	0.009 W
Silicon Diode Rake	1.212 W
Total Heat Leak through Penetrations	1.50 W
Total Heat Leak through SOFI + Surf-Mounted Instr.	326 W

VC Pressure: 8.1E-6 Torr	**Warm Boundary: 281 K**	**Cold Boundary: 79 K**	**Fill Level: Rapidly Changing**

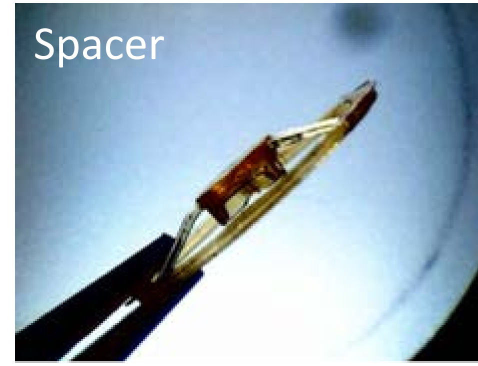
VATA 2a: LBMLI/BAC Shield Thermal and Acoustic Test

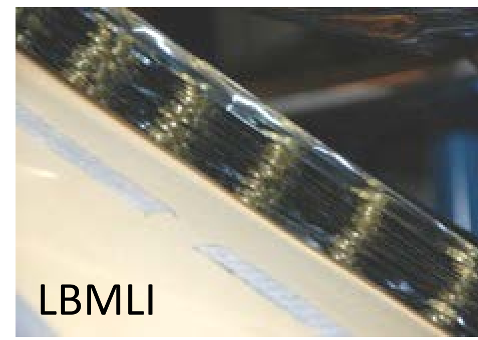
- Game Changing Technology with CPST cost share
- Objective: Assess the structural performance of an LBMLI/BAC shield assembly subjected to launch acoustic loads.

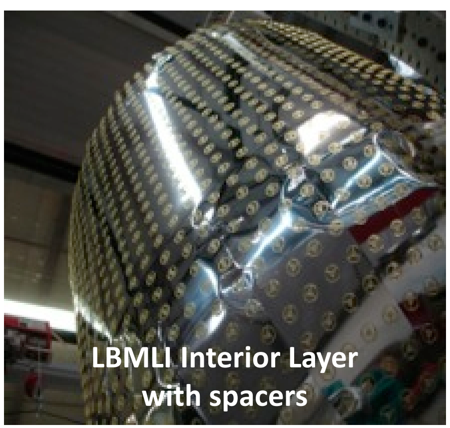
0.5" – 4.5" SOFI	19-layer, 5.5/cm inner LBMLI	BAC shield	30-layer, 20/cm outer MLI

VATA 2a Overview

- **Background:** Game Changing Development funded (w/CPST cost share) activity to evaluate Load-Bearing MLI (LBMLI), a proprietary Ball/Quest product.
- **Configuration**: 19 layers LBMLI, BAC shield with no support standoffs, 30 layers traditional MLI outside BAC shield
- **Test is a repeat of VATA 1a test matrix:**
  - Thermal Test 1: completed 01/24/13
    - Fill
    - Passive SS Heat Leak
    - Active SS Heat Leak
  - Acoustic Test: completed 03/14/13
  - Thermal Test 2: completed 04/06/13
    - Fill
    - Passive SS Heat Leak
    - Active SS Heat Leak







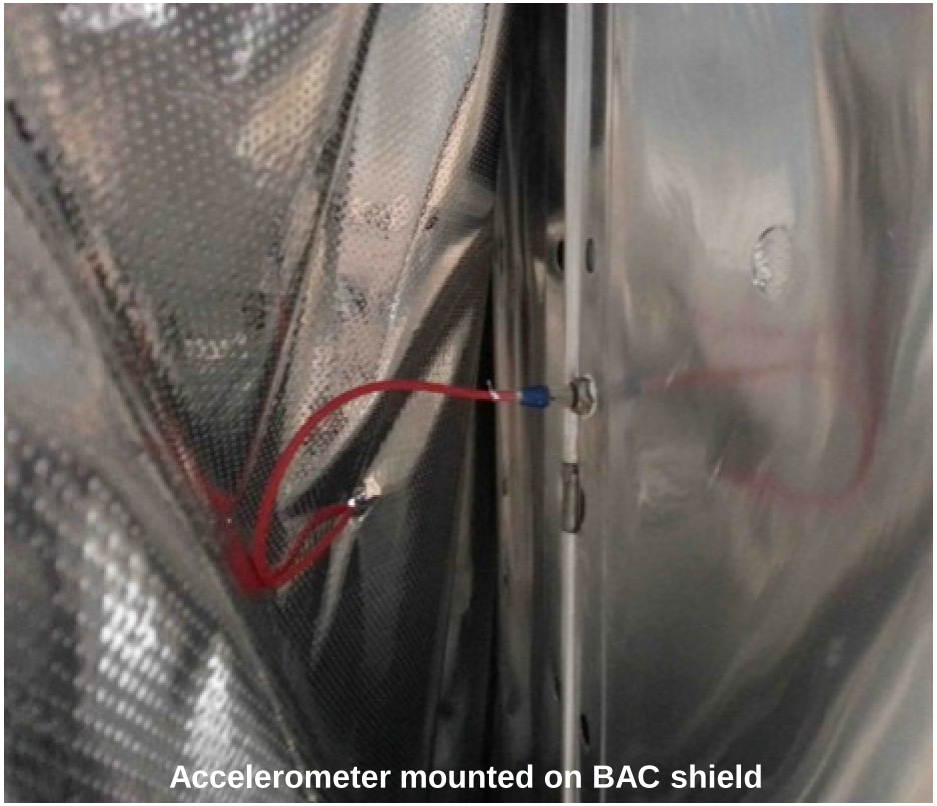
Results Summary: VATA 2a
Pre-Acoustic Thermal Test Results

HEAT LEAK TYPE	PRE-ACOUSTIC TEST PASSIVE DATA	PRE-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	7.44 W	4.53 W
All 6 Struts	1.002 W	1.074 W
Vent Line	0.335 W	0.437 W
Fill/Drain Line	0.023 W	0.022 W
BAC inlet	0.001 W	0.0001 W
BAC outlet	0.0002 W	0.0004 W
Silicon Diode Rake	1.413 W	1.397 W
Total Heat Leak from Penetrations	2.774 W	2.929 W
Total Heat Leak through MLI, Surface-Mounted Instr.	4.67 W	1.60 W
Heat Removed from BAC Shield	-	15.07 W

VC Pressure: 6.3E-07 Torr	**Warm Boundary: 292 K**	**Cold Boundary: 79 K**	**Fill Level: 95%-93%**

VATA 2a Acoustic Test Setup

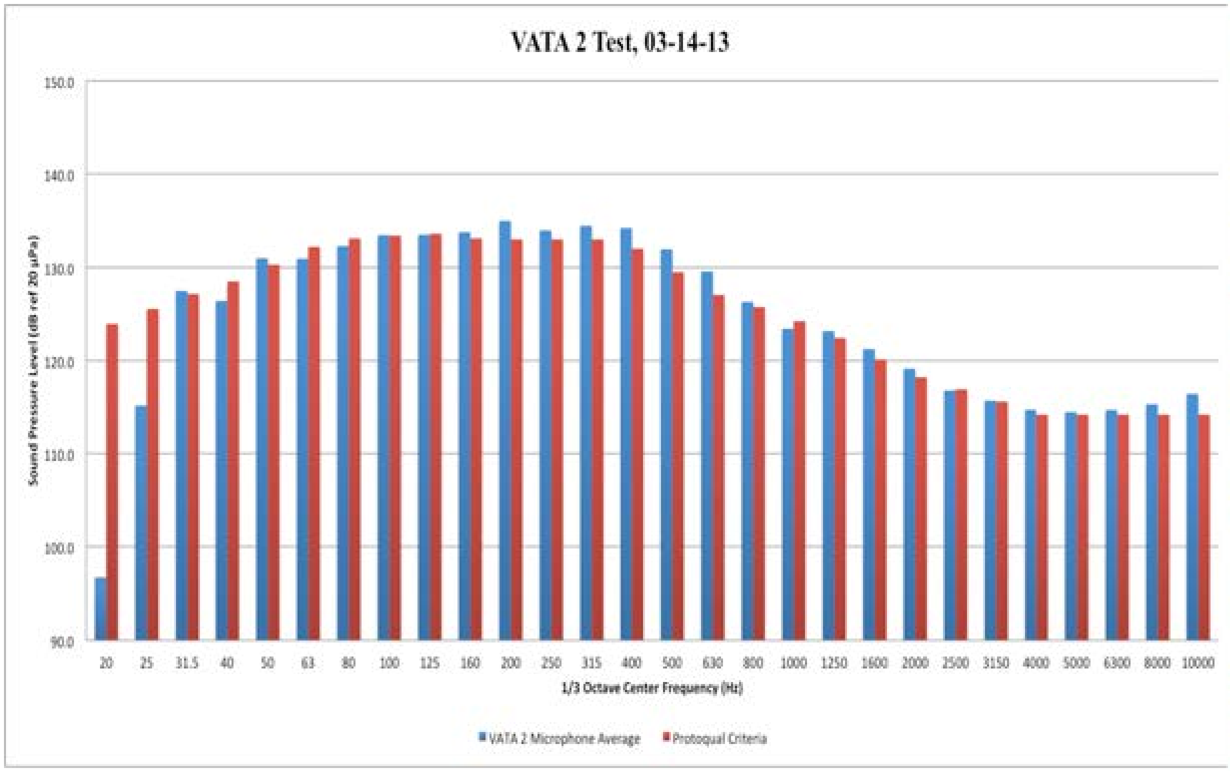
- Test Article transported from 4205 to 4619 to reverberating chamber for acoustic test.
- Test article was raised with extensions to be placed in the geometric center of acoustic chamber. Maximum acoustic power is at the room's center.
- All accelerometers in identical locations on tank except one. Accelerometer formerly on the Ultem Standoff midway along the tank is now mounted on the BAC shield in relative same location.



Accelerometer mounted on BAC shield

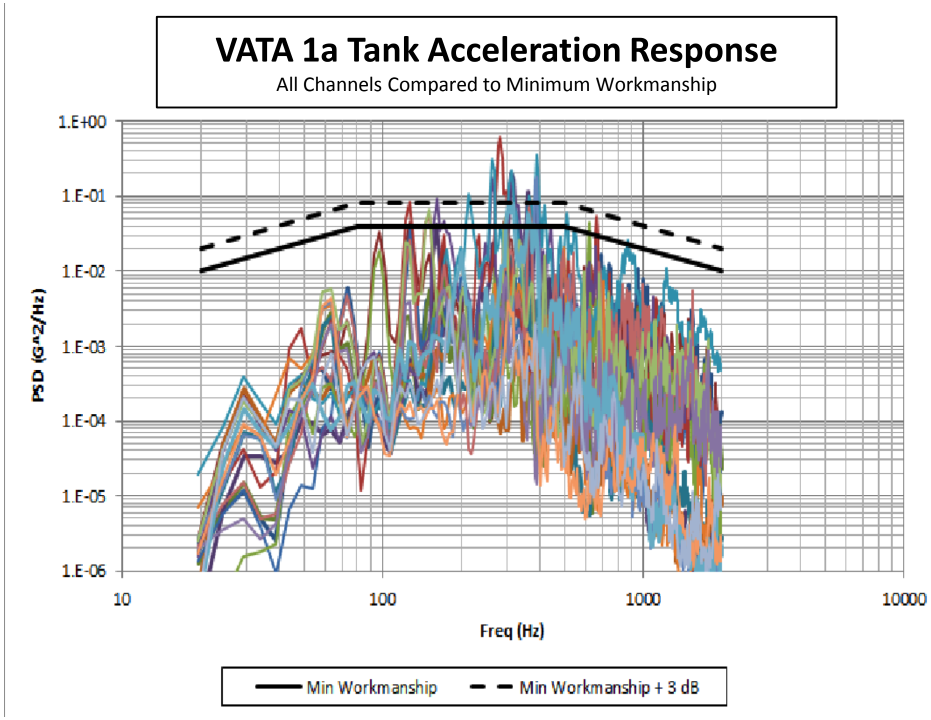
Results Summary: VATA 2a Acoustic Test Results

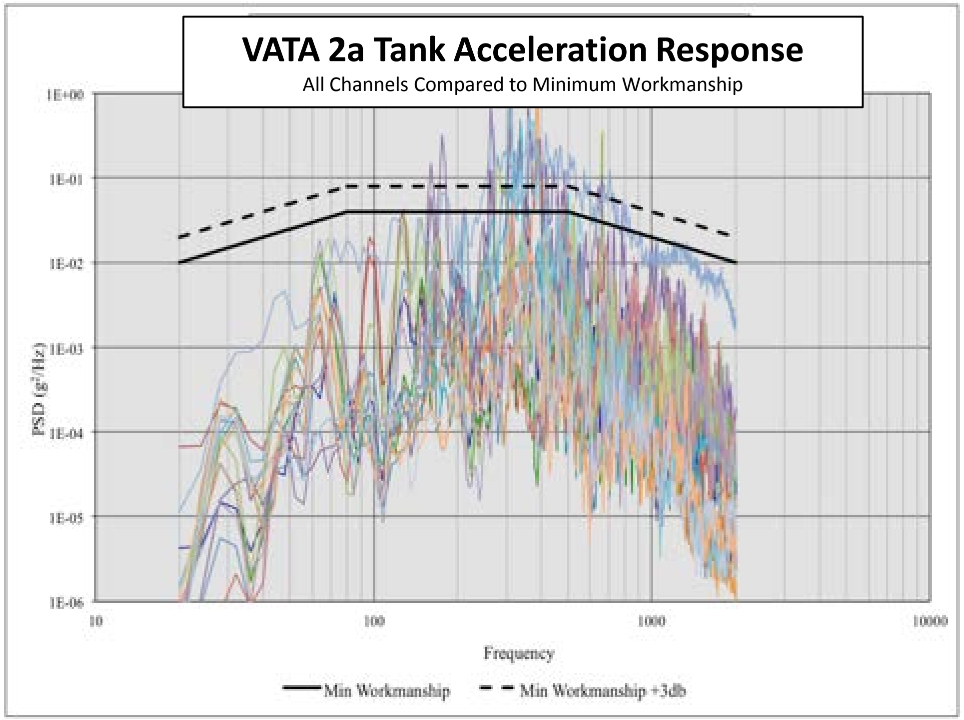
- Microphone data gives good relation with the Protoqual sound pressure level.
- Compared to VATA 1a microphone data, SPLs are higher at the upper frequency band (315-10,000 Hz).
- Acoustic inputs at low frequencies (below 50 Hz could not be generated due to size of reverberating chamber.



