Full Scale EDU Descent Sphere Thermal Insulation Test Results and Model Correlation

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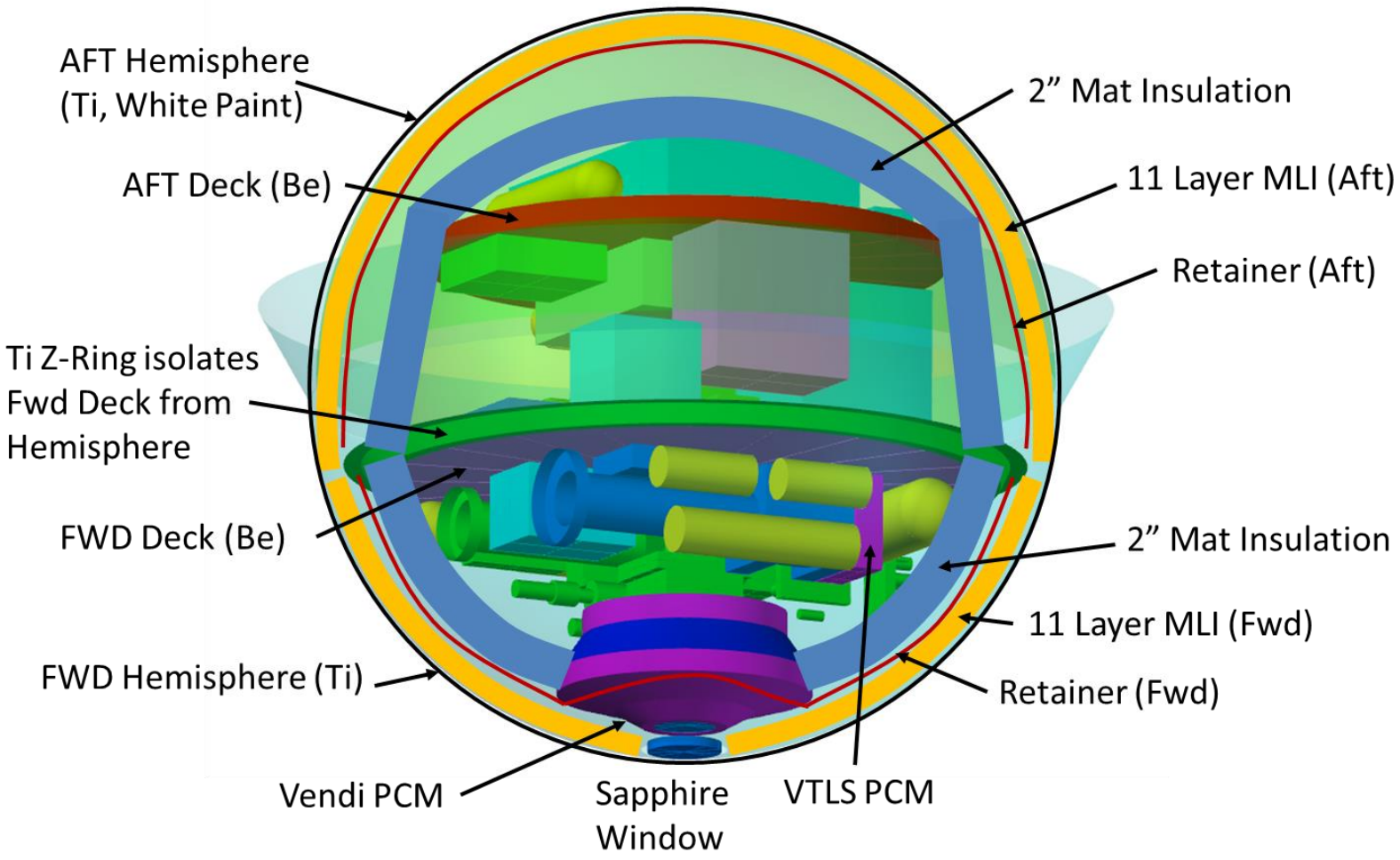
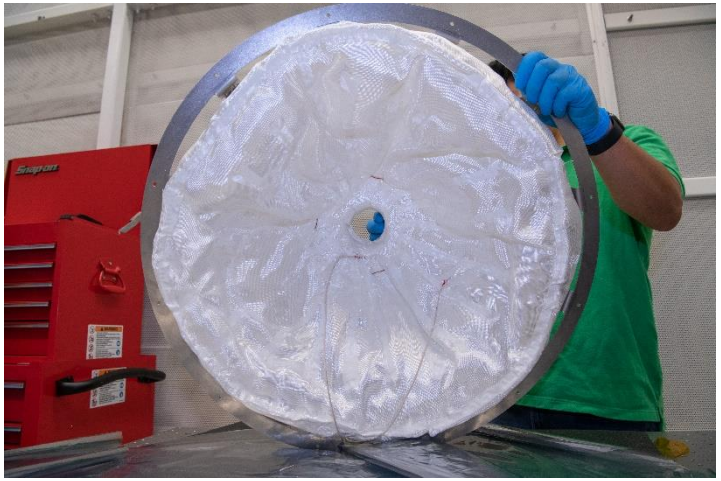
DAVINCI+ Descent Sphere Thermal Design



Insulation Thermal Design

- A 1” thick (11 layer), high temperature, MLI radiatively insulates the internal components from the hot outer surface of the DS
  - Inner Most Layer: (1 Layer) Astroquartz Glass Cloth (Style 581)
  - Internal layers: (5 layers) of 0.05 mm Aluminum Foil with alternating layers of Astroquartz Mat 550, 6.35 mm (0.25”)
  - Outer layer: (1 Layer) Astroquartz Cloth (Style 581)
  - Blanket construction sewn with high temperature thread (Nomex)
  - 3” cutouts in the MLI to represent the VENDI window covering
  - 3” cutout in the MLI for VMS inlet tubes
  - 2” cutout in the MLI at the umbilical connector
- High temperature Matt insulation around the aft, forward, and mid sections of the DS minimize convective air flow inside
  - 8 layers of 0.25” (6.35 mm) thick Astroquartz Mat 550
  - Outer and inner layer of Astroquartz Glass Cloth applied and sewn with Nomex thread.
  - 3” cutout in the mat insulation to represent the VENDI window covering
  - 2” cutout in the mat insulation at the umbilical connector

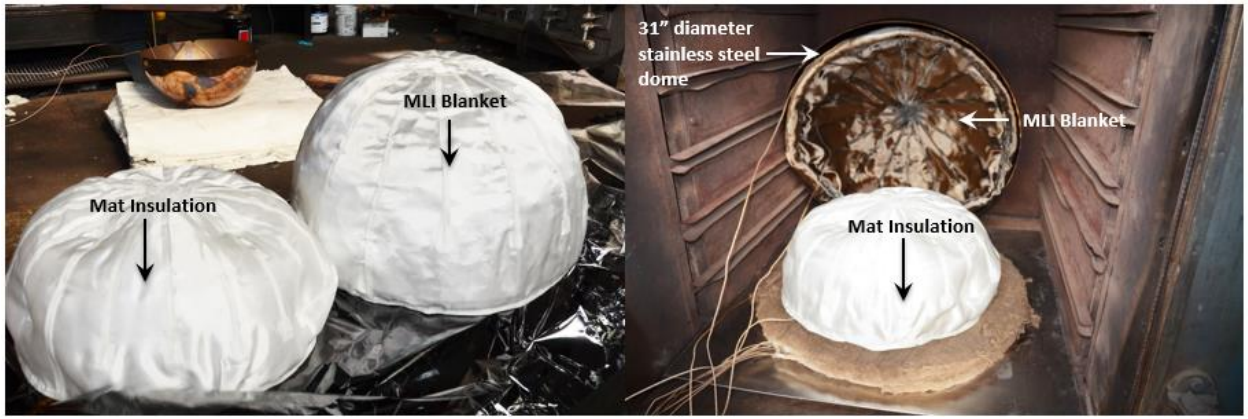
1” thick, high temperature MLI

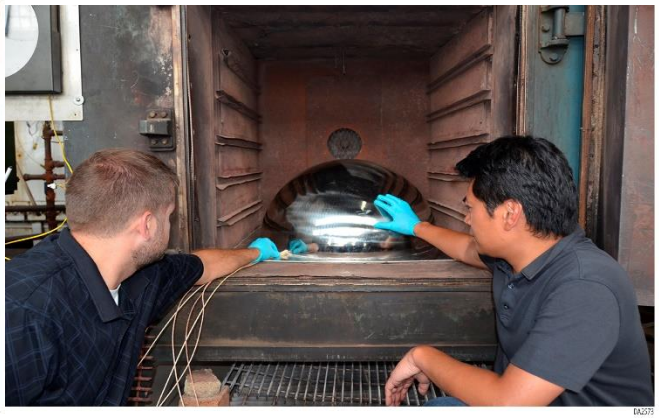


2” thick, high temperature mat insulation

2016 Hemisphere Insulation Tests

- In 2016, a thermal insulation test was performed with a stainless steel hemisphere to characterize the high temperature MLI and mat insulation performance.
  - Test 1 simulated the Venus ramp rate with no insulation to use as a baseline for comparison of the MLI and mat insulation performance
  - Test 2 added the MLI which significantly reduced the internal heat transfer. The MLI effective emittance was correlated to about 0.19 with 50% margin
  - Test 3 added the 2” Mat insulation with the MLI which further reduced the internal heat transfer. The thermal effective conductivity of the Mat insulation was correlated to about 0.03 W/m°C.



