Thermal Control of Boundaries for JWST Infrared Tests in Cryogenic Vacuum Configuration

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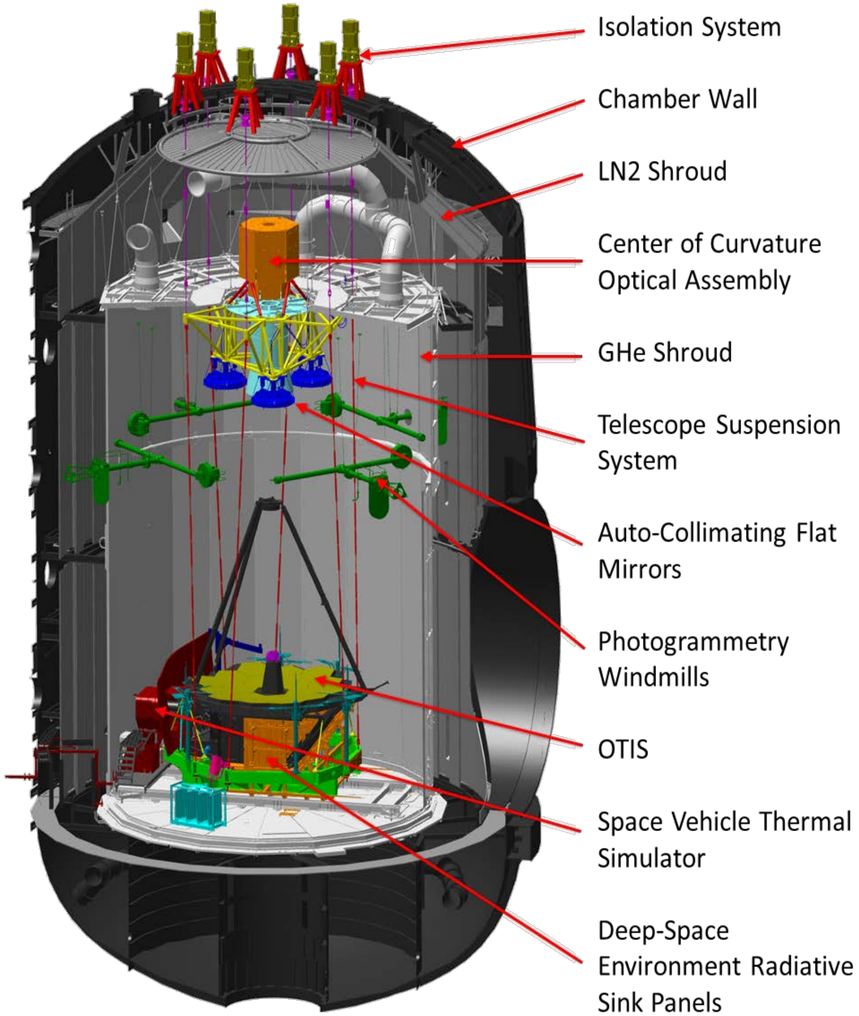
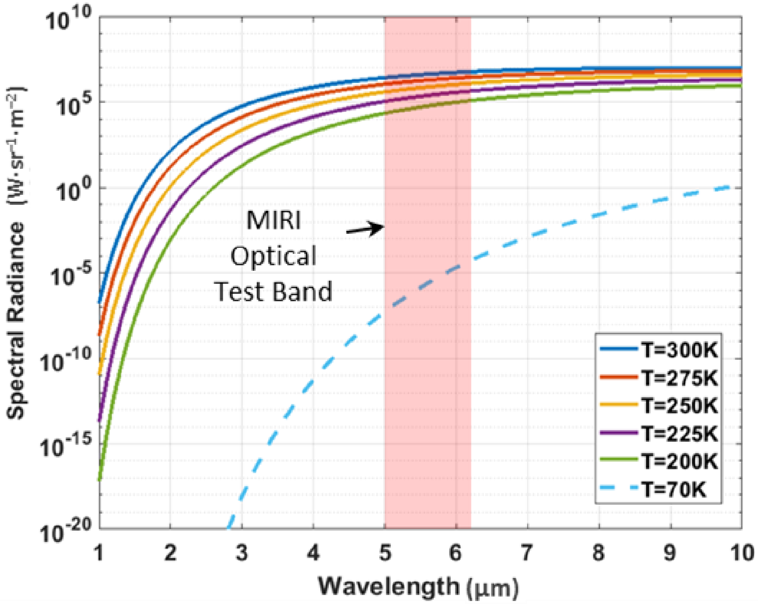
OTIS Test Overview