Frequency (Hz)	Vata 1 avg mics 1-3 (dB)	Vata 2 avg mics 1-3 (dB)	Difference (dB)
20	95.8	96.7	0.9
25	106.6	115.2	8.5
31.5	126.0	127.4	1.4
40	125.7	126.4	0.7
50	131.3	131.0	-0.4
63	132.9	130.9	-2.0
80	132.8	132.3	-0.5
100	135.3	133.5	-1.9
125	134.7	133.5	-1.2
160	133.5	133.8	0.3
200	134.2	135.0	0.7
250	133.8	134.0	0.1
315	132.5	134.5	2.0
400	131.4	134.2	2.8
500	129.8	131.9	2.2
630	128.2	129.6	1.4
800	125.3	126.2	0.9
1000	122.4	123.4	1.0
1250	121.7	123.1	1.4
1600	119.7	121.2	1.5
2000	117.4	119.1	1.8
2500	115.0	116.8	1.8
3150	113.7	115.7	2.0
4000	112.9	114.7	1.8
5000	112.9	114.5	1.6
6300	113.3	114.7	1.4
8000	114.1	115.3	1.2
10000	115.3	116.4	1.1

Results Summary: VATA 2a Acoustic Test Results

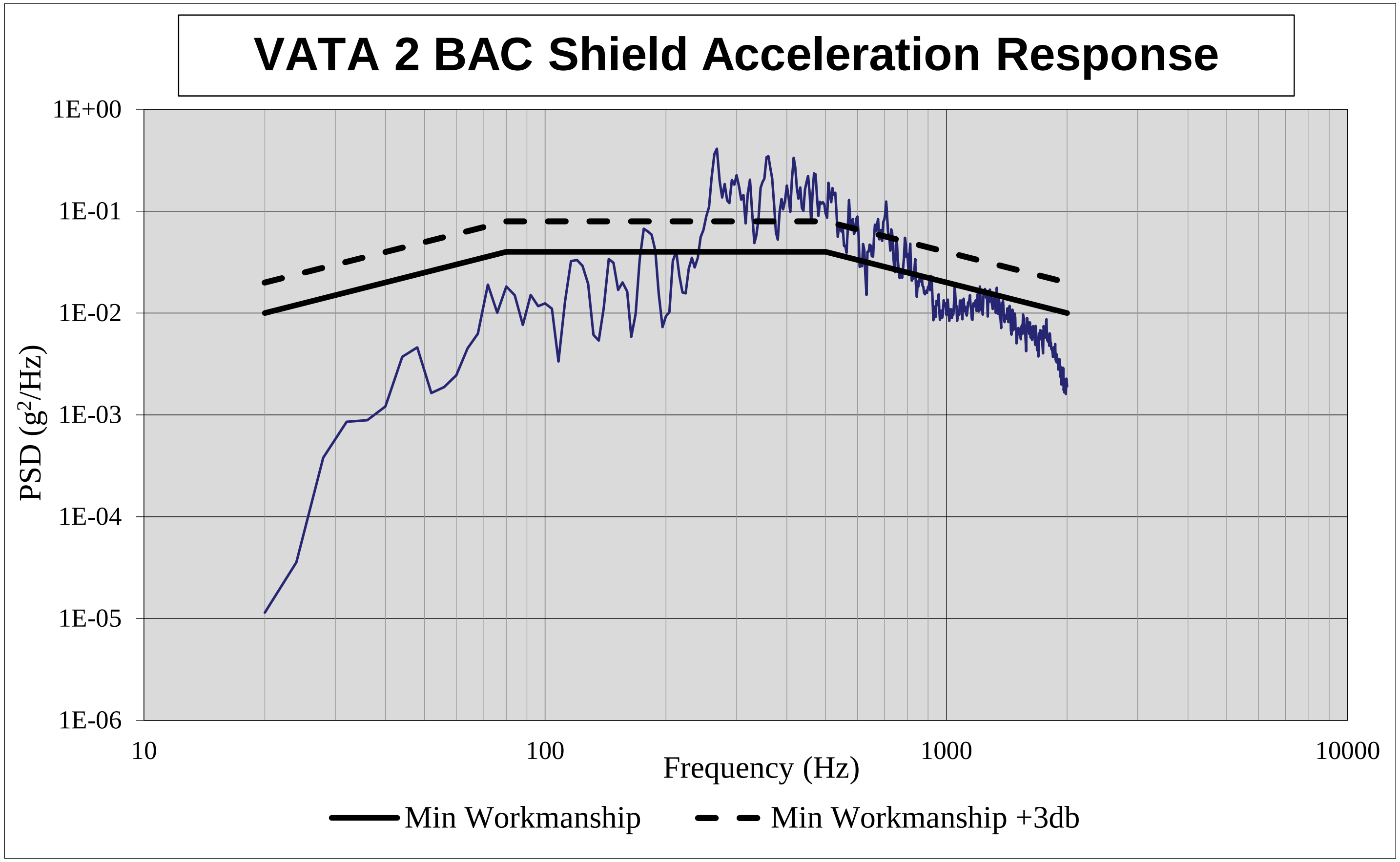




- Both tests show good relation with each other. Most accelerations fall below the min workmanship envelope with exception of BAC shield.
- Acoustic input could not be achieved at low frequencies for both cases (size of chamber).
- Sharp resonance peaks occur at the higher frequencies. Results typical of a lightly damped panel in acoustic environment.

Results Summary: VATA 2a Acoustic Test Results

VATA 2 Full Scale Tank Test	
Accelerometer	GRMS
R1R	1.498
R1L	1.551
R1T	0.867
R2R	4.709
R2L	1.31
R2T	0.728
R3R	1.24
R3L	1.089
R3T	2.982
R4R	6.407
R5R	3.041
R7L	3.061
R8L	8.697
R9R	2.051
R9L	1.576
R9T	0.991
R10R	5.22
R10L	1.046
R10T	0.769



- Results show highest GRMS at the BAC shield (8.7g). Highest VATA 1a GRMS was 4.8 at the standoff midway on tank equator.
- In general, VATA 2a acceleration responses show higher levels than VATA 1a test at the tank mounted accelerometers. A stiffer/heavier LBMLI blanket and slightly higher acoustic input at high frequencies a probable cause.

Results Summary: VATA 2a
Post-Acoustic Thermal Test Results

HEAT LEAK TYPE	POST-ACOUSTIC TEST PASSIVE DATA	POST-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	**7.50 W**	**4.50 W**
All 6 Struts	1.001 W	1.069 W
Vent Line	0.391 W	0.517 W
Fill/Drain Line	0.022 W	0.016 W
BAC inlet	0.0001 W	0.0001 W
BAC outlet	0.00007 W	0.0004 W
Silicon Diode Rake	1.414 W	1.408 W
Total Heat Leak from Penetrations	2.83 W	3.01 W
Total Heat Leak through MLI, Surface-Mounted Instr.	4.67 W	1.49 W
Heat Removed from BAC Shield	-	16.99 W

VC Pressure: 6.3E-07 Torr	**Warm Boundary: 291 K**	**Cold Boundary: 79 K**	**Fill Level: 95%-93%**

Results Summary: VATA 2a
Passive Thermal Test Results Comparison

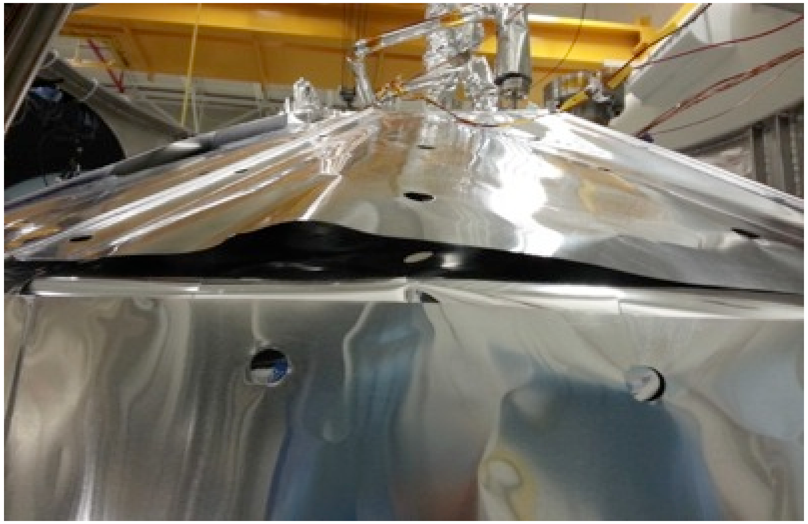
HEAT LEAK TYPE	PRE-ACOUSTIC TEST PASSIVE DATA	POST-ACOUSTIC TEST PASSIVE DATA
Total Heat Leak from Flow Meter Calculation	7.44 W	7.50 W
All 6 Struts	1.002 W	1.001 W
Vent Line	0.335 W	0.391 W
Fill/Drain Line	0.023 W	0.022 W
BAC inlet	0.001 W	0.0001 W
BAC outlet	0.0002 W	0.00007 W
Silicon Diode Rake	1.413 W	1.414 W
Total Heat Leak from Penetrations	2.77 W	2.828 W
Total Heat Leak through MLI, Surface-Mounted Instr.	4.67 W	4.67 W

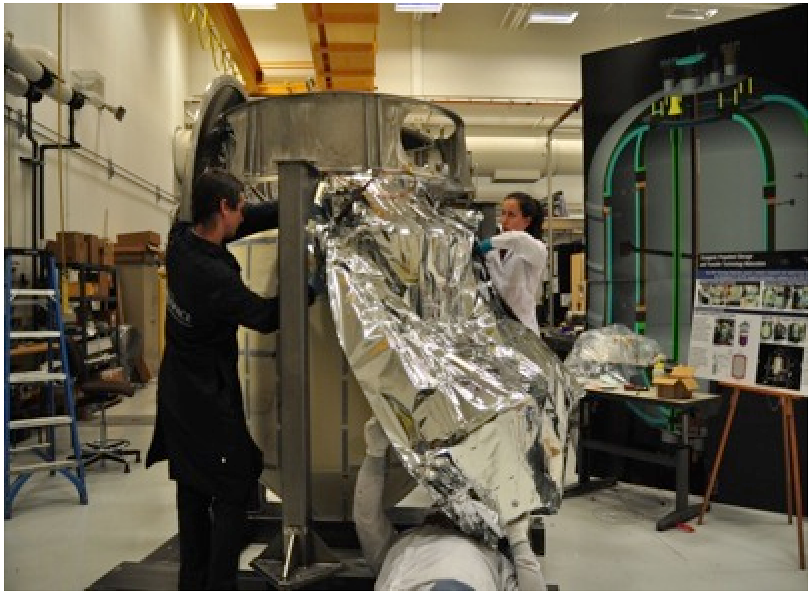
Results Summary: VATA 2a
Active Thermal Test Results Comparison

HEAT LEAK TYPE	PRE-ACOUSTIC TEST ACTIVE DATA	POST-ACOUSTIC TEST ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	4.53 W	4.50 W
All 6 Struts	1.074 W	1.069 W
Vent Line	0.437 W	0.517 W
Fill/Drain Line	0.022 W	0.016 W
BAC inlet	0.0001 W	0.0001 W
BAC outlet	0.0004 W	0.0004 W
Silicon Diode Rake	1.397 W	1.408 W
Total Heat Leak from Penetrations	**2.93 W**	**3.01 W**
Total Heat Leak through MLI, Surface-Mounted Instr.	1.60 W	1.49 W
Heat Removed from BAC Shield	15.07 W	16.99 W

Post-Test Visual Inspection

- Outer tMLI Blanket Removal
  - No severe physical damage to outer blanket
  - Normal "wear and tear" damage by handling of the blanket
- BAC Shield Removal
  - No severe visible damage of note
  - BAC shield shows bulging of aluminum shield between bonded tubes; this was noticed during installation of BAC shield onto LBMLI
  - Ultem standoffs of VATA 1a provided enough tension on the aluminum shield to eliminate this
- LBMLI Removal
  - LBMLI removed with aid from Ball Aerospace
  - An estimated ~50 Ultem tripod posts de-bonded from the blanket during disassembly (total of ~54,000 used for entire assembly of LBMLI)
  - LBMLI was able to maintain its original structural rigidity; blanket can be reused





VATA 2a Conclusions

- VATA 2a acoustic test shows the LBMLI/BAC system can survive the CPST MEFL +3db with no physical damage to structure.
- Post acoustic thermal test shows no thermal performance degradation of the LBMLI after experiencing an acoustic environment.
- Post acoustic thermal test also shows no thermal performance degradation in the BAC shield.
- Thermal test shows LBMLI does provide a reduction in heat leak through MLI into the tank compared to the VATA 1a tMLI (7.5 W compared to 11.9 W).
- Thermal test also shows a performance increase in the LBMLI/BAC system of VATA 2a compared to the traditional MLI/BAC of VATA 1a (4.5W compared to 6.8W).