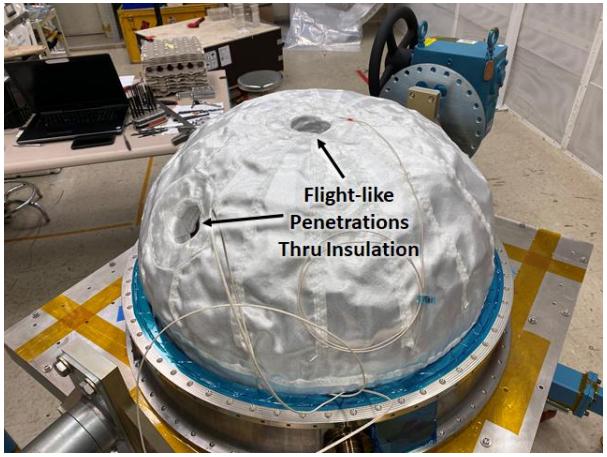


Full Scale EDU Descent Sphere Insulation Test

- Objectives:
  - To further characterize the MLI and mat insulation performance and reduce uncertainties thru model correlation
  - To simulate flight-like penetrations thru the insulation to simulate flight-like heat leaks
  - To simulate the DS internal pressure increase as the sphere temperature rises to 460°C
- Two transient thermal tests were performed with varying temperature ramp rates and a thermal model was correlated against the test data.