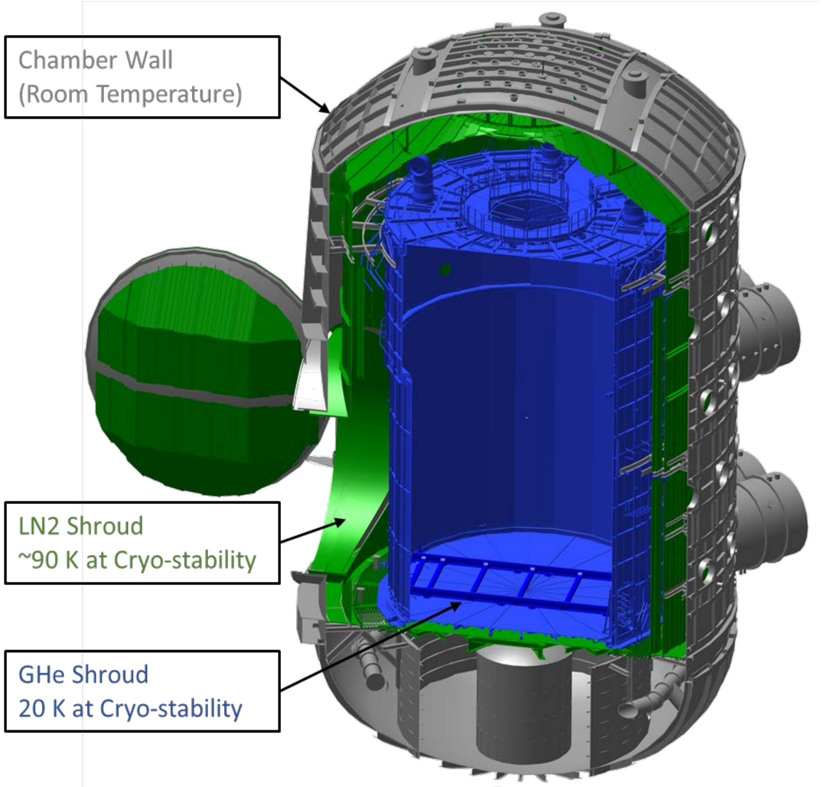
- **Optical Telescope Element and Integrated Science Instrument Module assembled into OTIS in 2016**
- **Cryogenic vacuum testing performed in 2017 at Johnson Space Center to:**
  - Verify alignability and wavefront performance of the OTE
  - Perform end-to-end testing of the OTE and science instruments
  - Verify thermal hardware workmanship
  - Gather thermal balance test data for model comparisons
- **Nine story chamber with 1100 m^2, multi-panel GHe shroud**
- **30-day cool down to test temperature**



Infrared Instrument Testing Requirements

- **Stray light from warm sources can saturate instruments and interfere with optical testing of science instruments**





- **A conservative maximum allowable temperature requirement of 70 K was levied on all surfaces with a view to the optical path**
- **All penetrations in the GHe shroud and all test equipment entering it required thermal management**

Thermal Control Overview

- **Thermal Control Objectives:**
  - Eliminate direct viewfactors from the chamber wall into the GHe shroud.
  - Minimize direct viewfactors from the LN_2 shroud into the GHe shroud.
  - Minimize reflective (non-black or specular) surface finishes in view of the optical path.
  - Achieve < 70 K on all surfaces within view of the optical path.
- **Thermal Control Methods:**
  - Shroud penetration closeouts
    - Stationary and movable
  - Thermal anchoring of electrical cables entering the shroud
  - Thermal control systems for test equipment operating inside the shroud

Reradiation of SLI Covers

- **Many penetration closeouts were designed as simple SLI covers**
- **SLI temperature can be calculated as a function of its emissivities and the two environments it separates:**