VATA 2b: LBMLI and Vapor Cooled Shield Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a Vapor Cooled Shield integrated with an LBMLI and tMLI system.
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, “Active” Steady-State Test at 93% Fill Level (VCS operating), Drain

0.5” – 4.5” SOFI	19-layer, 5.5/cm inner LBMLI	Vapor Cooled Shield	30-layer, 20/cm outer MLI

VATA 2b Description and Configuration

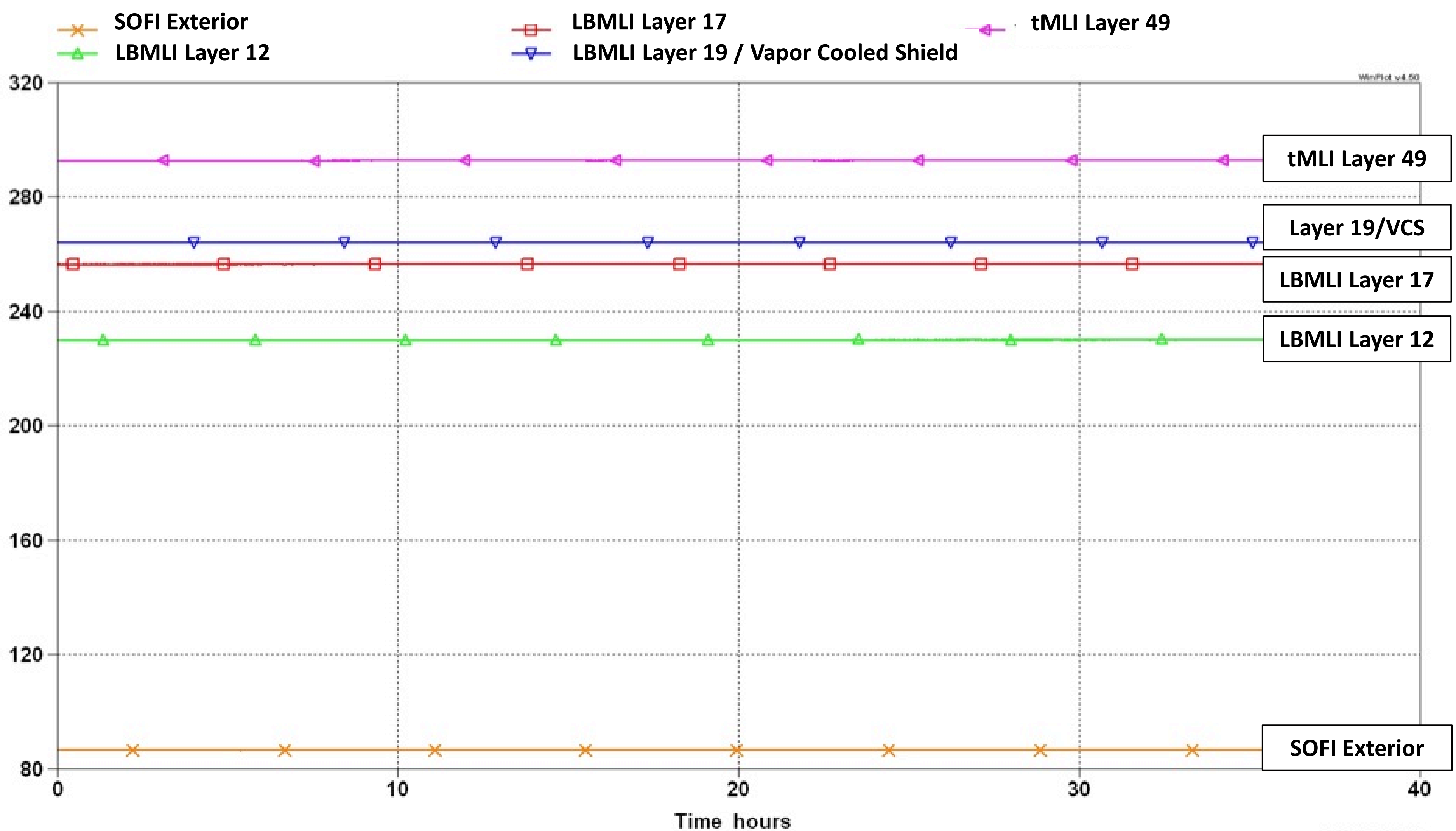
- Concept of a Vapor Cooled Shield is attractive for several reasons:
  - Uses available tank boil-off to decrease system heat leak
  - Does not require a cryo-cooler, saving weight and reducing power requirement
- Evaluation of a Vapor Cooled Shield was conducted with minimal impact to the existing VATA 2 configuration:
  - Tank boil-off vapor was used to cool the BAC shield
  - Boil-off was routed to the BAC shield inlet manifold from the tank vent
  - Vapor Cooled Shield outlet was routed to Back Pressure Control System to maintain a constant tank pressure
- Results Summary:
  - Reduced heat leak from 7.55 W to 7.26 W, a 3.8% improvement

Results Summary: VATA 2b Thermal Test Data

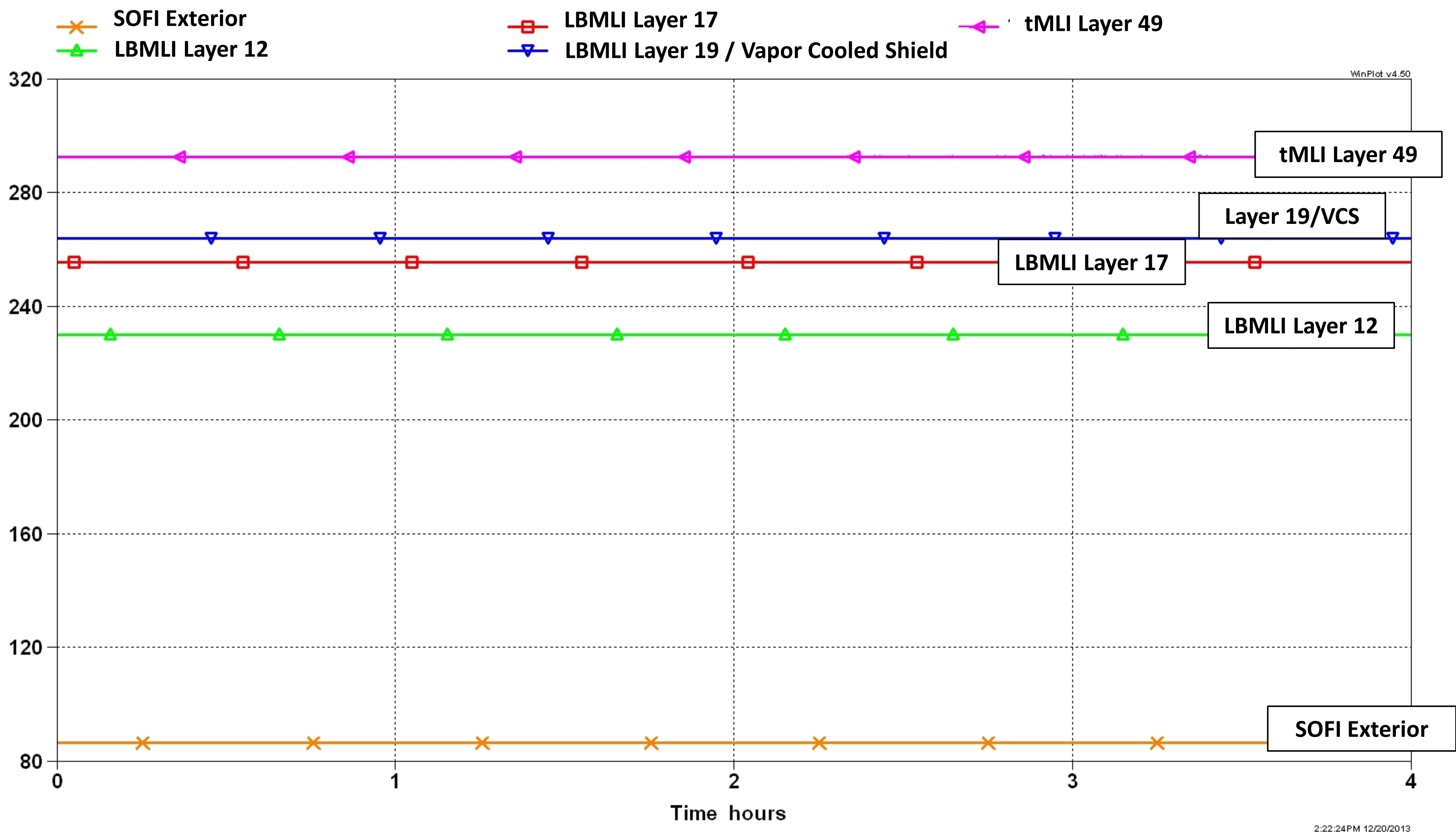
HEAT LEAK TYPE	PASSIVE DATA	ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	**7.55 W**	**7.26 W**
All 6 Struts	1.013 W	1.027 W
Vent Line	0.0093	0.202 W
Fill/Drain Line	0.018 W	0.018 W
BAC outlet	0.0007 W	0.0015 W
Silicon Diode Rake	1.401	1.396 W
Total Heat Leak from Penetrations	2.423 W	2.645 W
Total Heat Leak through MLI, Surface-Mounted Instr.	5.13 W	4.62 W
Power Absorbed by Boil-Off in Vapor Cooled Shield	-	3.71 W

VC Pressure: 6.4E-07 Torr	**Warm Boundary: 292 K**	**Cold Boundary: 79 K**	**Fill Level: 95%-93%**

Results Summary: VATA 2b Passive MLI Profile

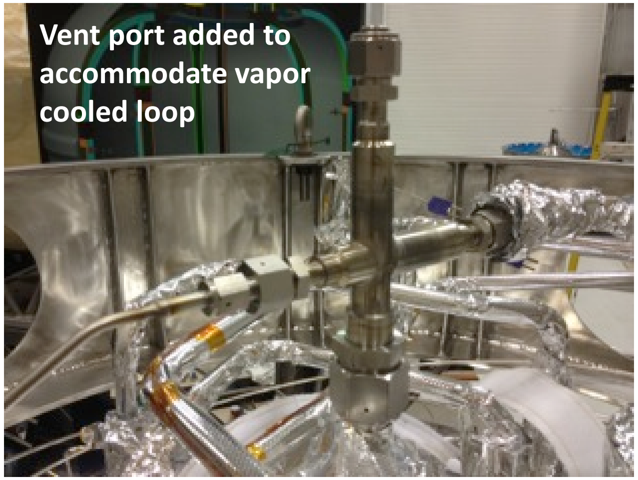


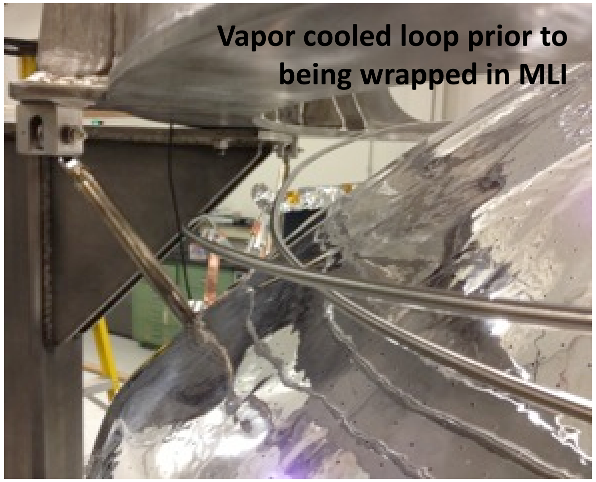
Results Summary: VATA 2b
Active MLI Profile



VATA 2c: LBMLI and Vapor Cooled Struts Thermal Test

- VATA Follow-On Testing
- Objective: Evaluate the performance of a Vapor Cooled Struts integrated with an LBMLI and tMLI system.
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, "Active" Steady-State Test at 93% Fill Level (vent through cooling loop), Drain





0.5" – 4.5" SOFI | 19-layer, 5.5/cm inner LBMLI | Vapor Cooled Struts | 30-layer, 20/cm outer MLI

VATA 2c Description and Configuration

- Penetrations account for a significant percentage of overall heat leak to tank, making active cooling of struts attractive
- Tank boil-off vapor was used to cool struts
- Strut Cooling Design:
  - ¼” tubing
  - Routed to each strut pair
  - Copper strap thermally connects cooling loop to strut
  - Apiezon N thermal grease between copper to tubing and copper to strut interfaces
- Results Summary:
  - Reduced boil-off from 7.91 W to 7.30 W , an 8% improvement

Results Summary: VATA 2c Thermal Test Data

HEAT LEAK TYPE	PASSIVE DATA	ACTIVE DATA
Total Heat Leak from Flow Meter Calculation	**7.92 W**	**7.30 W**
All 6 Struts	0.410 W	0.523 W
Vent Line	0.011 W	0.014 W
Fill/Drain Line	0.017 W	0.017 W
Silicon Diode Rake	1.43 W	1.44 W
Total Heat Leak from Penetrations	1.87 W	2.00 W
Total Heat Leak through MLI, Surface-Mounted Instr.	6.05 W	5.30 W

VC Pressure: 1.2E-06 Torr	**Warm Boundary: 292 K**	**Cold Boundary: 79 K**	**Fill Level: 96%-95%**

VATA 2d: LBMLI Thermal Test

- MSFC/ER24 Initiated Test
- <u>Objective</u>: Evaluate the performance of an LBMLI-only configuration (19 layers of LBMLI)
- <u>Test Matrix</u>: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

0.5" – 4.5" SOFI	19-layer, 5.5/cm inner LBMLI

VATA 2d Description and Configuration

- VATA 2d test was conducted to evaluate the thermal performance of a SOFI/LBMLI-only configuration

- Outer tMLI Removed
- BAC Shield Removed
- Velcro Taped Over

Results Summary: VATA 2d Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	8.3 W
All 6 Struts	1.00 W
Vent Line	0.010 W
Fill/Drain Line	0.016 W
Silicon Diode Rake	1.305 W
Total Heat Leak through Penetrations	2.33 W
Total Heat Leak through MLI + Surf-Mounted Instr.	5.97 W

VC Pressure: 7.1E-07 Torr	**Warm Boundary: 291 K**	**Cold Boundary: 79 K**	**Fill Level: 95%**

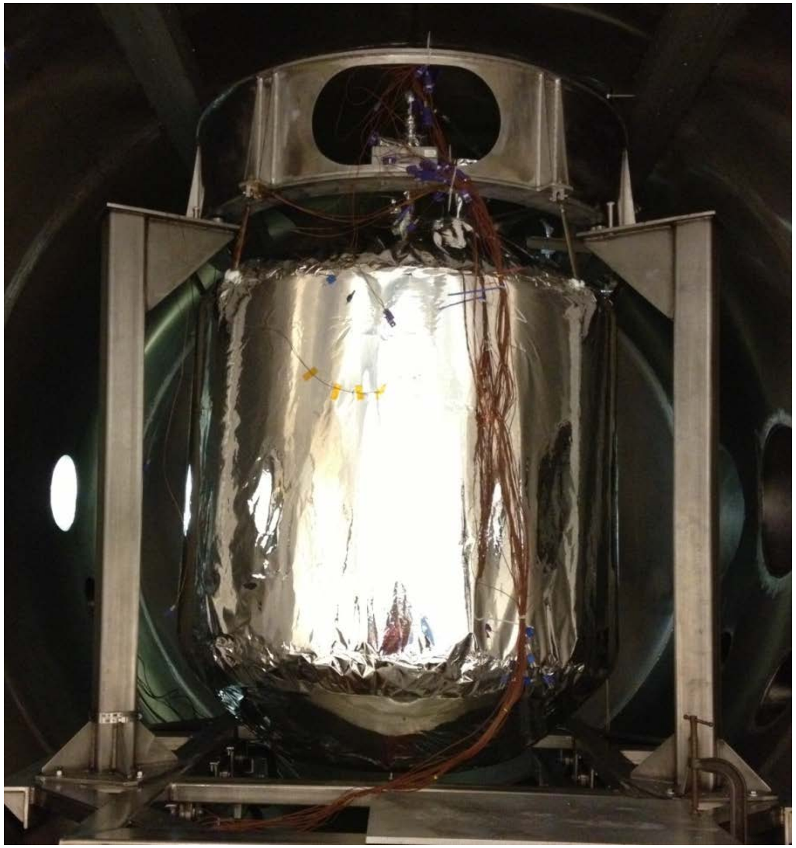
VATA 3a: tMLI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a tMLI configuration with matching layer count as VATA 2d (19 layers of tMLI)
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