EDU Instrumented with External TCs

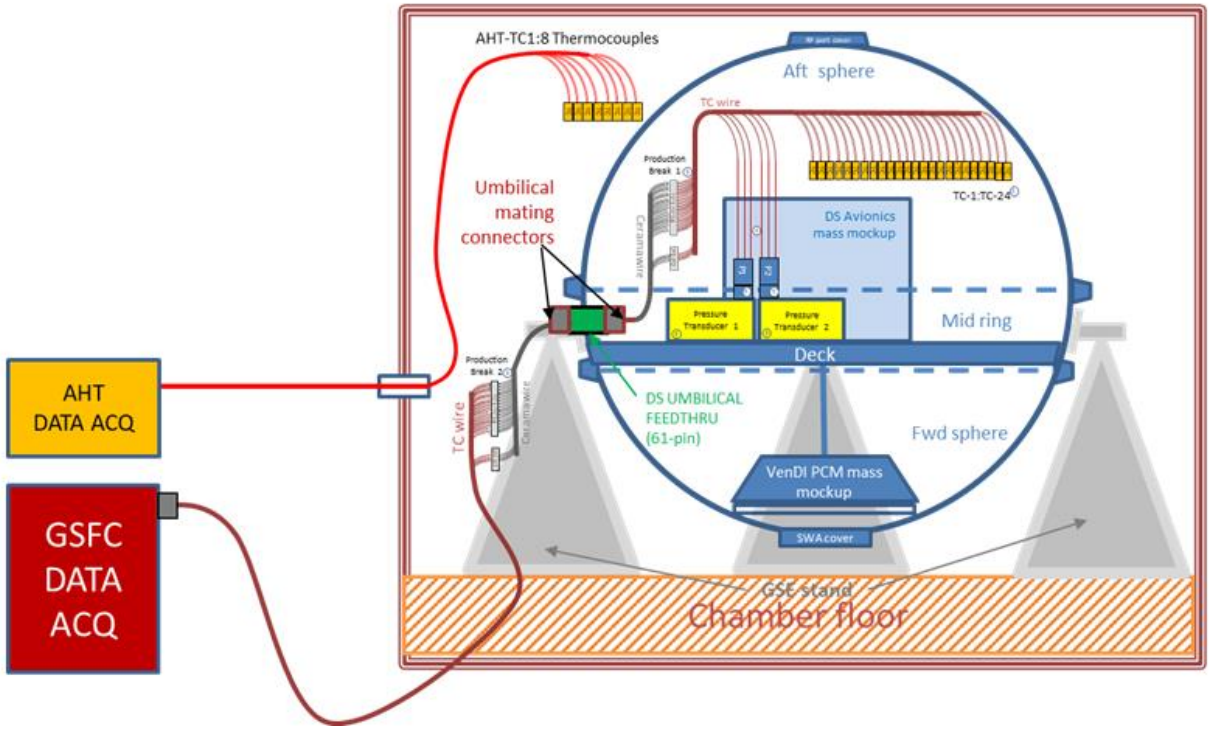
Aft Insulation and Retainer



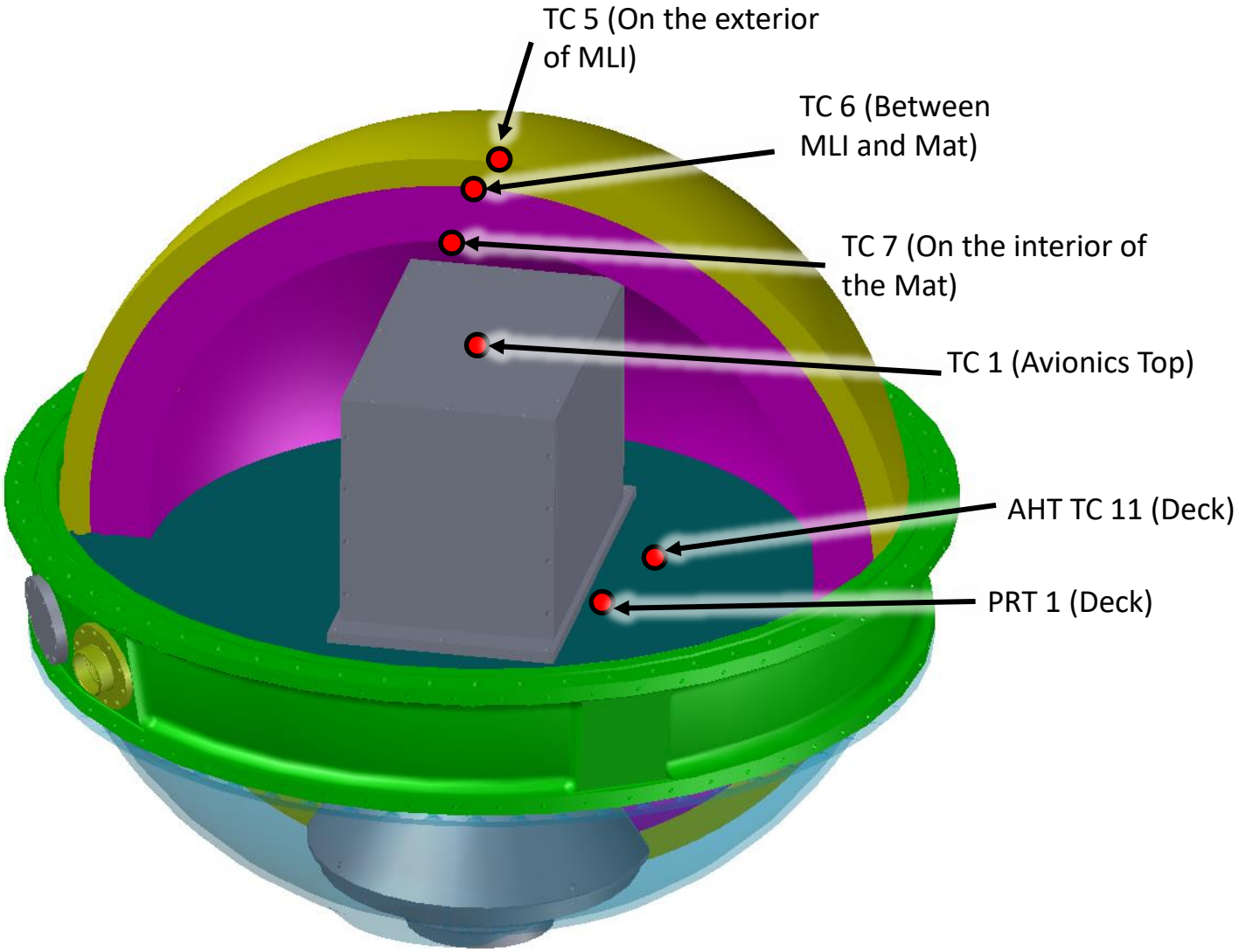
MLI with Flight-like Penetrations

Full Scale EDU Test Setup

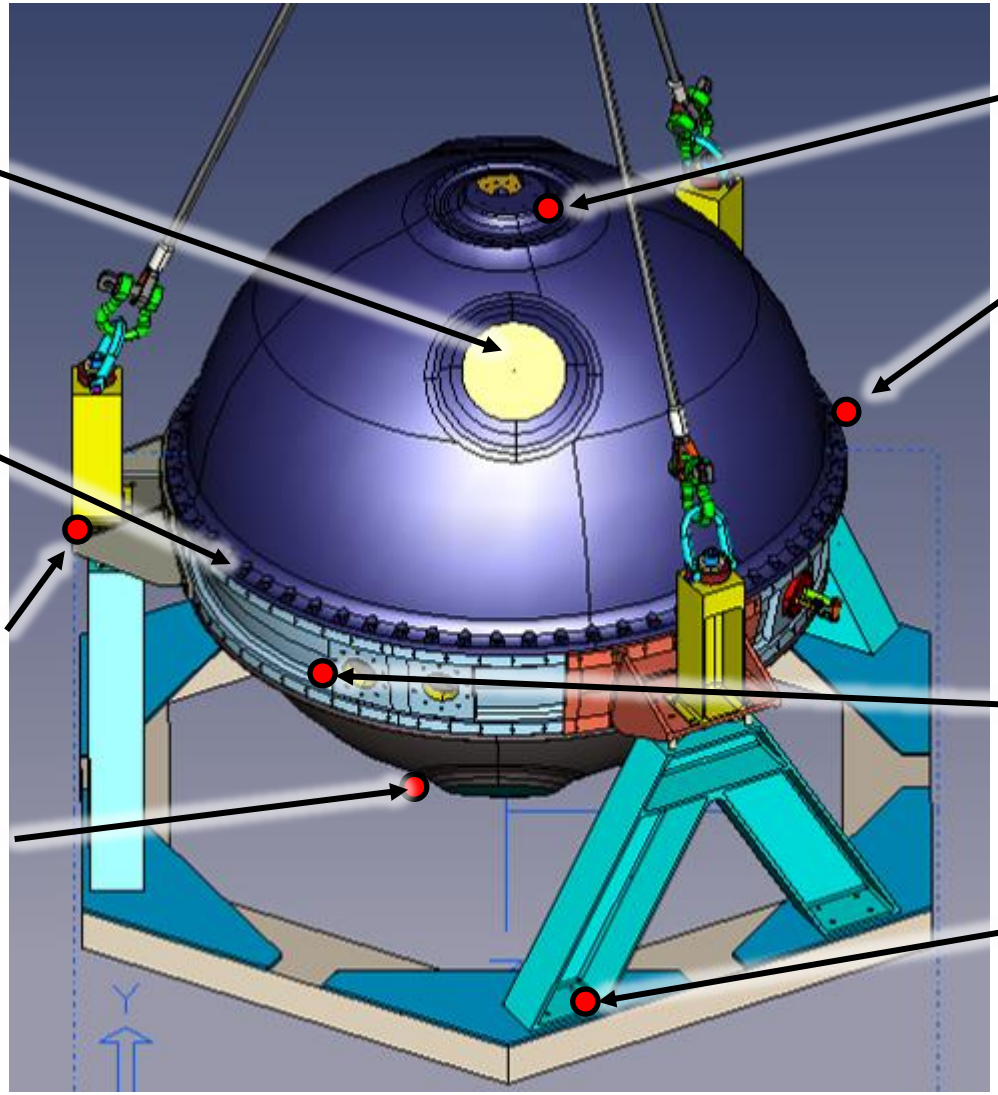
- Full-scale Ti DS houses the MLI, mat, and internal mass simulators
- 1 inch-thick, flight-like aft and fwd MLI and mat insulation installed
- A half-inch thick aluminum deck is isolated from the mid ring (MR) by ¾” titanium spacers.
- Mass simulators for both the avionics box and the VENDI instrument were mounted to the aft and forward side of the deck respectively.
- 6 internal and 8 external temperature sensors read (24 installed)



Internal TCs



External TC's (FWD PV)



TC_AHT 1 (on the PV at the antenna plate)

TC_AHT 5 (on the FD port plate)

TC_AHT 10 (on MR opposite TC 6)

TC_AHT 6 (on MR opposite TC 10)

TC_AHT 9 (on the stand near the IF with the MR)

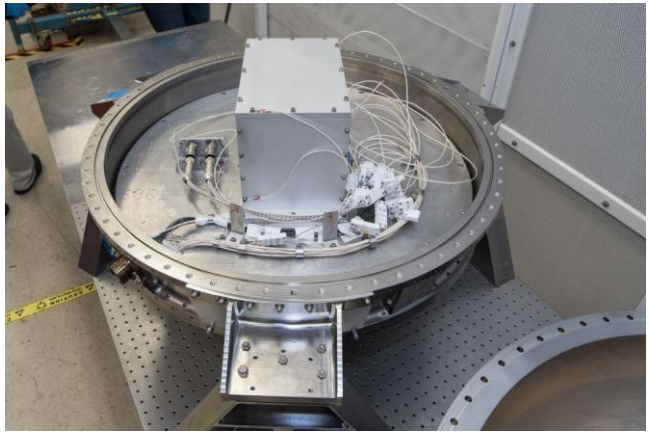
TC_AHT 8 (on the PV at the umbilical)

TC_AHT 12 (on the VENDI plate)

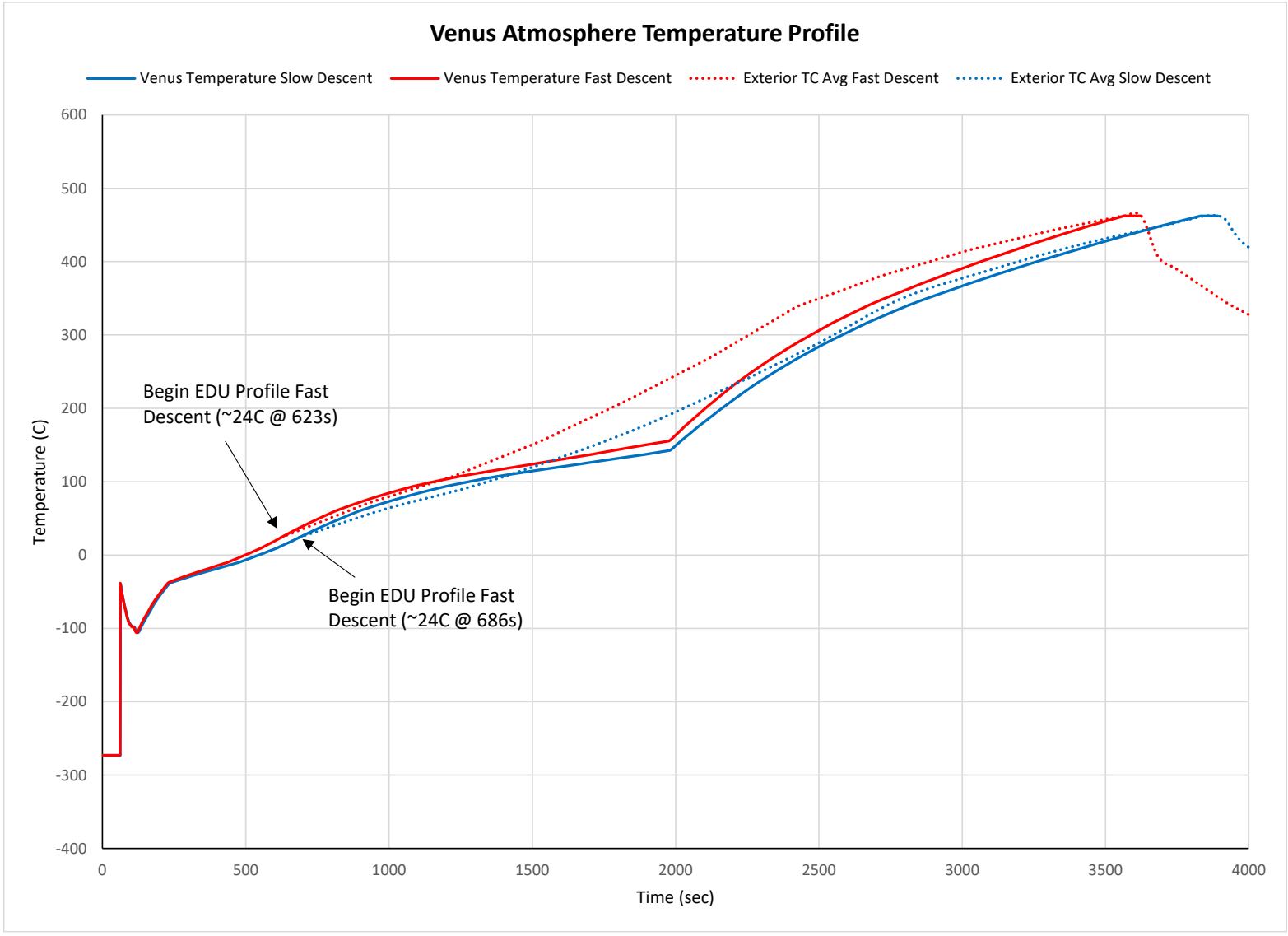
TC_AHT 7 (on the base at the IF between the stand leg and the base plates)