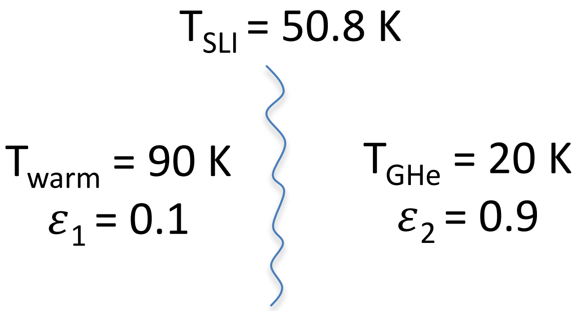
$$T_{SLI} = \left(\frac{\varepsilon_1 T_{Warm}{}^4 + \varepsilon_2 T_{GHe}{}^4}{\varepsilon_1 + \varepsilon_2}\right)^{\frac{1}{4}}$$

- **Knowing this temperature, the heat flux reradiated into the test cavity is:**

$$q_{rerad} = \varepsilon_2 \sigma (T_{SLI}{}^4 - T_{GHe}{}^4)$$

- **Without the closeout, heat flux into the test cavity is*:**

$$q_{cavity} = \varepsilon_2 \sigma (T_{Warm}{}^4 - T_{GHe}{}^4)$$


T_{SLI} = 50.8 K

T_{warm} = 90 K
ε_1 = 0.1

T_{GHe} = 20 K
ε_2 = 0.9

- **To understand how much energy is blocked by the closeout, consider the ratio:**

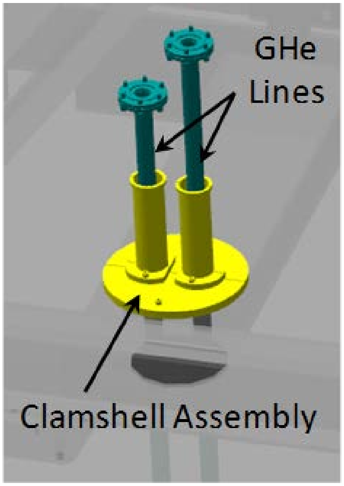
$$\frac{q_{rerad}}{q_{cavity}} = \frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2}$$

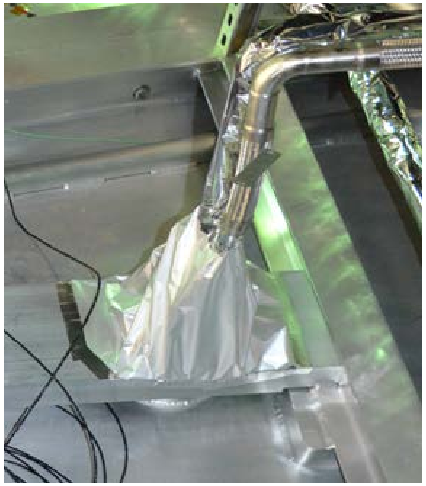
- **Using low emissivity on the warm side of the closeout results in a ratio of 10% reradiated, or a 90% reduction in heat flux into the shroud.**

* Assumes Warm surface emissivity = SLI ε_2 emissivity

Stationary Penetration Closeouts

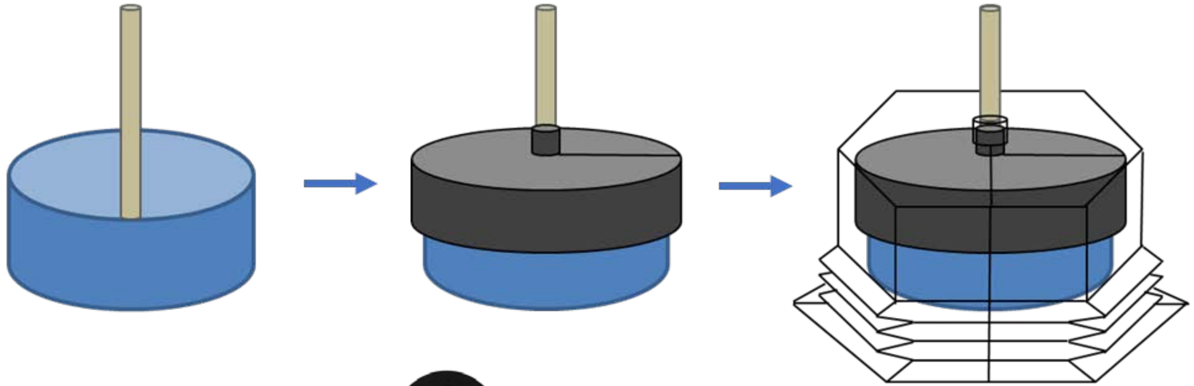
- **The majority of shroud penetrations were cutouts required for access or metrology during integration of test hardware.**
- **Many had metallic, purpose-built covers for mechanically sealing the openings after integration.**
- **Additional effort to ensure light tightness could be required, especially if:**
  - Covers could not be securely fastened to shroud
  - Covers were multi-part components with seams that might open due to cryoshift.
  - Test hardware fed through the penetration without completely sealing it.
- **Single layer polyimide or polyester was typically used to ensure a light-tight cover in these instances.**