0.5” – 4.5” SOFI | 19-layer, 14/cm inner tMLI

VATA 3a Description and Configuration

- VATA 3a test was conducted to evaluate the thermal performance of a SOFI/tMLI configuration with 19 layers
- Configuration Changes between VATA 2d and VATA 3a:
  - All 19 layers of LBMLI were removed from VATA
  - 19 layers of tMLI were installed
    - Materials
      - ¼ mil Double Aluminized Mylar (DAM)
      - 2, B4A Dacron netting spacers for surface area
      - 2-mil Kapton cover layers
    - Interleaved seams
      - DAM layers were overlapped and secured with tape at even intervals
      - B4A netting layers were sewed together at regular intervals to prevent DAM layers from touching near at the seams



Results Summary: VATA 3a Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	9.0 W
All 6 Struts	1.00 W
Vent Line	0.009 W
Fill/Drain Line	0.018 W
Silicon Diode Rake	1.35 W
Total Heat Leak through Penetrations	2.38 W
Total Heat Leak through MLI + Surf-Mounted Instr.	6.62 W

VC Pressure: 8.1E-07 Torr	**Warm Boundary: 291 K**	**Cold Boundary: 79 K**	**Fill Level: 95%**

VATA 3b: tMLI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a mass matched tMLI configuration with VATA 2d (42 layers of tMLI – 11.09 kg)
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

0.5" – 4.5" SOFI 42-layer, 14/cm inner tMLI

VATA 3b Description and Configuration

- VATA 3b test was conducted to evaluate the thermal performance of a SOFI/tMLI configuration with 42 layers (mass matching blanket)

- Configuration Changes between VATA 3a and VATA 3b:
  - Additional 23 layers of tMLI were installed to match mass of VATA 2d
    - Materials
      - ¼ mil Double Aluminized Mylar (DAM)
      - 2, B4A Dacron netting spacers for surface area
      - 2-mil Kapton cover layers
    - Interleaved seams
      - DAM layers were overlapped and secured with tape at even intervals
      - B4A netting layers were sewed together at regular intervals to prevent DAM layers from touching near at the seams

VATA 3b Testing Issues

- 08/05/2013: tank topped off per standard procedure.
- 08/06/2013: the cryo pumps shut down due to a building power outage.
- 08/11/2013: the 4205/108 air handler was shut off; the lab was hot and humid, causing the ESTF vacuum chamber wall temperature to reach 297K.
  - ESTF vacuum chamber wall temperatures for all VATA testing is maintained between 290K and 292K.
- 08/18/2013: there was an issue with the cryo pump chiller.

Results Summary: VATA 3b Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	7.3 W
All 6 Struts	1.03 W
Vent Line	0.012 W
Fill/Drain Line	0.017 W
Silicon Diode Rake	1.30 W
Total Heat Leak through Penetrations	2.36 W
Total Heat Leak through MLI + Surf-Mounted Instr.	4.94 W

VC Pressure: 5.6E-07 Torr	**Warm Boundary: 291 K**	**Cold Boundary: 79 K**	**Fill Level: 95%**

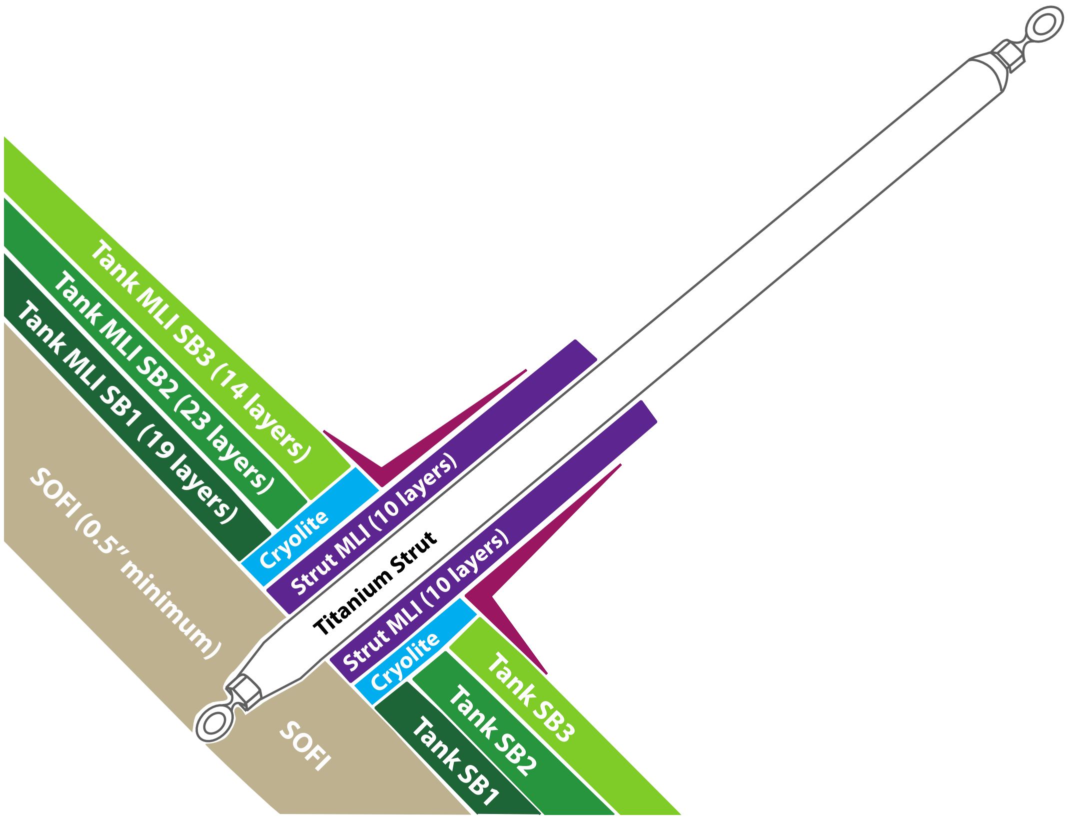
VATA 3c: tMLI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a volume matched tMLI configuration with VATA 2d (56 layers of tMLI)
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

0.5" – 4.5" SOFI	56-layer, 14/cm inner tMLI

VATA 3c Description and Configuration

- VATA 3c test was conducted to evaluate the thermal performance of a SOFI/tMLI configuration with 56 layers (volume matching blanket)
- Configuration Changes between VATA 3b and VATA 3c:
  - **Additional 14 layers of tMLI were installed to volume match VATA 2d:**
    - Materials
      - ¼ mil Double Aluminized Mylar (DAM)
      - 2, B4A Dacron netting spacers for surface area
      - 2-mil Kapton cover layers
    - Interleaved seams
      - DAM layers were overlapped and secured with tape at even intervals
      - B4A netting layers were sewed together at regular intervals to prevent DAM layers from touching near at the seams



- **Strut insulation and instrumentation:**
  - Two thermocouples were added to each of the four struts that were not previously instrumented.
  - Struts were insulated with 10 layers of roll-wrapped MLI. This insulation extended four-inches up from the tank MLI outer surface. This MLI covers the thermocouples described in the previous bullet.

Results Summary: VATA 3c Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	6.9 W
All 6 Struts	0.77 W
Vent Line	0.01 W
Fill/Drain Line	0.018 W
Silicon Diode Rake	1.26 W
Total Heat Leak through Penetrations	2.05 W
Total Heat Leak through MLI + Surf-Mounted Instr.	4.8 W

VC Pressure: 7.9E-07 Torr	**Warm Boundary: 293 K**	**Cold Boundary: 79 K**	**Fill Level: 94%**

VATA 3d: tMLI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a volume matched tMLI configuration with VATA 2d (56 layers of tMLI)
- Test Matrix: Transient Fill to 65%, Passive Steady-State Test at 60% Fill Level, Drain

0.5” – 4.5” SOFI 56-layer, 14/cm inner tMLI

VATA 3d Description and Configuration

- VATA 3d test was conducted to evaluate the thermal performance of a SOFI/tMLI configuration with 56 layers (volume matching blanket)

- Configuration Changes between VATA 3c and VATA 3d:
  - No change in MLI hardware
  - Fill level of 60% to compare to VATA 3c 95% fill level data

Results Summary: VATA 3d Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	6.3 W
All 6 Struts	0.77 W
Vent Line	0.015 W
Fill/Drain Line	0.017 W
Silicon Diode Rake	1.22 W
Total Heat Leak through Penetrations	2.02 W
Total Heat Leak through MLI + Surf-Mounted Instr.	4.28 W

VC Pressure: 4.5E-07 Torr	**Warm Boundary: 293 K**	**Cold Boundary: 79 K**	**Fill Level: 60%**

VATA 4a: tMLI Thermal Test

- MSFC/ER24 Initiated Test
- Objective: Evaluate the performance of a composite struts as compared to titanium struts
- Test Matrix: Transient Fill to 99%, Passive Steady-State Test at 95% Fill Level, Drain

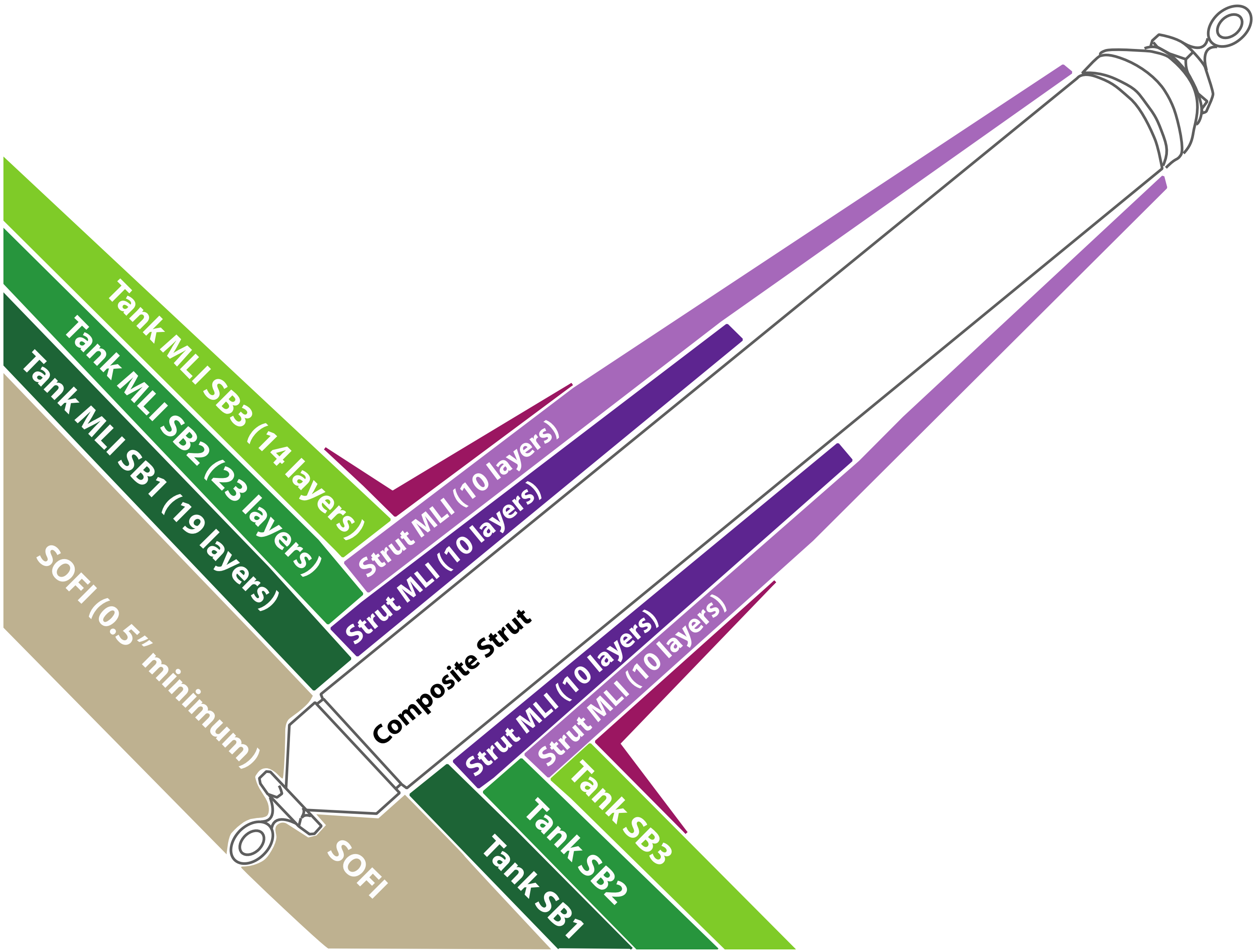
0.5" – 4.5" SOFI	56-layer, 14/cm inner tMLI

VATA 4a Description and Configuration

- VATA 4a test was conducted to evaluate the thermal performance of composite struts compared to the original titanium struts.

- Configuration Changes between VATA 3d and VATA 4a:
  - Titanium struts were removed and composite struts installed in their place
  - Tank MLI blanket layer number remained constant
  - MLI was cut and patched to allow for strut removal and replacement
  - 2, 10 layer MLI blankets were wrapped around the strut, covering the entire composite section of the strut

VATA 4a Strut MLI



Results Summary: VATA 4a Thermal Test Data

HEAT LEAK TYPE	PASSIVE STEADY STATE DATA
Total Heat Leak from Flow Meter Calculation	6.7 W
All 6 Struts	0.9 W
Vent Line	0.01 W
Fill/Drain Line	0.017 W
Silicon Diode Rake	1.22 W
Total Heat Leak through Penetrations	2.15 W
Total Heat Leak through MLI + Surf-Mounted Instr.	4.55 W

VC Pressure: 7.9E-07 Torr	**Warm Boundary: 293 K**	**Cold Boundary: 79 K**	**Fill Level: 95%**

VATA Test Data Comparisons

- This section identifies meaningful relationships between the data taken from key thermal tests.