Fwd side facing down

Test Setup Photos



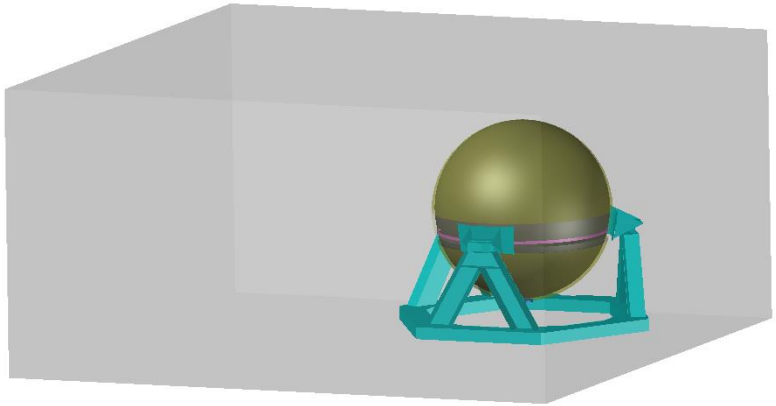
DAVINCI+ Descent Profiles



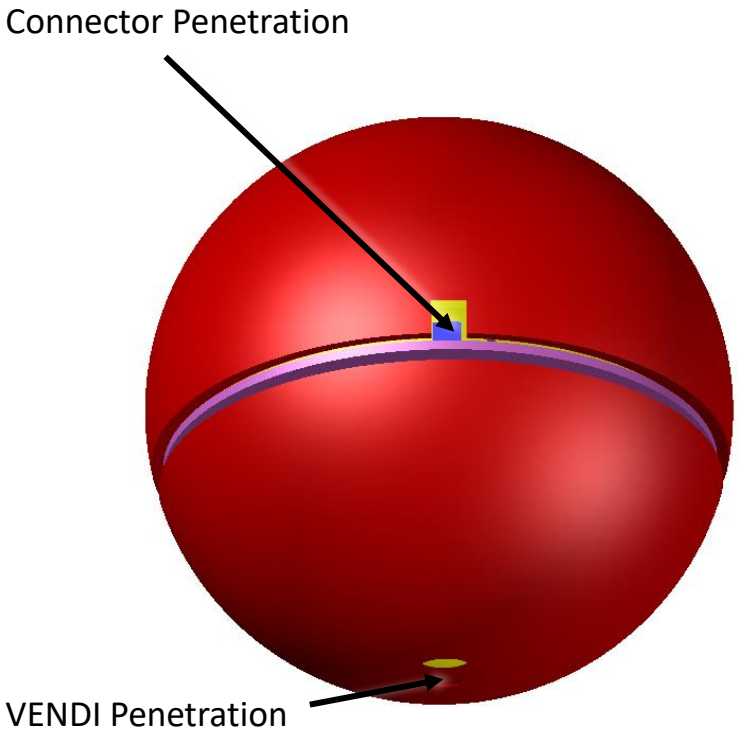
Thermal Model Overview (1 of 3)

- A thermal model of the EDU was generated in Thermal Desktop (TD) to provide initial temperature predicts and to be correlated after the test
- All thermal and mechanical hardware were weighed prior to installation and those values were flowed into the model
- Internal convection was modeled between surfaces using an h value that was varied for correlation
  - Initial assumption was that this value was uniform throughout the DS
  - Data showed that h varied with pressure
- MLI insulation was modeled as a 1 inch thick solid during correlation to better capture mass properties as well as the radiative transfer between the MLI, the exterior of the DS and the mat insulation
- Mat insulation was also modeled as a 2 inch thick solid in TD
- The aft and fwd mat retainer was added to the model
- After testing, the exterior of the DS was broken into 6 regions representing the 6 exterior TCs and modeled as a boundary

Thermal Model Overview (2 of 3)