Movable Penetration Closeouts Down Rods Example

- **Top-mounted, hanging configuration of the OTIS test resulted in critical load-bearing hardware penetrating the shroud ceilings.**
- **Dynamic quiescence required that closeouts minimize shorts.**
- **A two-part system was used in this example:**
  - Baffle mounted to rod and sized to prevent touching shroud was used to remove direct energy paths into test cavity
  - Flexible outer layer created light-tight seams



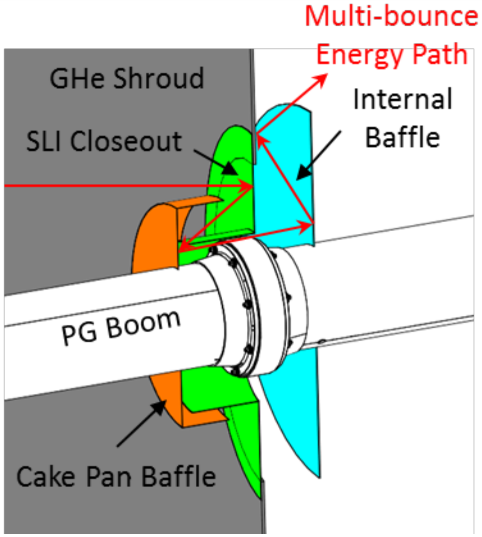
Starting Configuration

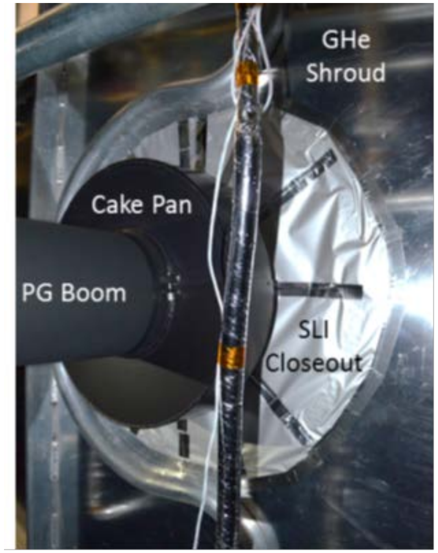
Cake Pan Baffle Installed on Rod to Overlap Vertical Shroud Collar

Flexible Outer Closeout Attached with Light-tight Seams at Down Rod and Shroud Ceiling