Results Summary: Thermal Test Data Comparison

Configuration	Total Heat Leak	MLI Heat Leak
VATA 1a (Traditional MLI, Passive BAC shield, 42 Standoffs, 95% fill)	10.8 W	6.1 W
VATA 1a (Traditional MLI, 160K BAC shield, 42 Standoffs, 93% fill)	6.8 W	3.6 W
VATA 1b (Traditional MLI, No BAC shield, No Standoffs, 95% fill)	9.4 W	7.3 W
VATA 1c (SOFI, rapidly changing fill level)	327 W	-
VATA 2a (LBMLI, Passive BAC shield, No Standoffs, 95% fill)	7.5 W	4.7 W
VATA 2a (LBMLI, 160K BAC shield, No Standoffs, 93% fill)	4.7 W	1.5 W
VATA 2b (LBMLI, Passive Vapor Cooled Shield, No Standoffs, 95% fill)	7.6W	5.1 W
VATA 2b (LBMLI, 265K Vapor Cooled Shield, No Standoffs, 93% fill)	7.3 W	4.6 W
VATA 2c (LBMLI, Passive Vapor Cooled Struts, No Standoffs, 96% fill)	7.9 W	6.1 W
VATA 2c (LBMLI, Vapor Cooled Struts, No Standoffs, 95% fill)	7.3 W	5.3 W
VATA 2d (LBMLI, No Shield or Structural Cooling, No Standoffs, 95% fill)	8.3 W	6.0 W
VATA 3a (19-layers tMLI, 95% fill)	9.0 W	6.6 W
VATA 3b (42-layers tMLI, 95% fill)	7.3 W	4.9 W
VATA 3c (56-layers tMLI, 95% fill, 10-layer strut MLI)	6.9 W	4.8 W
VATA 3d (56-layers tMLI, 60% fill, 10-layer strut MLI)	6.3 W	4.3 W
VATA 4a (56-layers tMLI, 95% fill, 10-layer strut MLI, composite struts)	6.7 W	4.6 W

Follow-On Results Summary: VATA 1a, 1b, and 2 Thermal Test Data Comparison

Data Summary for VATA 1a, 1b, and 2a:

Configuration	Heat Leak
VATA 1a (Traditional MLI, Passive BAC shield, 42 Standoffs, 95% fill)	10.8 W
VATA 1a (Traditional MLI, 160K BAC shield, 42 Standoffs, 93% fill)	6.8 W
VATA 1b (Traditional MLI, No BAC shield, No Standoffs, 93% fill)	9.4 W
VATA 2a (LBMLI, Passive BAC shield, No Standoffs, 95% fill)	7.4 W
VATA 2a (LBMLI, 160K BAC shield, No Standoffs, 93% fill)	4.6 W

Passive Ref → (VATA 1b)

Data Comparison and Interpretation:

VATA 1b	VATA 1a passive	% Change	Significance
9.4 W	10.8 W	14.9%	BAC shield/standoffs heat leak penalty in passive case
VATA 1b	**VATA 1a active**	**% Change**	**Significance**
9.4 W	6.8 W	27.7%	BAC benefit in active case relative traditional passive MLI
VATA 1b	**VATA 2a passive**	**% Change**	**Significance**
9.4 W	7.4 W	21.3%	LBMLI benefit in passive case relative to traditional MLI
VATA 1b	**VATA 2a active**	**% Change**	**Significance**
9.4 W	4.6 W	51.1%	LBMLI benefit in active case relative to traditional MLI

VATA 1a, 1b and 2a Observations: Passive MLI

	VATA 1a passive	VATA 1b Ref	VATA 1a passive	VATA 2a passive	VATA 1b	VATA 2a passive
Heat Leak	6.08 W	7.26 W	6.08 W	4.67 W	7.26 W	4.67 W
Comparison	+19%		-23%		-36%	

- 19% increase in MLI heat leak with removal of BAC/standoffs to an MLI only configuration.
- 23% reduction in MLI heat leak with LBMLI compared to traditional MLI with BAC/standoffs.
- 36% reduction in MLI heat leak with LBMLI compared to traditional MLI, no BAC/standoffs.

- **Configuration differences between the VATA 1a and 2a:**
  - Seams: VATA 1a included MLI blankets with sewn Velcro seams while VATA 2a incorporated LBMLI with interleaved, temperature-matched seams. Seams introduce a thermal short and significant compression of the blanket layers. Seamed blankets were necessary in order to make them removable and reusable for the LBMLI tests.
  - BAC shield structure: Standoffs were in the VATA 1a configuration and were removed for VATA 2a. Standoffs allow heat transfer between the tank wall and the BAC shield.
  - Reflector layer spacing: VATA 1a MLI blankets use Dacron netting to isolate reflector layers while VATA 2a LBMLI blankets employ low-conductivity spacers (54,000).

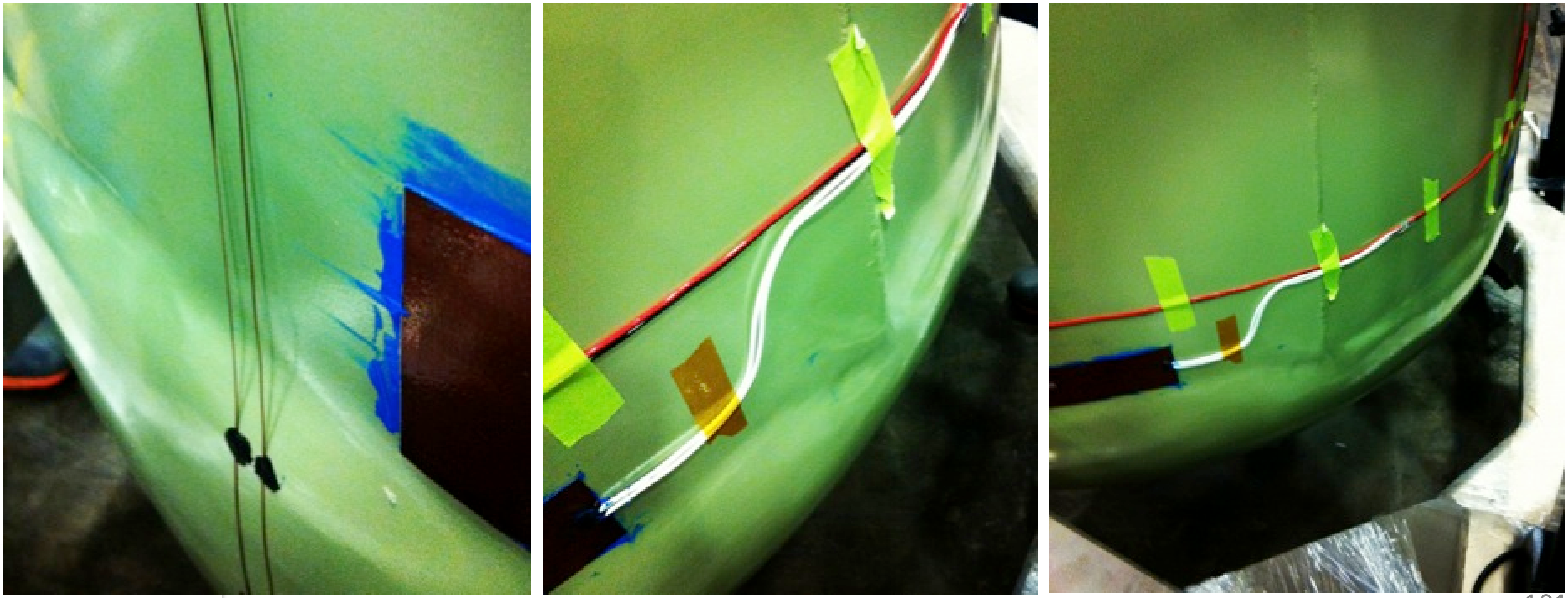
VATA 1a and 2a Observations: BAC Shield

	Passive Heat Leak	Active Heat Leak	Heat Leak Reduction	Heat Extraction Requirement
VATA 1a	10.8 W	6.8 W	4.0 W (37%)	12.9 W
VATA 2a	7.5 W	4.7 W	2.8 W (37%)	15 W

- BAC Shield operation reduced heat leak to tank.
- Heat removed from BAC shield increased from VATA 1a to VATA 2a. The standoffs in VATA 1a cooled the BAC shield ~30K from the non-operational BAC shield temperature in VATA 2a.
  - System implication is mass of electrical power system required to cool shield
- **Departure from Plan:** GRC's RBO I did not have the same number of BAC shield standoffs as VATA 1a.
- **An integrated MLI and BAC shield system that is optimized for both thermal and structural performance has not been tested.**

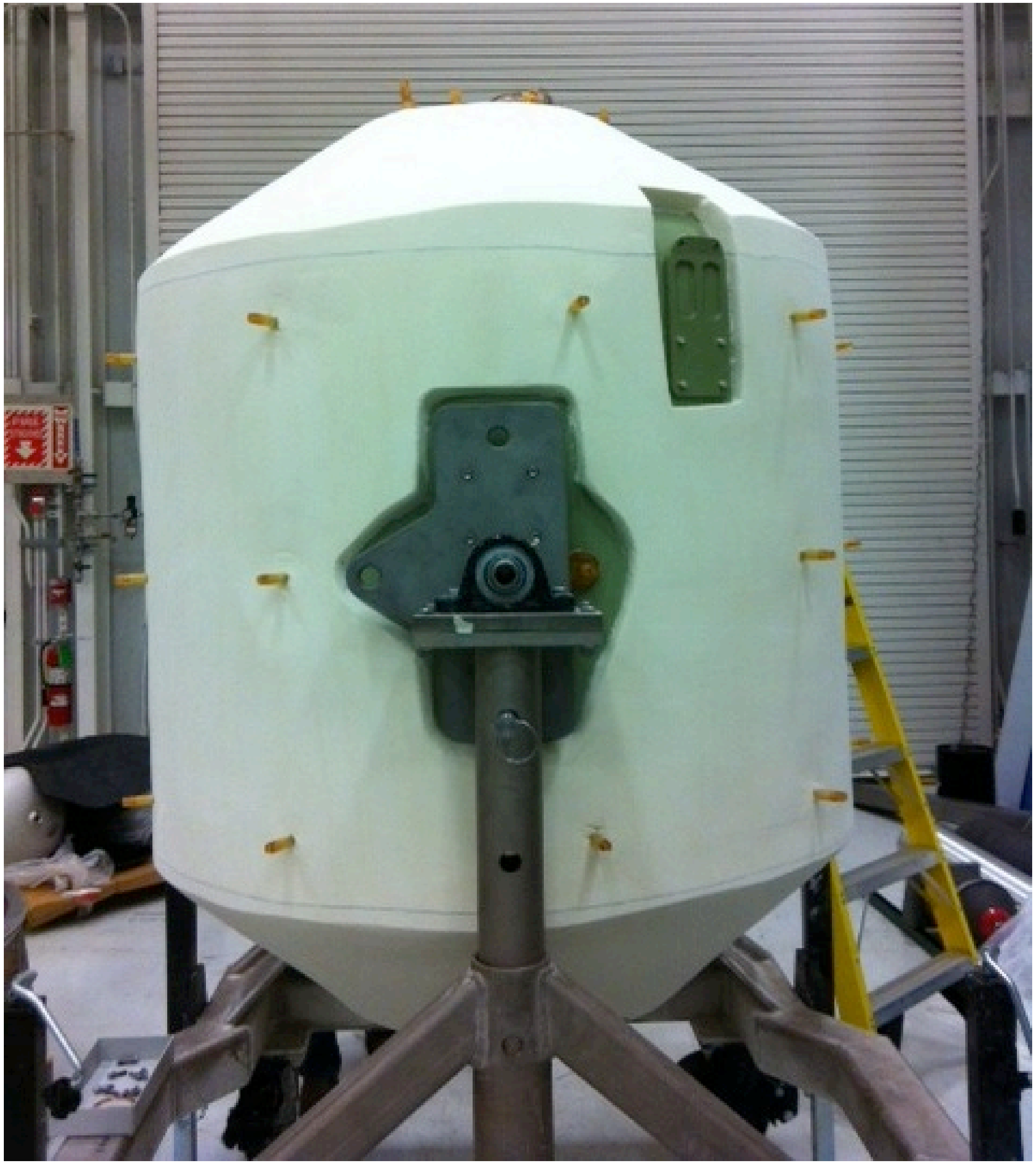
Issues / Concerns / Lessons Learned: Tanks

- Three identical tanks were procured for CPST Technology Maturation use at MSFC and GRC.
- All three tanks were delivered with varying degrees of nonconformance; the most severe tank was sent back to the supplier for rework while the other two tanks were inspected by the MSFC/GRC Pressure Safety Offices. The inspection process resulted in a small MAWP de-rating.
- Inconsistent, uneven tank OML resulted in difficulty installing BAC shield standoffs and a non-uniform SOFI thickness on the tank cylinder.



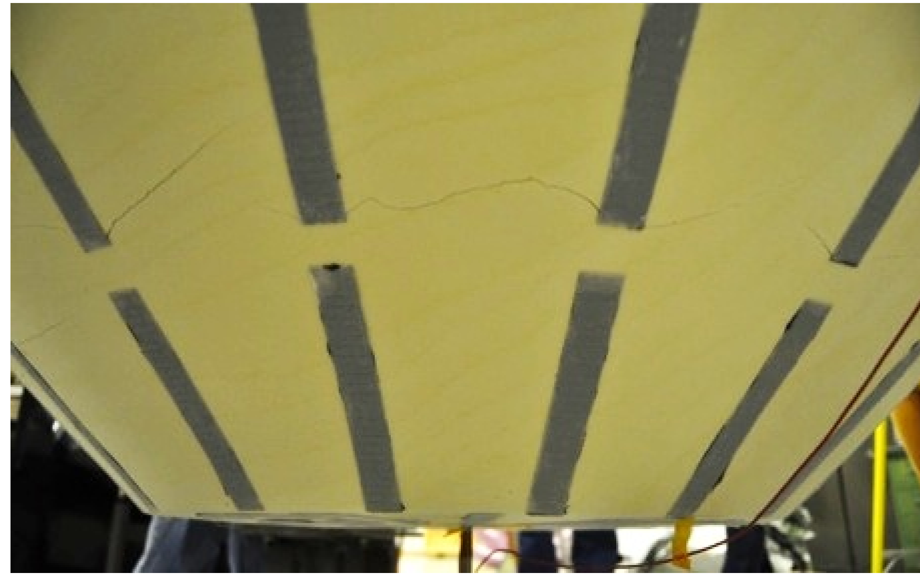
Issues / Concerns / Lessons Learned: SOFI

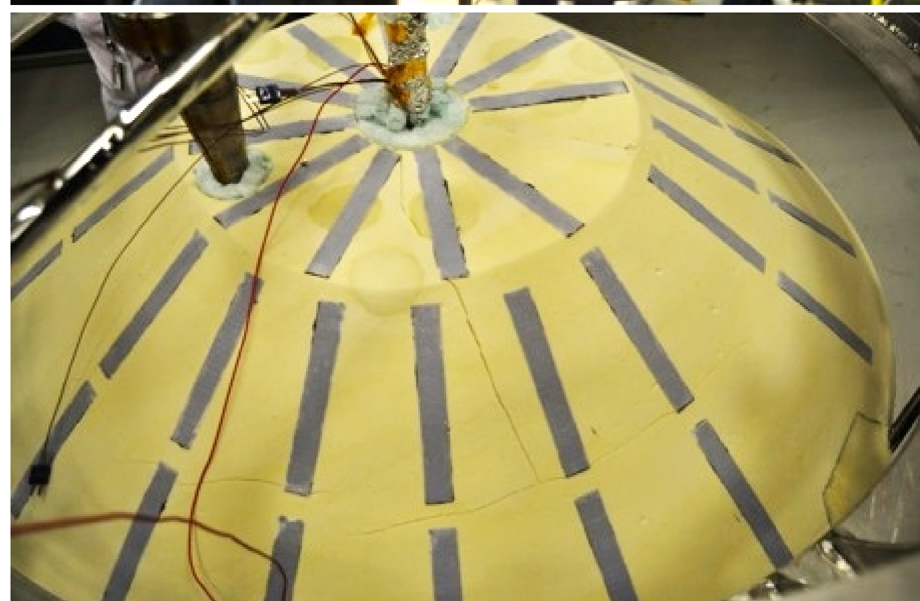
- SOFI size, shape, and thickness were problematic.
- Inadequate SOFI trimming resulted in an Outer Mold Line (OML) too large for the pre-fabricated MLI blankets to fit around, so the MLI blankets had to be modified. The faceted shape of the foam was a new challenge for the SOFI group.