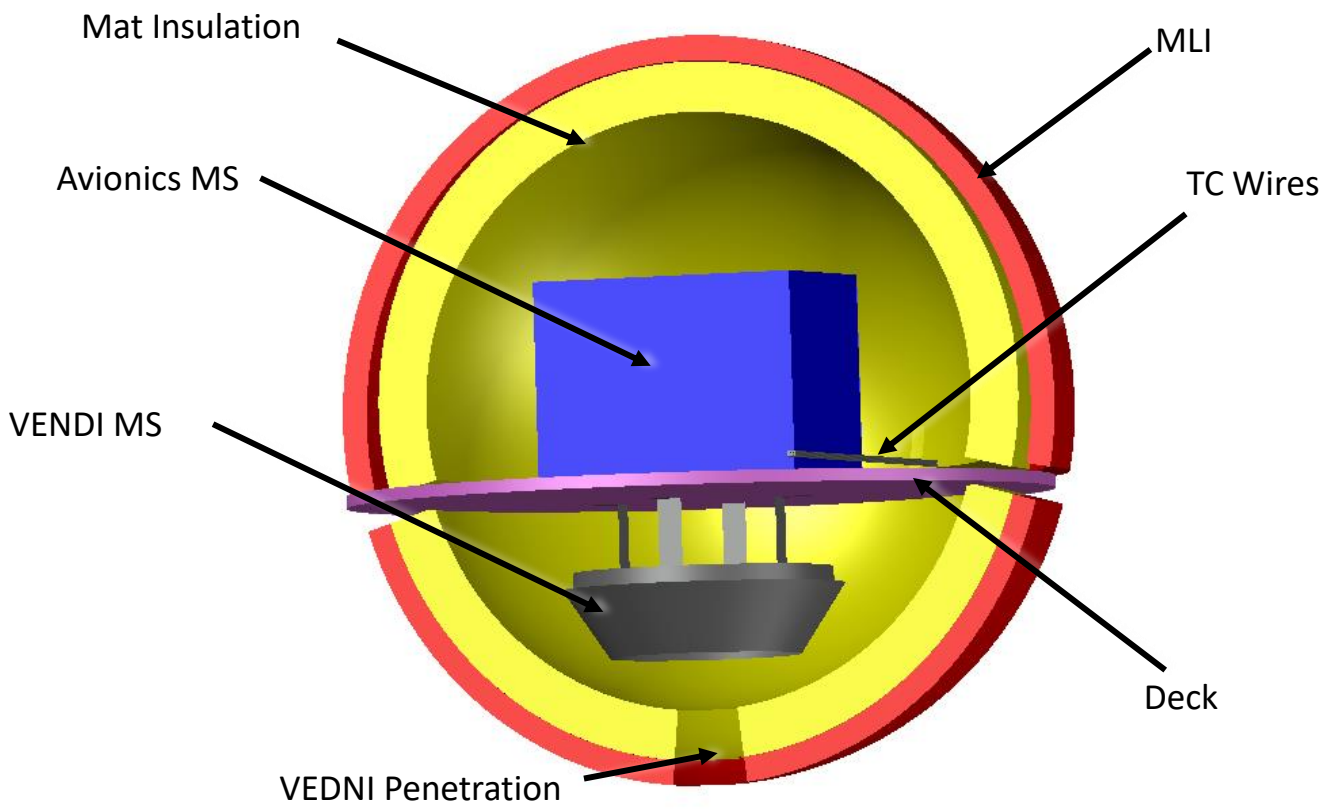


DAVINCI+ EDU Inside the Chamber



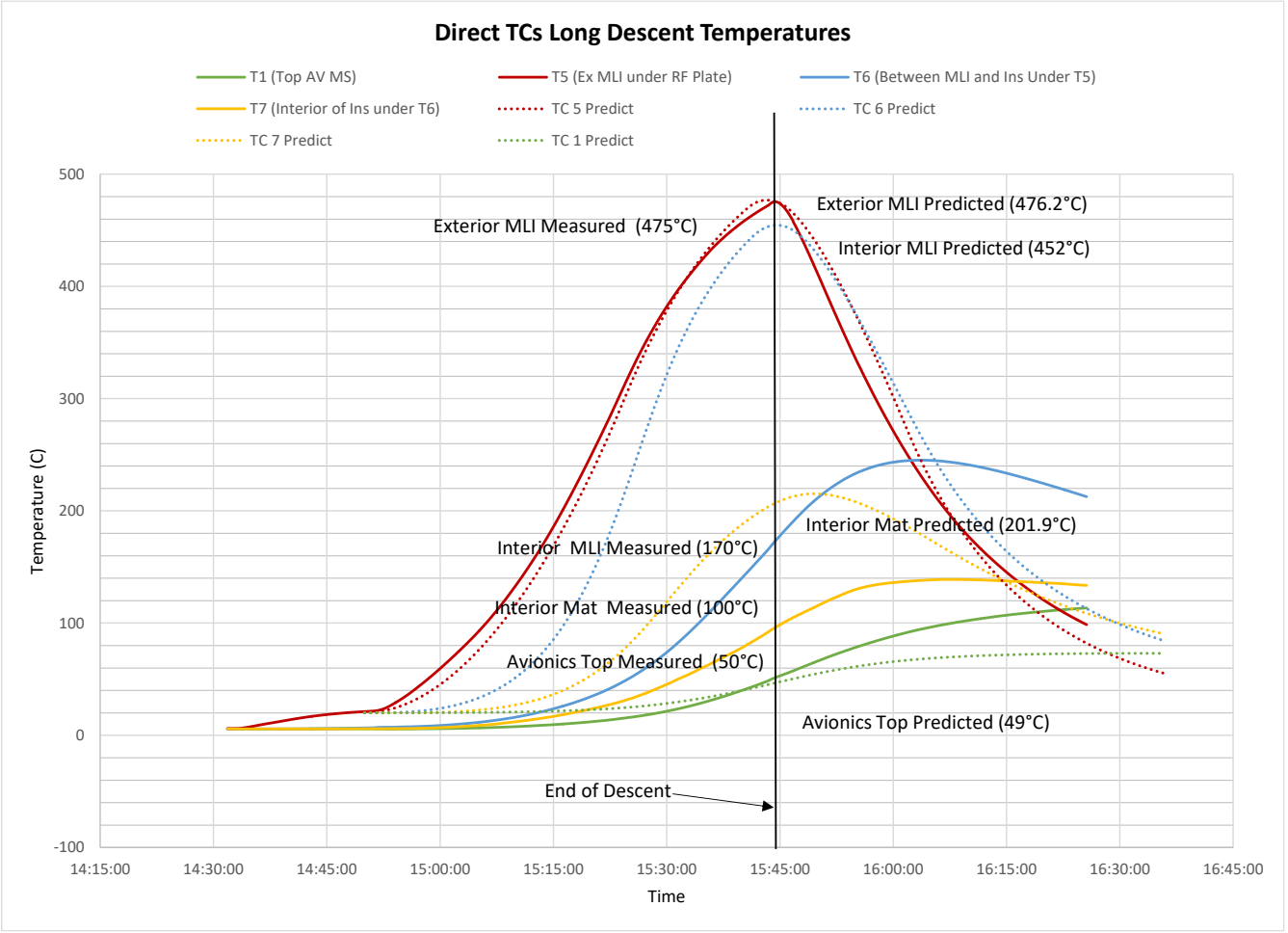
DAVINCI+ EDU Insulation (External)

Thermal Model Overview (3 of 3)



DAVINCI+ EDU Interior

Test Data vs Pre-Test Predicts (slow descent)



- TC data shows good performance through the insulation
- Data from the skin of the DS to the avionics box is sufficient to correlate the insulation on the Aft sphere
- Predicts show that the MLI assumptions were more conservative than the data shows
- Internal convection coefficient appears to be greater than initial analysis assumes

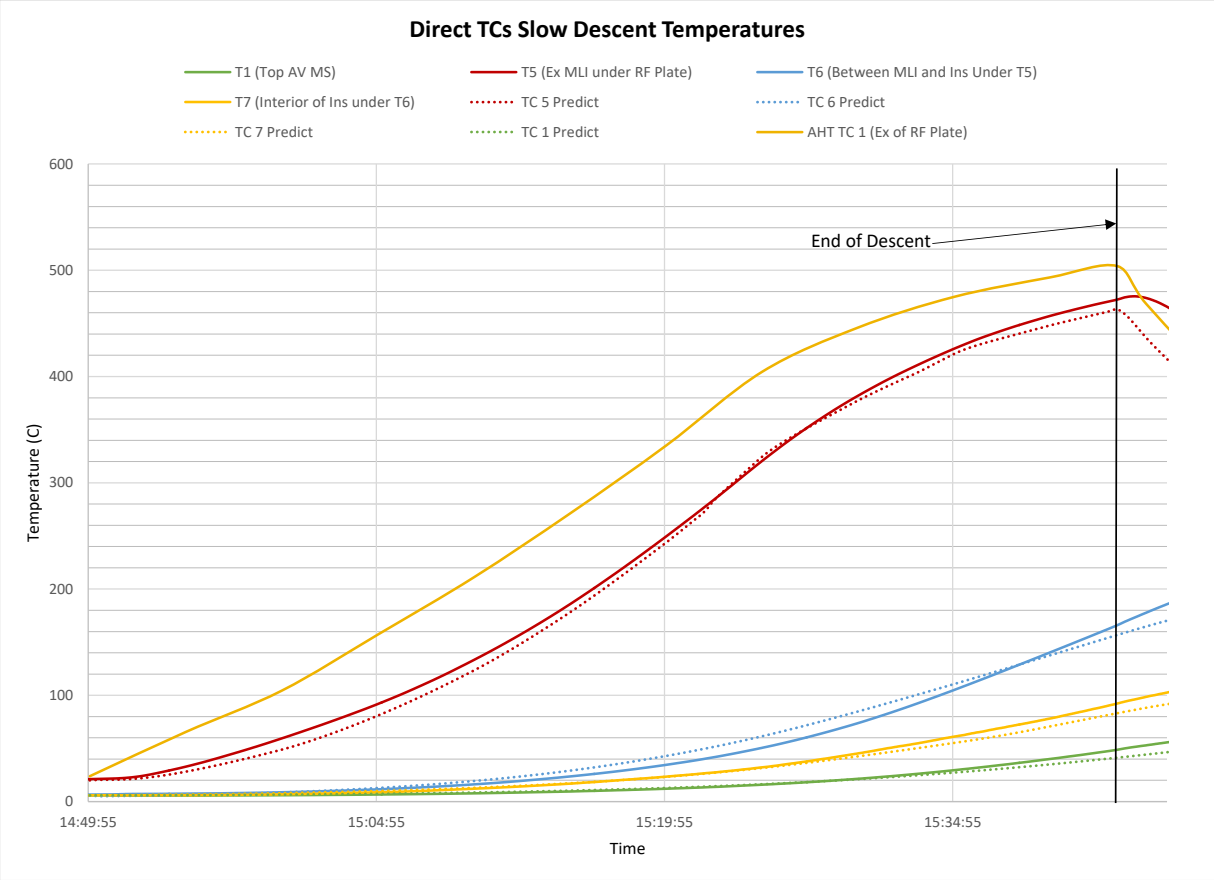
Correlated Parameters

Description	Initial Value	Correlated Value	Comments
MLI e*	0.19	0.14 (keff = 0.057)	Initial value from hemispherical test
Mat insulation Keff	0.03 W/m-C	0.05 W/m-C	Initial value from hemispherical test. Pioneer Venus showed 0.03 to 0.09 W/m-C.
Internal convection coefficient	0.1 W/m2-C	5 W/m2-C average	Initial assumptions assumed uniform h value. Data showed as pressure increased h increased as well.

- MLI e* was calculated using the keff from TD and converting it according to the equation below. The value of e* was averaged over the descent.

$$e* = \frac{k_{eff}*(T_h - T_c)}{l*\sigma*(T_h^4 - T_c^4)}$$

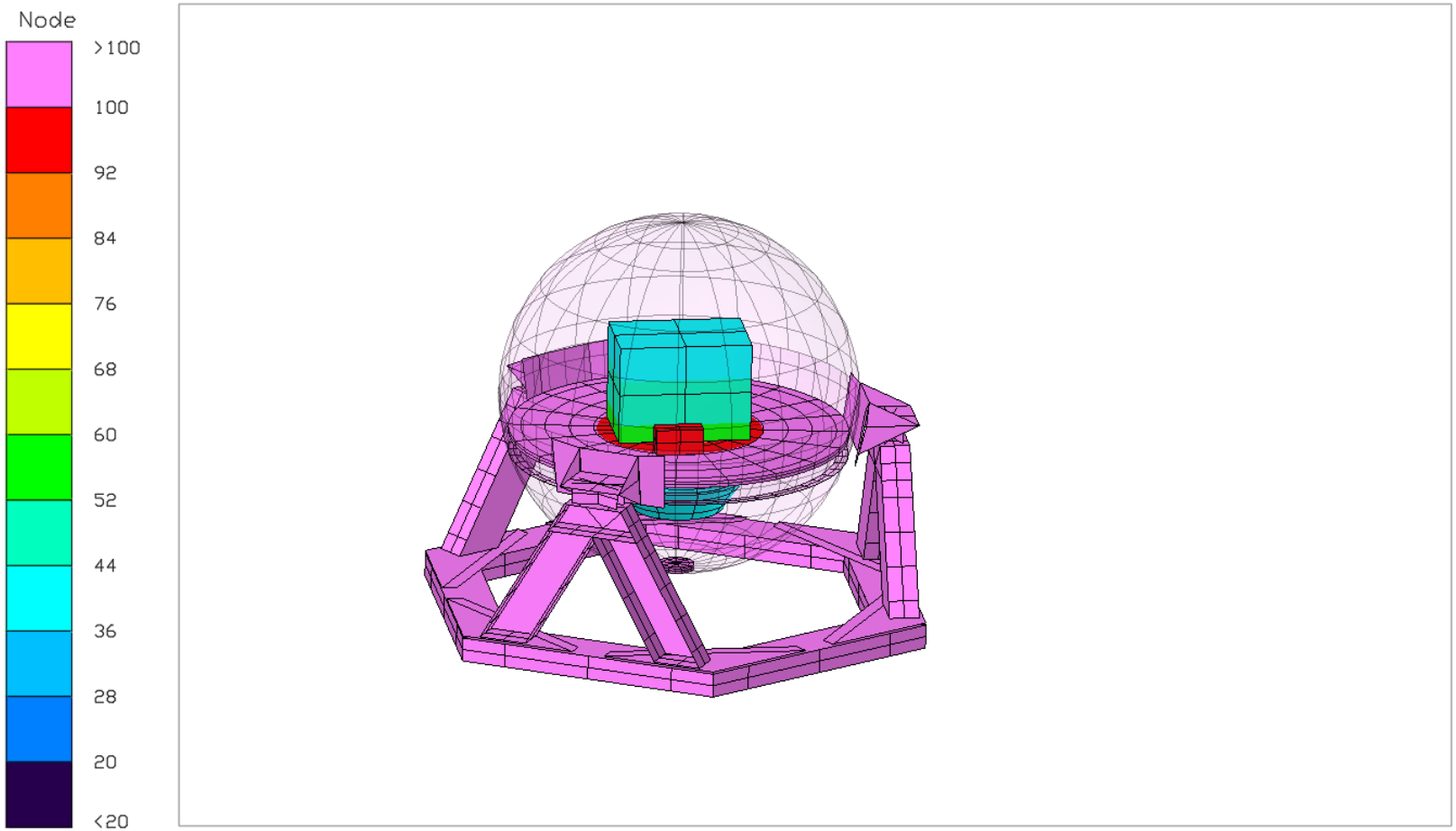
Test Data vs Correlated Predicts (Slow Descent)