Movable Penetration Closeouts PG Boom Example

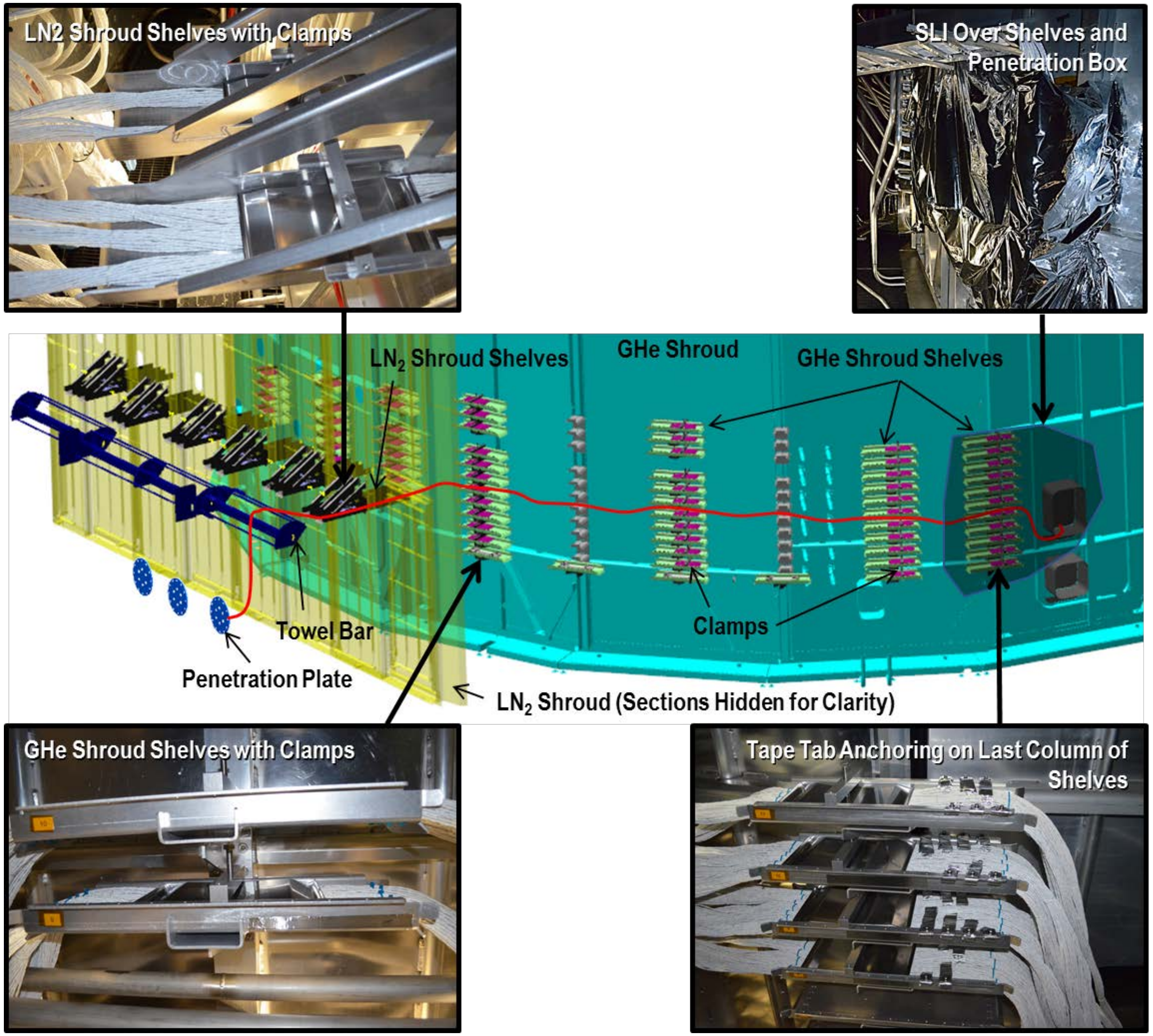
- **Complicating factors of this closeout job:**
  - Large shroud cutout – approximately 0.25 m^2
  - 355 degree rotation requirement of the PG Boom
  - Had to survive at least 5 cryo-cycles
- **Multi-part Baffle Solution:**
  - Wire-stiffened SLI closeout attached to shroud necks down energy through-path.
  - Aluminum cake pan baffle attached to GHe-cooled PG Boom and overlapping SLI closeout eliminates direct viewfactors from LN$_2$ and chamber wall to SLI gap.
  - Aluminum internal baffle attached to GHe-cooled PG Boom completely blocks direct energy from cutout area and redirects energy back to shroud wall