Issues / Concerns / Lessons Learned: SOFI

- SOFI size, shape, and thickness were problematic:
  - Requirement for a faceted shape drove large thicknesses in the SOFI at the top and bottom domes. These excessive thicknesses resulted in significant cracking in the foam.
  - Circumferential cracks appeared on the test article during the VATA 2 tests. These cracks were not observed during the VATA 1 series.
  - Cracks propagate from the Velcro strips used to attach LBMLI to the SOFI.
  - The largest concentration of cracks are located in the dome section where the SOFI is the thickest (2- 4.5”).
  - Comparison with the GRC RBO tank revealed the circumferential cracks along the Velcro edges are not unique to VATA.





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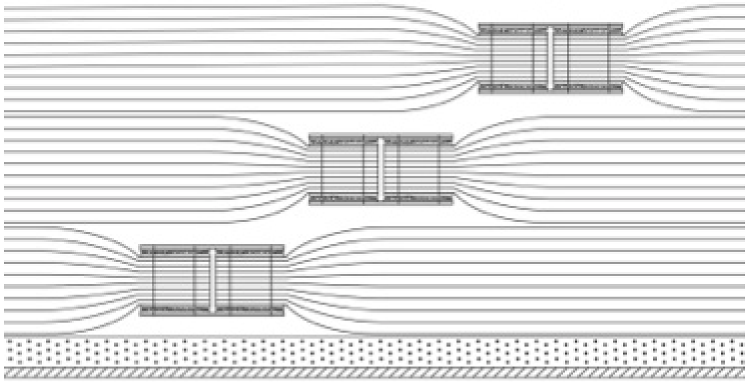
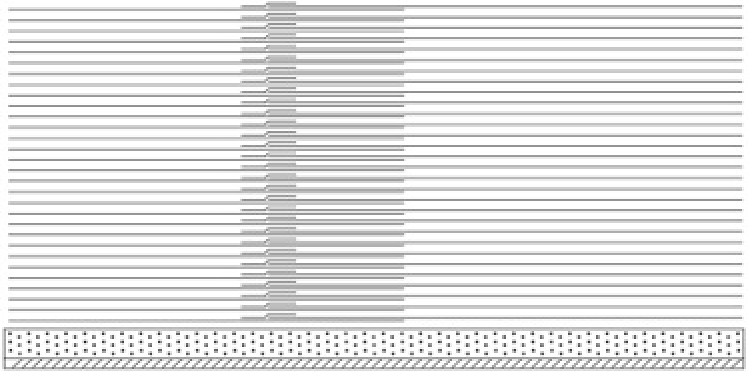
Issues / Concerns / Lessons Learned: tMLI

- A butt joint, sewn Velcro seam configuration for GRC's RBO I and VATA 1 was selected for several reasons:
  - Aggressive CPST Technology Maturation schedule did not allow for enough hands-on tank time to roll-wrap tMLI on GRC's RBO I or VATA 1
  - Removal and reinstallation of blankets was identified as a desired feature
- These fully compressed seams may have contributed to a significant reduction in the thermal performance of the tMLI blankets.
  - Future tMLI designs should employ a roll-wrap with interleaved seams method (such as MHTB) or a modular blanket method with interleaved seams
- Thermal versus Structural
  - LBMLI clearly provides a thermally superior method for structurally supporting a BAC shield than a tMLI blanket with standoffs.
  - Without the requirement to support a BAC shield, tMLI with interleaved seams may provide an attractive solution from a thermal performance and weight perspective.
- The VATA 3 series explored the performance of tMLI with interleaved seams.

Compressed Seams (RBO I and VATA 1)



Interleaved Seams



VATA Test Summary

- VATA 1a and VATA 2a successfully demonstrated two different methods of integrating a passive MLI and and active BAC shield configuration able to survive a worst-case acoustic launch environment and met all test KPPs.
- Acoustic testing performed in this effort showed promise for both the implementation of VATA 1a and VATA 2a designs for flight.
- VATA 2a (LBMLI inner blanket) has increased thermal performance compared with VATA 1a (traditional MLI inner blanket).

BACKUP SLIDES

Broad Area Cooling (BAC) Line Strength Assessment

- Background work on the support and constraint of BAC shield tubes for the expected launch acoustic environment.
- Work completed by Jeff Oliver (MSFC/ER41/DCI)
- January 12, 2012

VATA Structural Assessment

Design requirement to maintain the position of the BAC Shield within the MLI layers through launch

Determined that the best option was use of rigid standoff supports for tubes

NASTRAN finite element model of the BAC lines and the VATA/CBRS tank was developed

BAC Shield and MLI blankets modeled as non-structural mass (NSM) along the lines and it was assumed that the shield added no stiffness to the BAC lines.

Tank contraction could load the vertical BAC tube segments in compression, a comparison analysis was done to determine if stress loops would be needed.

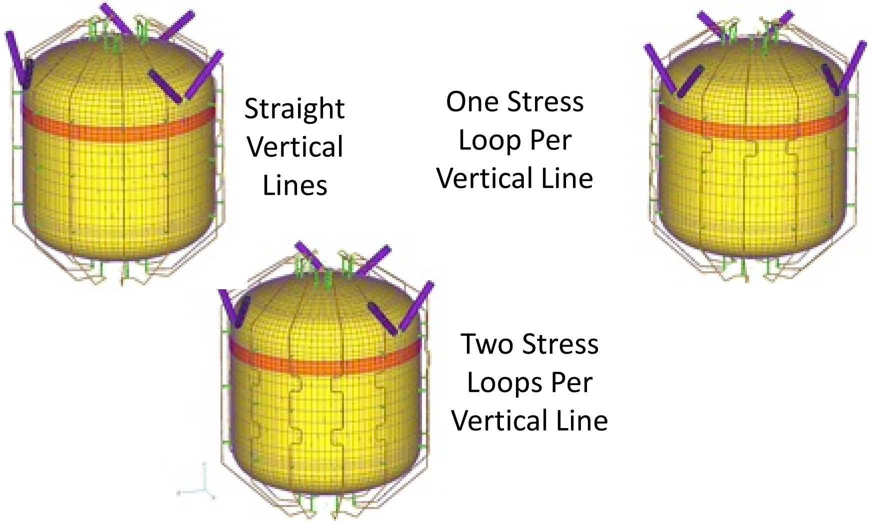
Analysis showed that the BAC tubes extending over the tank domes provided enough flexibility.

BAC Standoffs assessed by separate analysis of Ultem post cross sections.

0 BAC Thermal / Acoustic Test FEM

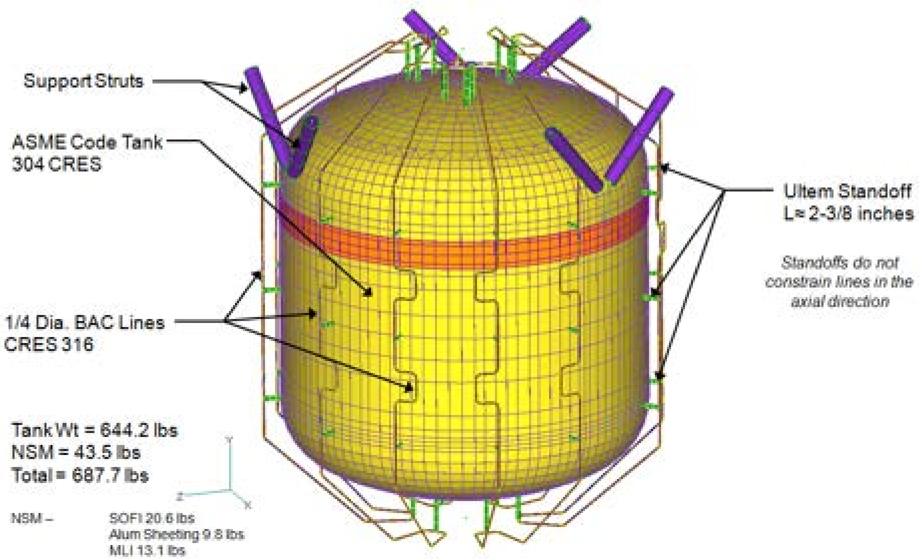
BAC Line Configuration

- ¼ inch diameter CRES lines.
- 40 psi line pressure.
- BAC Shield: two sheets of 2-5 mil thick aluminum with unbonded lap joints between the three BAC Shield sectors.
- NASTRAN FEM used for BAC lines and tank
- The BAC Shield and MLI blankets modeled as non-structural mass (NSM) along the lines and it was assumed that the shield added no stiffness to the BAC lines.
- Since tank contraction could load the vertical BAC tube segments in compression, a comparison analysis was done to determine if stress loops would be needed. **Analysis showed that the BAC tubes extending over the tank domes provided enough flexibility.**
- BAC Standoffs assessed by simple hand analysis of Ultem tube cross sections..



BAC Shield Line Assessment

- The purpose was to determine how many line support attachments needed.
- The VATA BAC shield standoff design would be leveraged for GTA and flight payload.
- A critical design requirement was that the position of the BAC Shield within the MLI layers had to be maintained once the tank was on orbit. It was determined that the best option of maintaining the BAC Shield orientation through payload ascent was to use relatively rigid standoff supports.



0 BAC Thermal / Acoustic Test FEM

BAC Standoff Spacing - Estimated Flight Level Stresses

$$\sigma_{Flight} \approx 22ksi = \frac{Mc}{I} = \frac{wl^2c}{12I}$$

$$w = 16g \cdot (0.0068\frac{lb}{in} + 0.0078\frac{lb}{in})$$

$$w = 16g \cdot (0.0146\frac{lb}{in}) = 0.23\frac{lb}{in}$$

$$\sigma_{Flight} \approx 22ksi \geq \frac{0.23\frac{lb}{in} \cdot (0.125in) \cdot l^2}{12(0.00014in^4)}$$

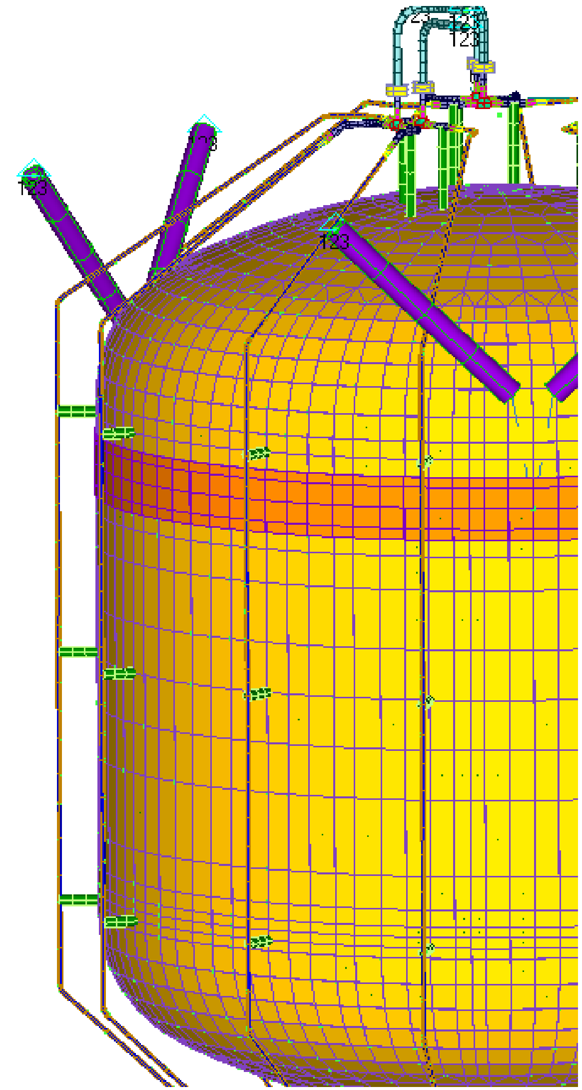
$$l_{Max} \approx 36in$$

Maximum unsupported line length for the expected flight environment. Maintaining a positive MOS with a FS of 1.0 on yield.

This does not allow for additional line loading from MLI pressure differential.