	Max Delta	Standard Deviation
TC 1 Delta	7.46	1.69
TC 5 Delta	11.61	3.19
TC 6 Delta	11.53	3.86
TC 7 Delta	9.12	2.63

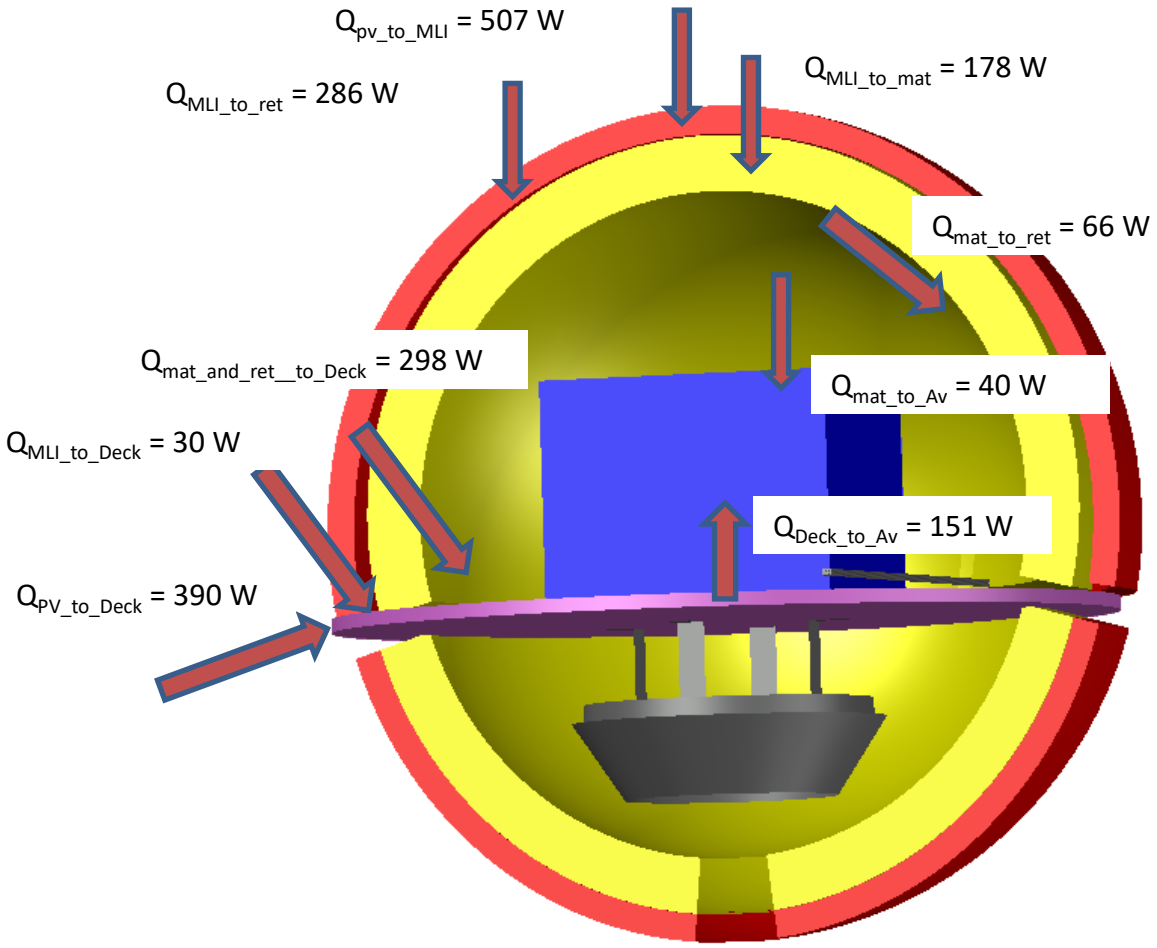
- Predicts and measured data correlated to within 12C during descent
- Standard deviation <4C

Slow Descent Temperature Map



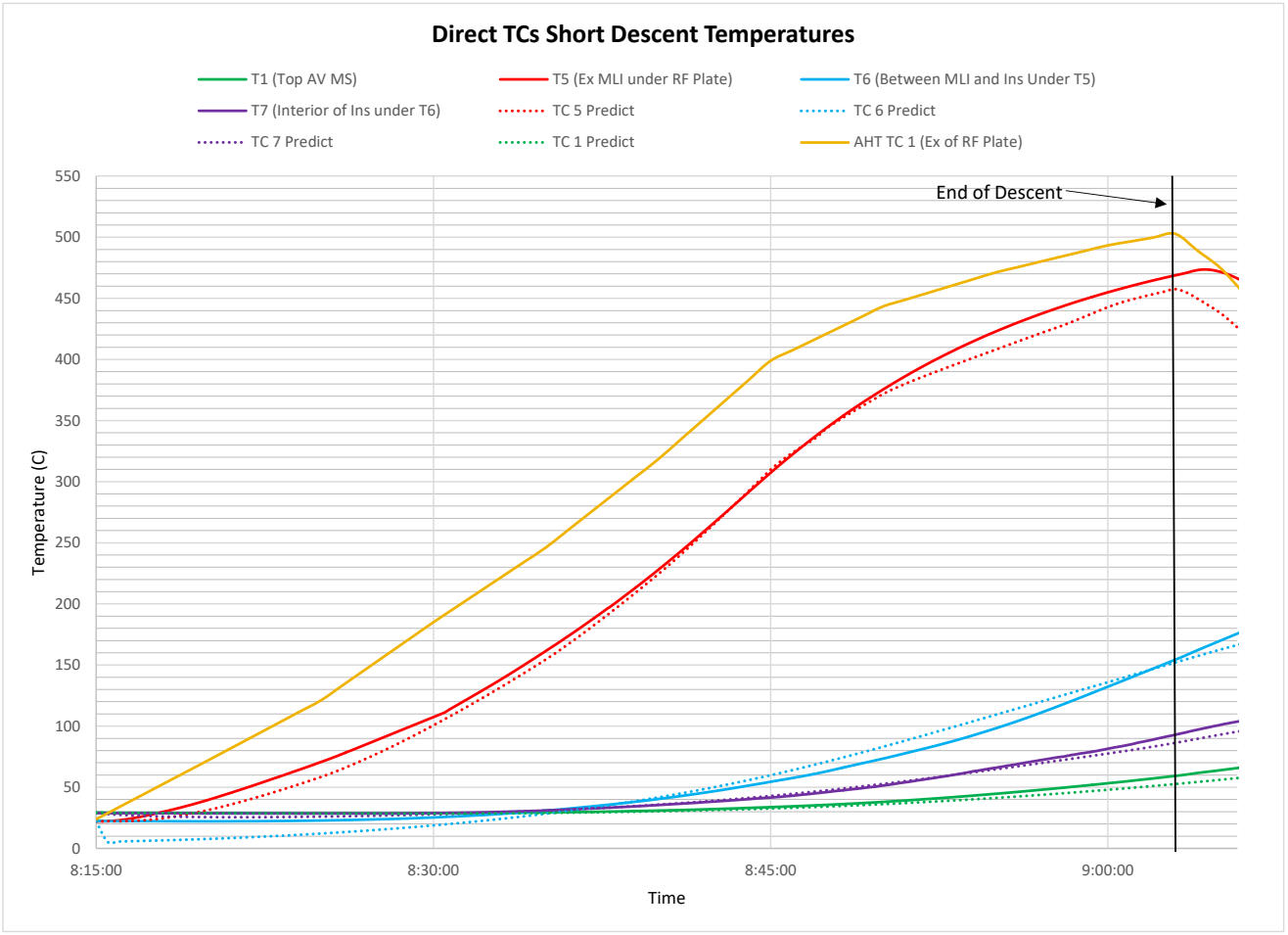
- Temperature map shown at end of descent