Axial Flight Load 28g

Radial Flight Load 16g



VATA 1a: Cryogenic Epoxy Selection

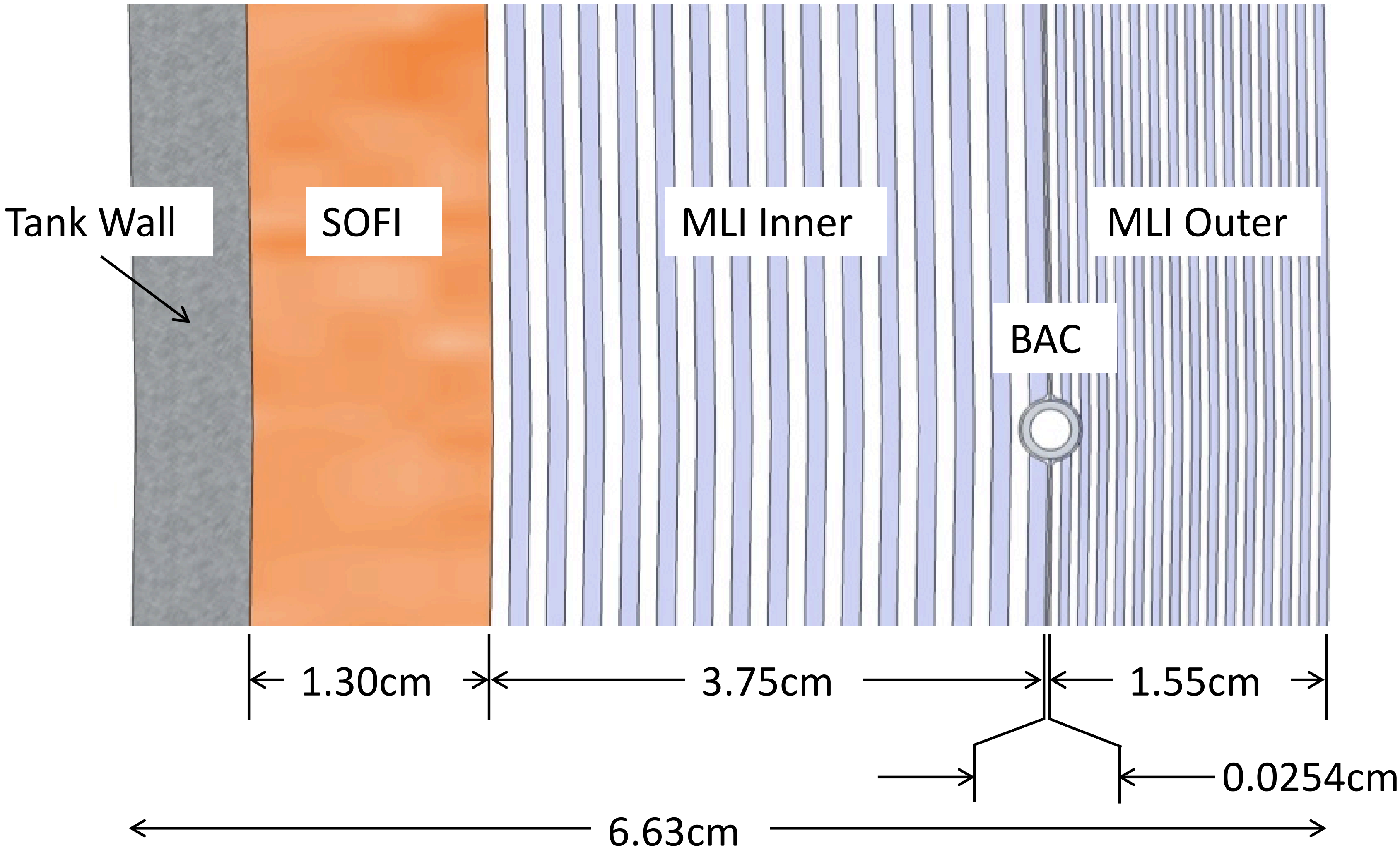
- CPST Technology Maturation

- Objective: Select an epoxy suitable for bonding the Ultem standoffs to the VATA tank.

Background

- The Cryogenic Propellant Storage and Transfer (CPST) Project evaluated the effectiveness of a Broad Area Cooling (BAC) shield in conjunction with Multi-Layer Insulation (MLI).
- The test program was divided into parts:
  - Cryogenic Boiloff Reduction System (CBRS)
  - Vibro-Acoustic Test Article (VATA)
- The CBRS test performed an in depth thermal characterization of the system.
- The VATA test evaluated the response of the system to simulated vibro-acoustic launch conditions.
  - Thermal tests conducted before and after the acoustic test evaluated if degradation to the system occurred.

Insulation System Cross-Section



BAC Shield Support

- Standoffs are used to support the BAC shield from the surface of the tank.
- Ultem 1000 (polyetherimide) material was selected for its high strength and low thermal conductivity.

Attachment of BAC Shield Standoffs

- The CBRS and VATA test articles are ASME pressure vessels (MAWP 131 psi).
- ASME certification prevents modification after manufacturing, requiring the Ultem standoffs to be adhesively bonded.
- A flight configuration would use mechanical attachment for the standoffs, but adhesive bonding in this test program has allowed for faster test article development and flexibility in design.
- A number of adhesives have been evaluated for attaching the Ultem standoffs.

Adhesive Selection Criteria

- Ability to bond substrates
  - Ultem bonded to the primed 304 SS tank
  - Standoffs support the weight of the BAC shield and MLI blankets, and vibro-acoustic loads.
- Ability to perform at cryogenic temperatures and handle differential thermal expansion between the materials
  - $\Delta L/L_{(RT \rightarrow 77K)}$ (304 SS) = -0.28%
  - $\Delta L/L_{(RT \rightarrow 77K)}$ (Ultem) = -0.80%
- Low-outgassing
- Low thermal conductivity preferred
- Room temperature cure cycle
  - Limits selection to two-part systems

Initial Adhesive Evaluation

Product	Cure Cycle	Manufacturer Recommended for Cryogenic Temperatures	NASA Low Off-Gassing Rated	Lap Shear Strength (psi)			
				Aluminum			Ultem
				20K	77K	RT	RT
3M 2216	RT – 7 days 65°C – 2h	X	X	2440	2740	3200	840
3M 1838-L	RT – 7 days 65°C – 2h	-	-	-	-	2500	1040
Hysol 9430	RT – 5 days 80°C – 1h	-	-	-	-	4700	-
Stycast 2850 FT	RT – 1 day 65°C – 2h	-	X	-	-	-	-

- 3M products are recommended by GE plastics for bonding Ultem.
- Hysol 9430 was used on the MLSTC program.
- Stycast 2850 FT is commonly used for attaching instrumentation to cryogenic tanks.

Initial Adhesive Testing

- 2” Ultem discs were bonded to bare 304 SS substrates.
  - Bonding surfaces were roughened and cleaned with isopropanol
- Samples were immersed in LN2 to evaluate the thermal shock resistance of the adhesives.
- The Scotch-Weld 2216 and Hysol 9430 epoxies survived the first cycle, but failed after the second immersion.
- Based on this test, Scotch-Weld 2216 was selected for further evaluation.

Continued Adhesive Testing

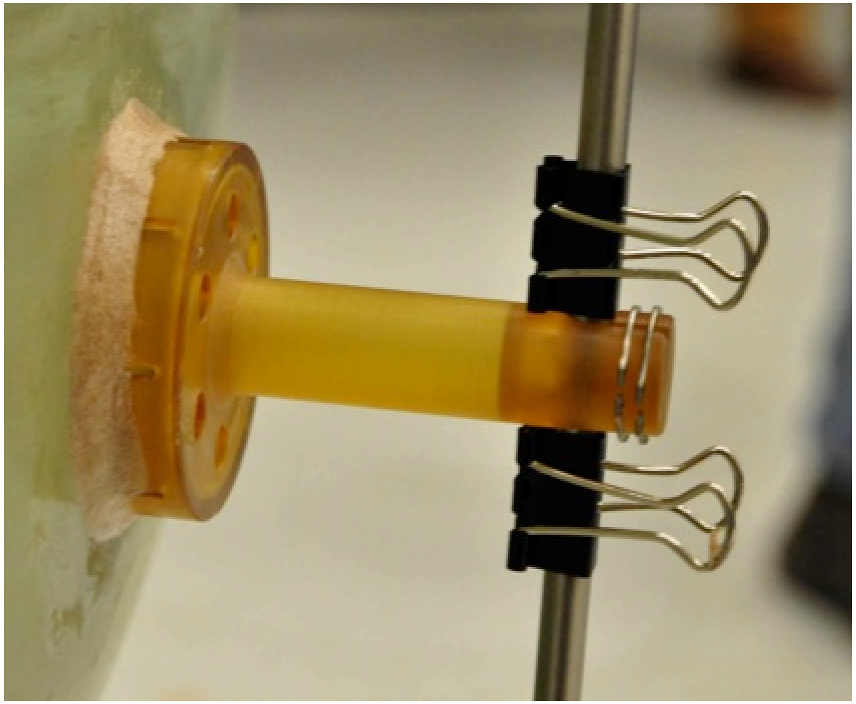
- Another round of evaluation was conducted with test conditions that better represented the application.
- Ultem samples were machined to match the dimensions of the standoff bases.
- Samples were bonded to the outside of primed 304 SS vessels that were filled with LN2.
- The entire setup was placed inside a block of SOFI to ensure complete chill down.
- All Scotch-Weld 2216 samples failed due to primer debonding within 2 thermal cycles.

Cryobond 920 Evaluation

- Cryobond 920, produced by CTD Materials, was compared to the Scotch-Weld 2216.
  - Flexible at cryogenic temperatures.
  - Specifically designed to accommodate thermal mismatch between different materials.
  - Modified with glass fiber and other fillers.
  - Low thermal conductivity.
- The Cryobond 920 samples all survived 5 thermal cycles and 2 LN2 dip tests.

Standoff Mounting Using Cryobond 920

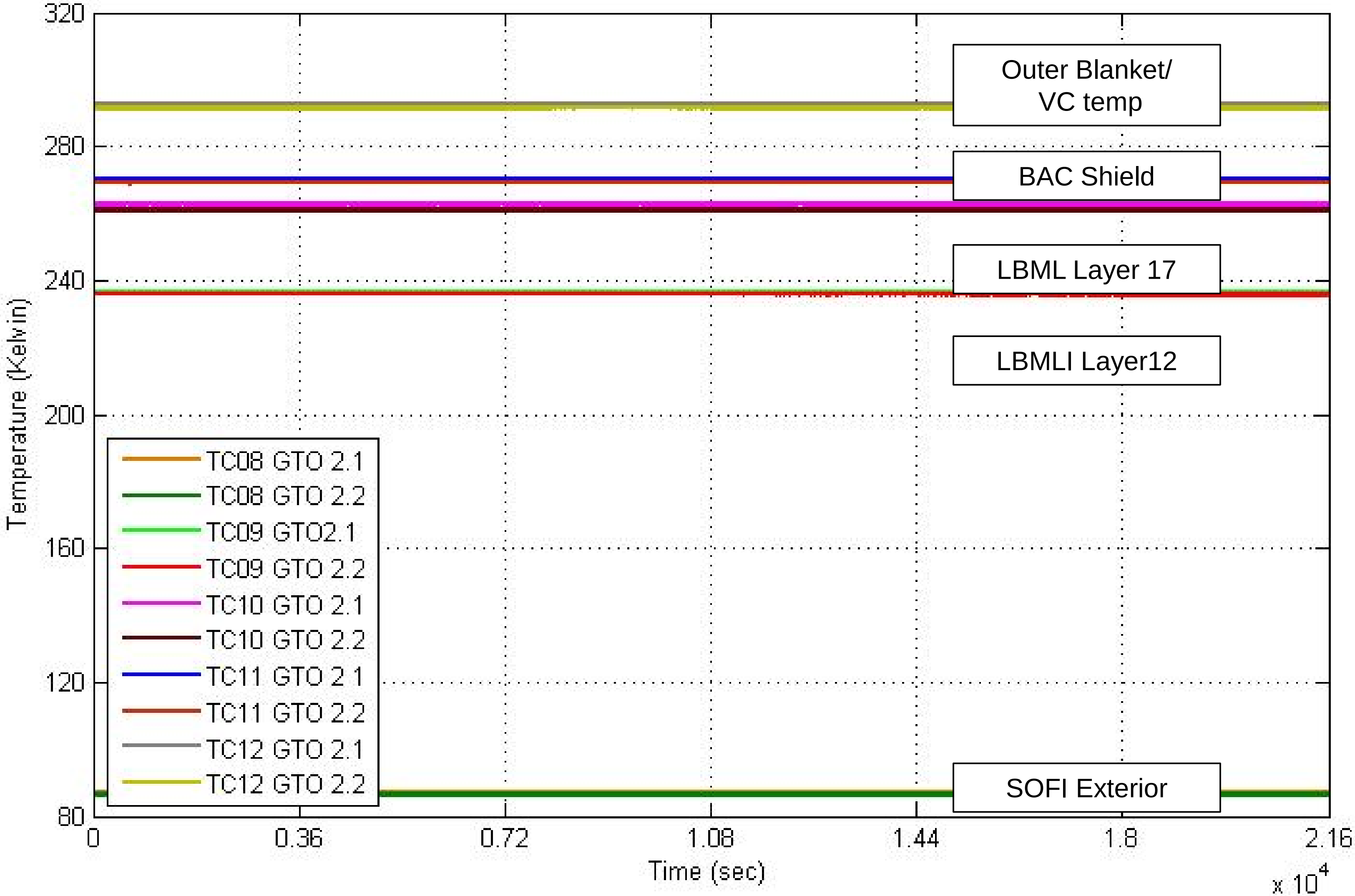
- Irregularities in the tank wall caused gaps between the tank walls and the standoffs.
- The high viscosity of the Cryobond 920 allowed the gaps to be filled, resulting in proper alignment between the standoffs and the BAC shield tubing lines.



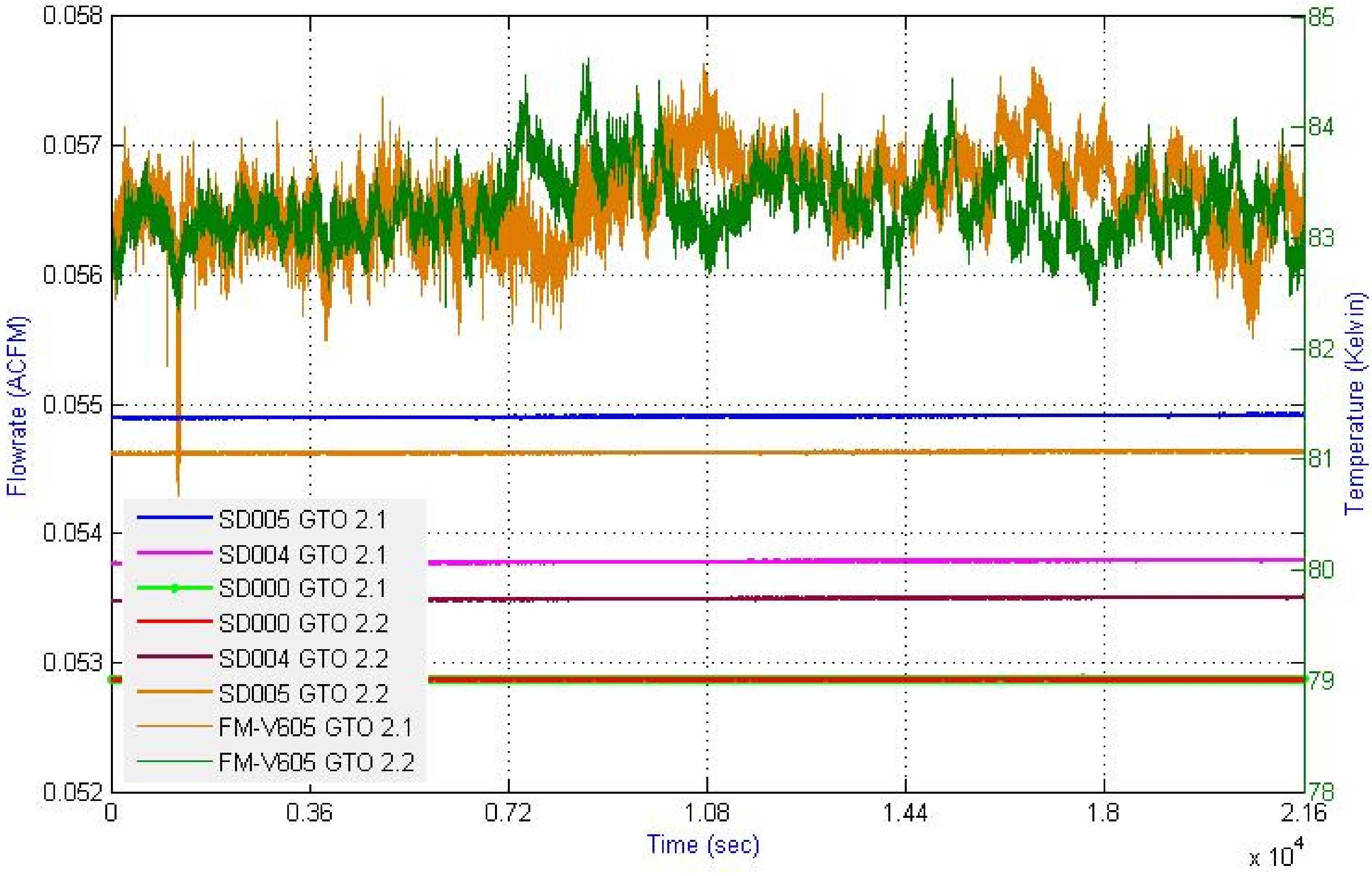
Conclusions

- Adhesive bonding of the Ultem standoffs to the CPST test articles allowed for design flexibility and faster manufacturing of the tank, but selecting a suitable adhesive for the harsh conditions proved difficult.
- Scotch-Weld 2216 was initially selected for this application, but the differential contraction between the Ultem standoffs and the stainless steel substrate was found to cause primer debonding.
- Cryobond 920 was selected to bond the Ultem standoffs used on the VATA test article. The flexibility at cryogenic temperatures was able to accommodate the strain between the standoffs and the stainless steel substrate.

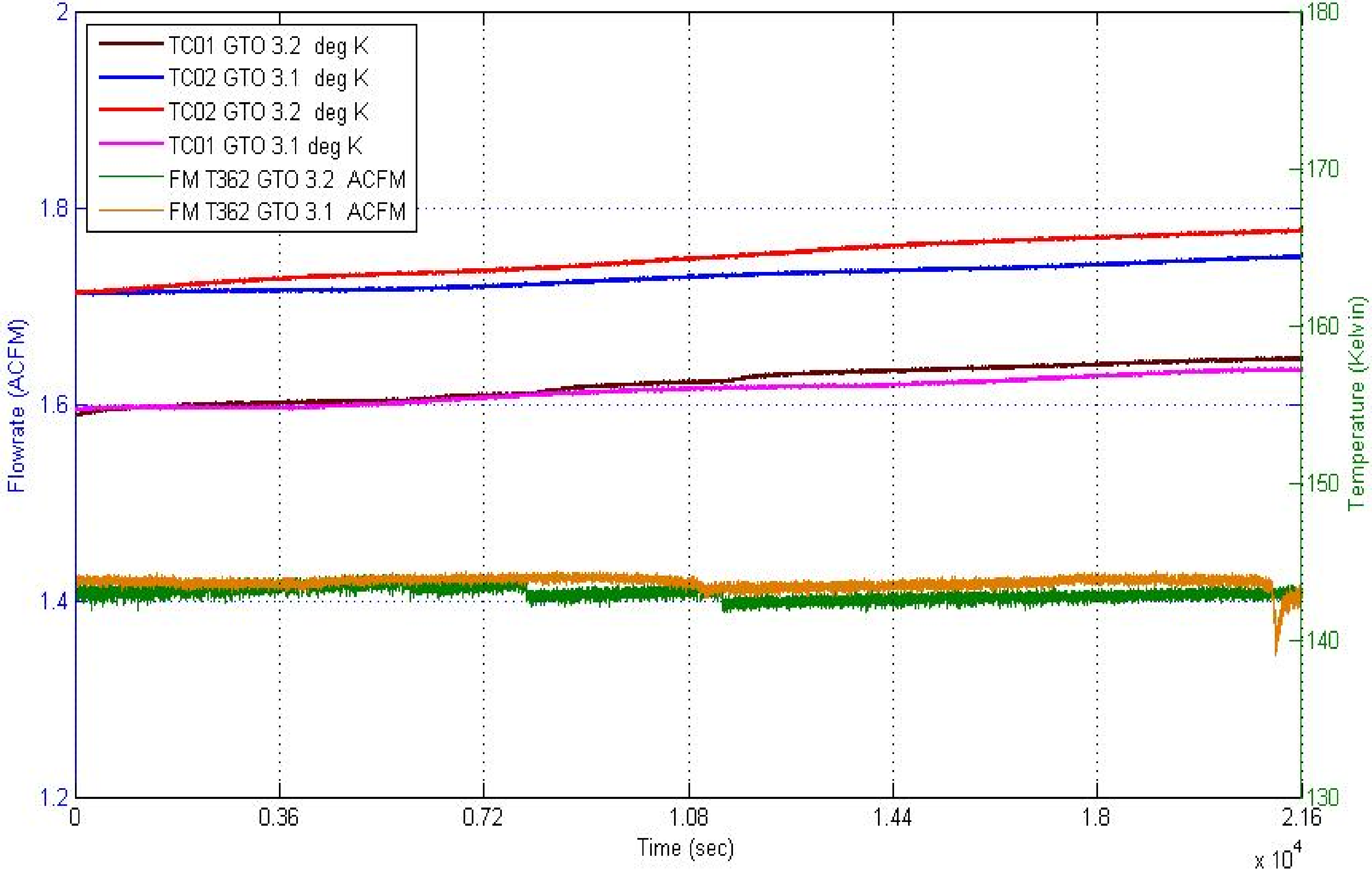
VATA 2a GTO 2.1 & 2.2: MLI Temperature Profile



VATA 2a GTO 2.1 & 2.2: Boiloff & Ullage Vapor Temp



VATA 2a GTO 3.1 & 3.2: BAC Shield Operations



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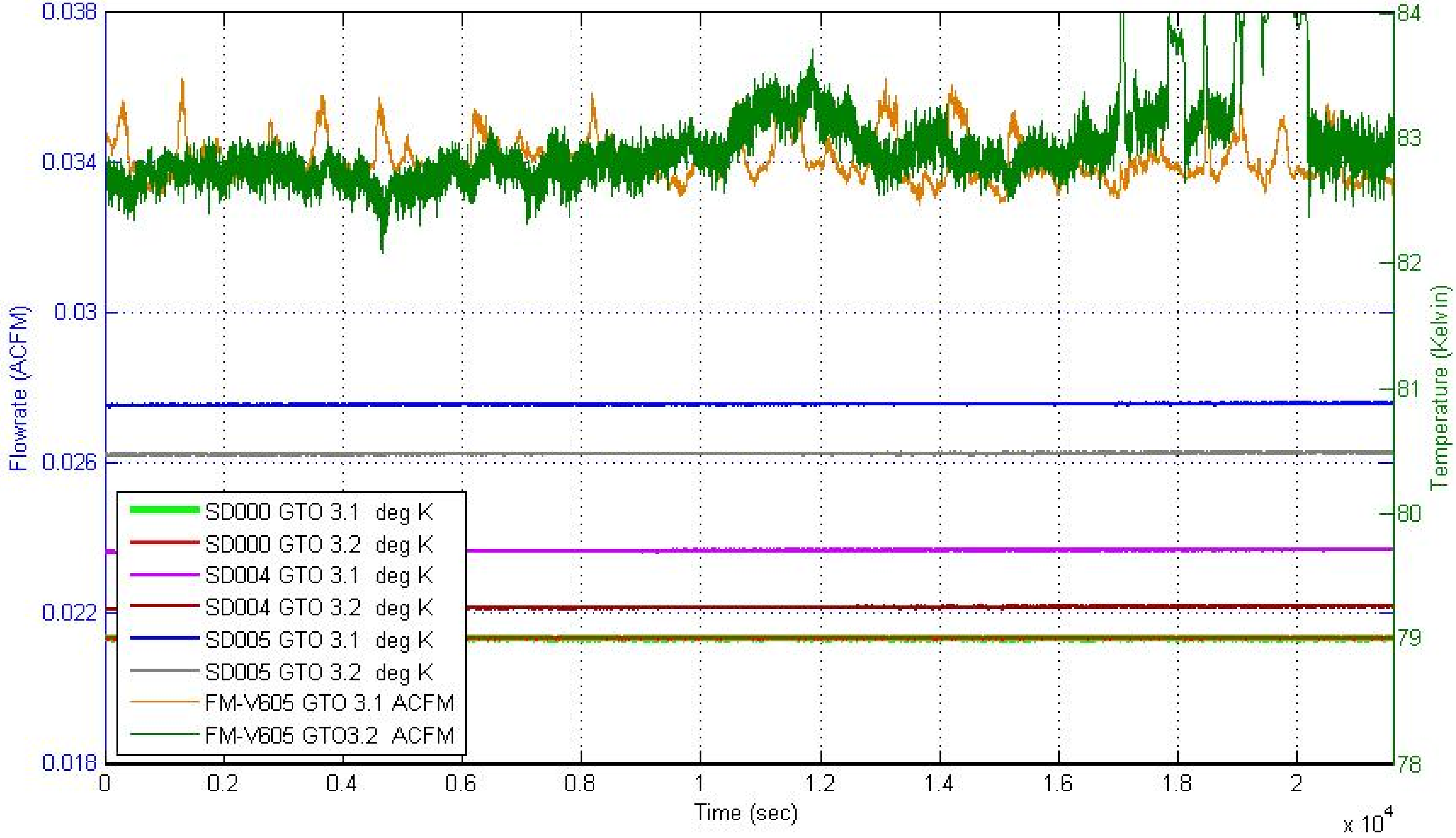
VATA 2a GTO 3.1 & 3.2: Boiloff & Ullage Vapor Temp



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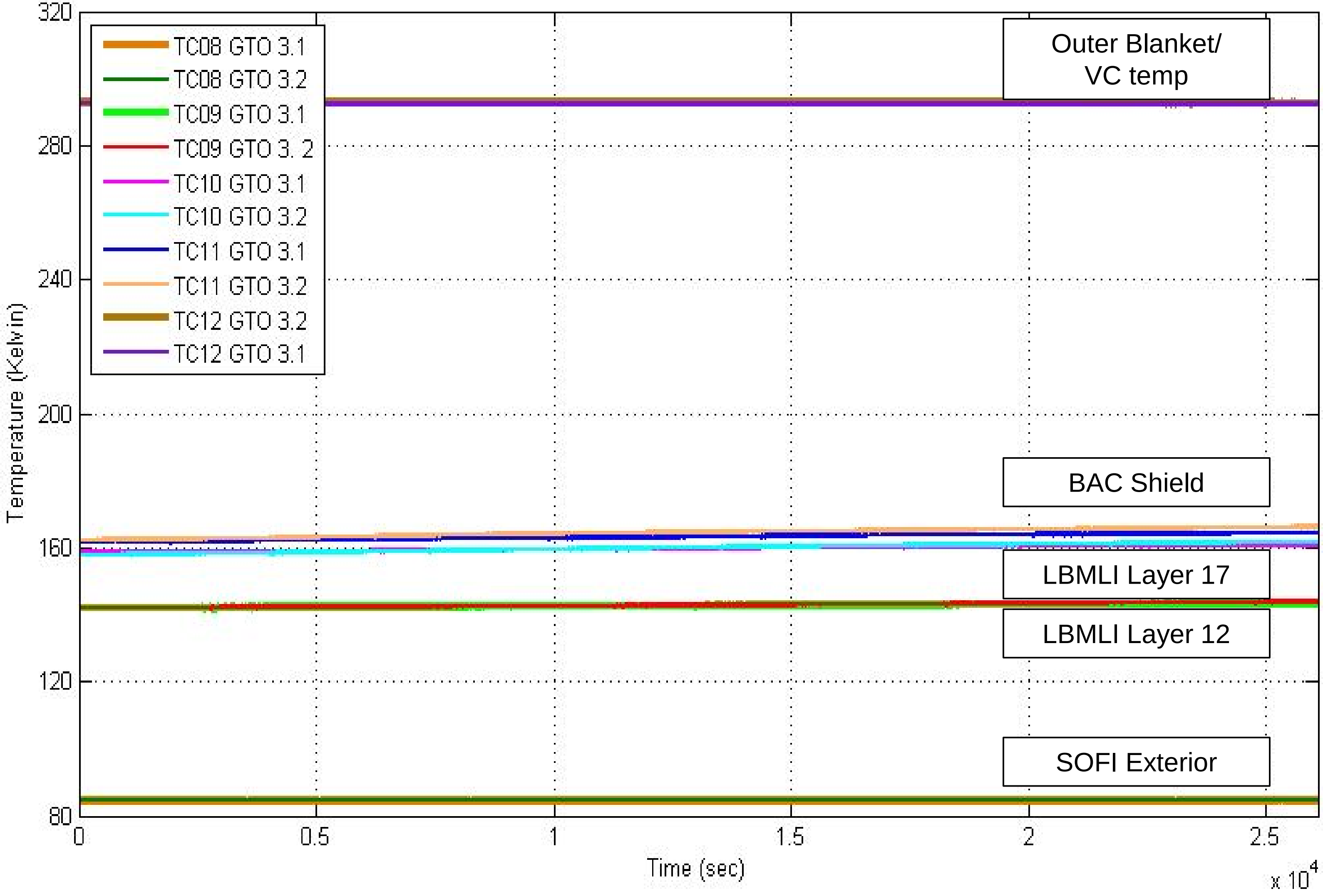
VATA 2a GTO 3.1 & 3.2: MLI Temperature Profile



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