Heat Flow Map Slow Descent



- Values shown at the end of descent

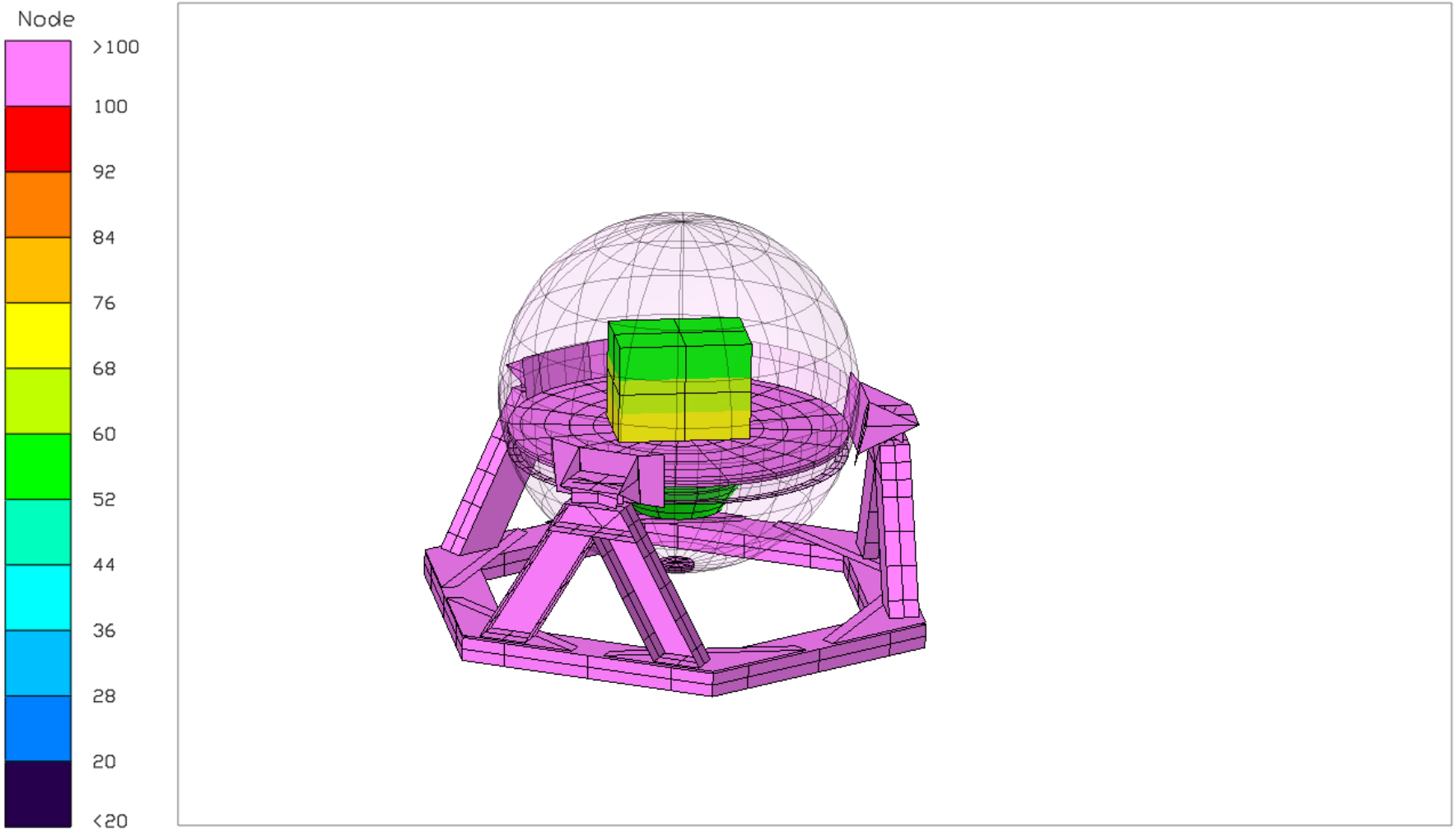
Internal TC Measurements and Correlated Predicts (Fast Descent)



	Max Delta	Standard Deviation
TC 1 Delta	6.61	1.81
TC 5 Delta	15.74	4.71
TC 6 Delta	16.88	4.71
TC 7 Delta	6.66	1.44

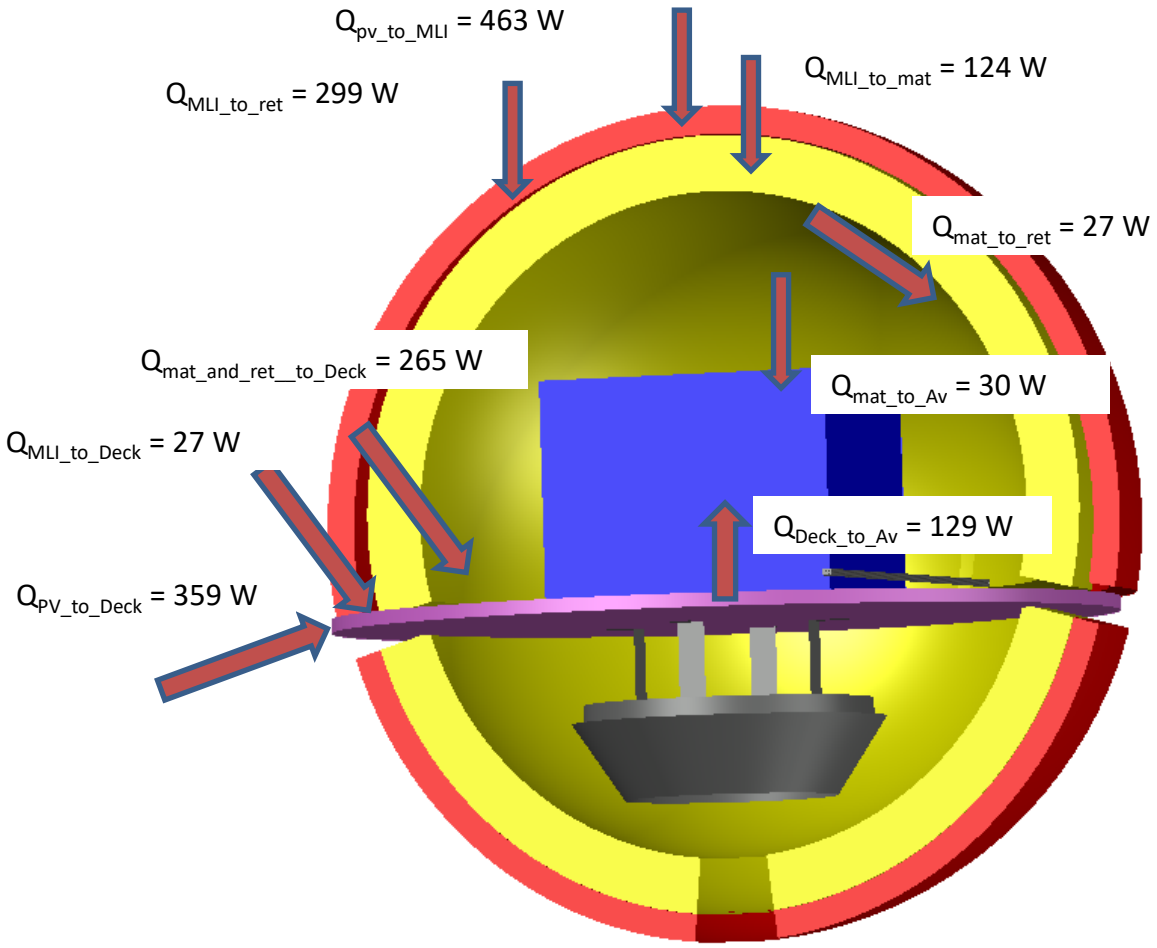
- Predicts and measured data correlated to within 17C during descent and cool down
- Standard deviation <5C
- A 17C delta in temperatures will result in as much as a 12% difference in e* yielding an e*=0.16 when margin is added
  - Value obtained using a T^4 ratio

Fast Descent Temperature Map



- Temperature map shown at end of descent

Heat Flow Map Fast Descent



- Values shown at the end of descent

Updated DAVINCI+ Flight Predicts

DS Component Operational	Limit (°C)	Updated Predict @ 63 mins (°C)	Updated Margin (°C)
Avionics	40	27.7	12.3
Battery	85	49.3	35.7
Instrument Electronics	50	26.2	23.8
Pressure Transducer	50	17.9	32.1
VMS/VTLS Inlet 3 Bypass	50	19.5	30.5
VMS/VTLS Inlet 1 Bypass	50	19.4	30.6
VMS/VTLS Pump External Volume	50	20.7	29.3
Transmitter	50	37.7	12.3
VASI Accel	78	24.3	53.7
VenDI Camera	60	19.9	40.1
VenDI Detector Electronics	60	24	36
VenDI Ebox	60	26.1	33.9
VenDI PCM	70	28	42
VMS CO2 Scrubber	50	0.7	49.3
VMS Manifold	200	184.8	15.2
VMS Gas Trap	100	22	78
VMS RF Electronics	60	25.8	34.2
VMS Getter 1	300	19.3	280.7
VMS Getters 2 and 3	300	21.2	278.8
VTLS Laser Plate	50	24.2	25.8
VMS WRP	50	39.5	10.5
VMS High Conductance Valve 1	50	30.6	19.4
VMS High Conductance Valve 2	50	30.6	19.4
VMS High Conductance Valve 3	50	30.6	19.4

- Updated parameters result in margins of >10C at the end of descent
- Test results show thermal design performs well with substantial margin at Venus temperatures

Summary

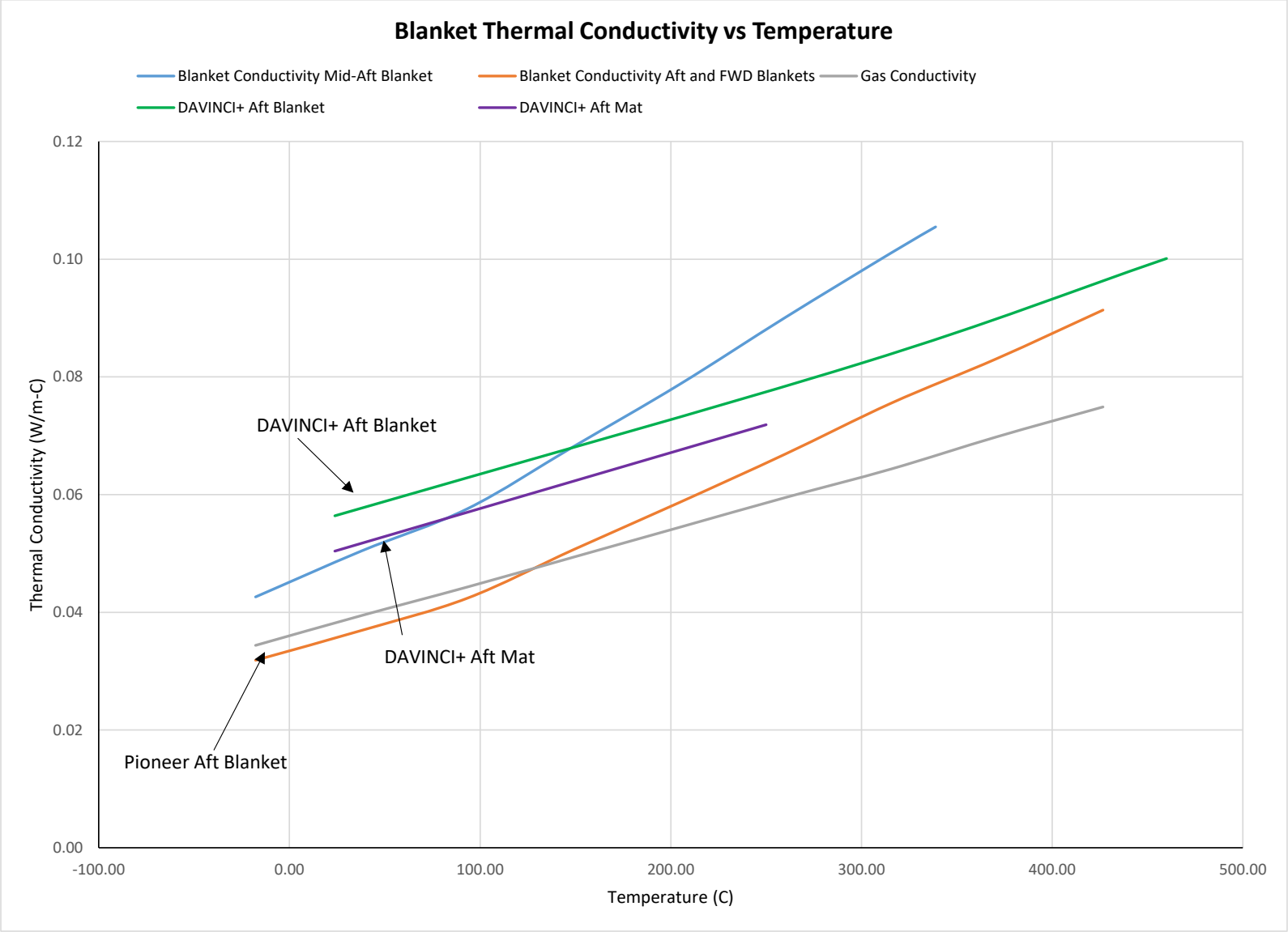
- The DS EDU insulation test was successful!
  - Gained valuable experience in assembly and manufacturing of the Descent Sphere
  - Mat insulation and MLI assumptions were consistent with values measured during previous testing
  - Internal convection coefficient showed higher than expected values
  - Updated predicts using correlated values still show temperature margins at impact

Future Testing and Lessons learned

- Future thermal test goals to include phase change material, beryllium decks, and titanium isolators
- Lessons learned
  - Use PRTs instead of Thermocouples
    - Thermocouples react with the harness (dissimilar metals) to producing large errors in calibration

Backup Slides

MLI Performance



Pioneer Thermal Design

- Inner surface of sphere lined with 40 layers of aluminized kapton (test limit is 300°C)
  - ~1 in thick
  - 39 layers are alternating 0.5 mil dimpled and 0.25 mil flat layers
  - 1 mil inner and outer kapton layers
  - Held in place by thin spherical Ti retainer
  - 2 mil kapton was used to close out all blanket penetrations and edges
  - Tested k* values of the blankets can be seen to the right (N_2/He mixture was used for testing due to the higher thermal conductivity of He which was being outgassed by some of the instruments during descent)
- Conductive isolation between the decks and the outer sphere was achieved through 24 Ti (6A1-4V) standoffs and a Ti standoff support structure (Z-ring)
- Low emittance coating (ε ≤ 0.1) on all interior surfaces to provide radiative isolation
- Silicone rubber adhesive (RTV 566) applied to mounting surfaces to create isothermal mass of payload and shelves
- Sphere pressurized to 1 atm of N_2
- Internal convective coefficients measured during testing to be between 0.5 and 2.0 Btu/hr-ft^2-^{o}F (2 to 11 W/m^2-^{o}C)

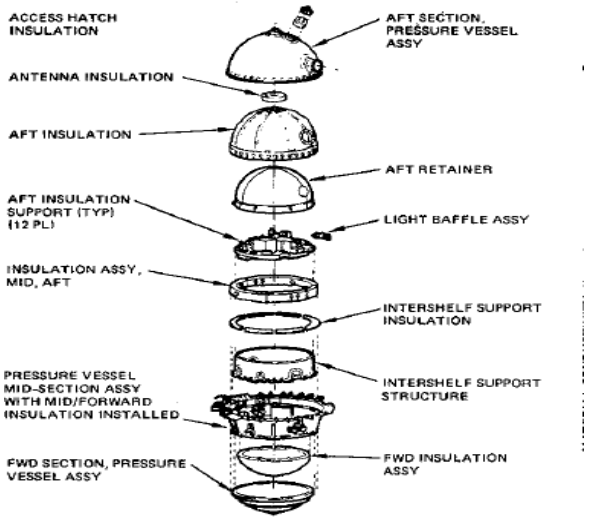


FIGURE 7. INSULATION CONFIGURATION

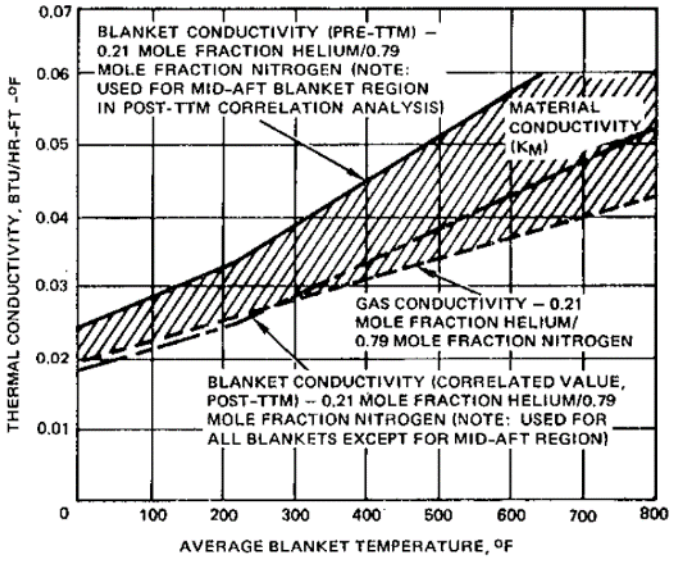


FIGURE 9. BLANKET THERMAL CONDUCTIVITY VERSUS TEMPERATURE