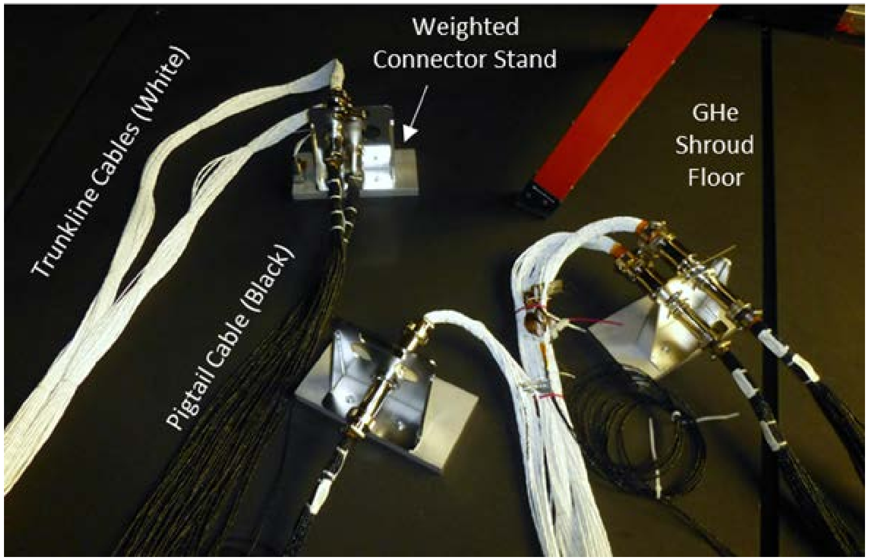
Thermal Anchoring of Cables

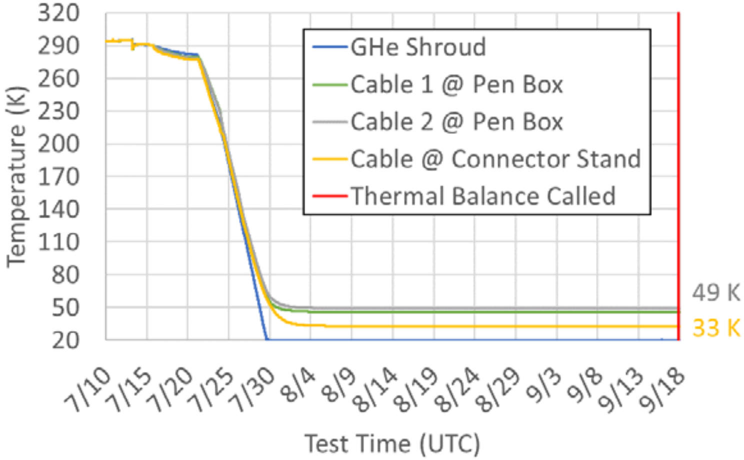
- **Test telemetry and thermal control systems required dozens of cable bundles enter the optical test cavity.**
  - 164 GSE Heaters
  - 964 GSE Sensors
- **Thermal management was required to ensure cables entered the 20 K environment below the 70 K limit.**



Cable Anchoring Test Results

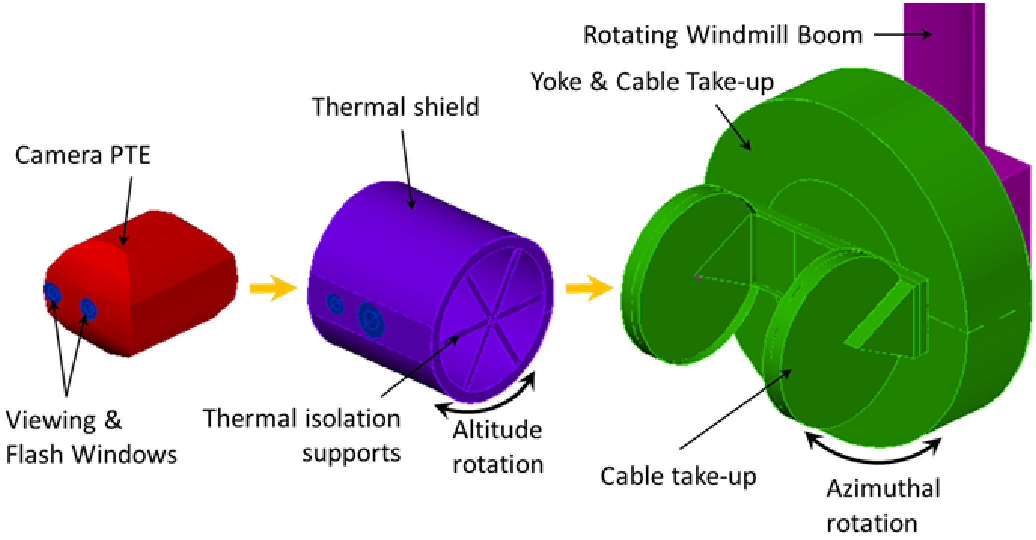
- **Inside the GHe Shroud, trunkline cables met pigtails and extra lengths of both were coiled on the floor providing further cooling.**
- **Temperature sensors on the cables a the penetration box and connector stands show that at cryostability:**
  - Cables entered the GHe Shroud just below 50 K.
  - Additional cooling inside the GHe Shroud resulted in cable temperatures under 35 K at the test article.





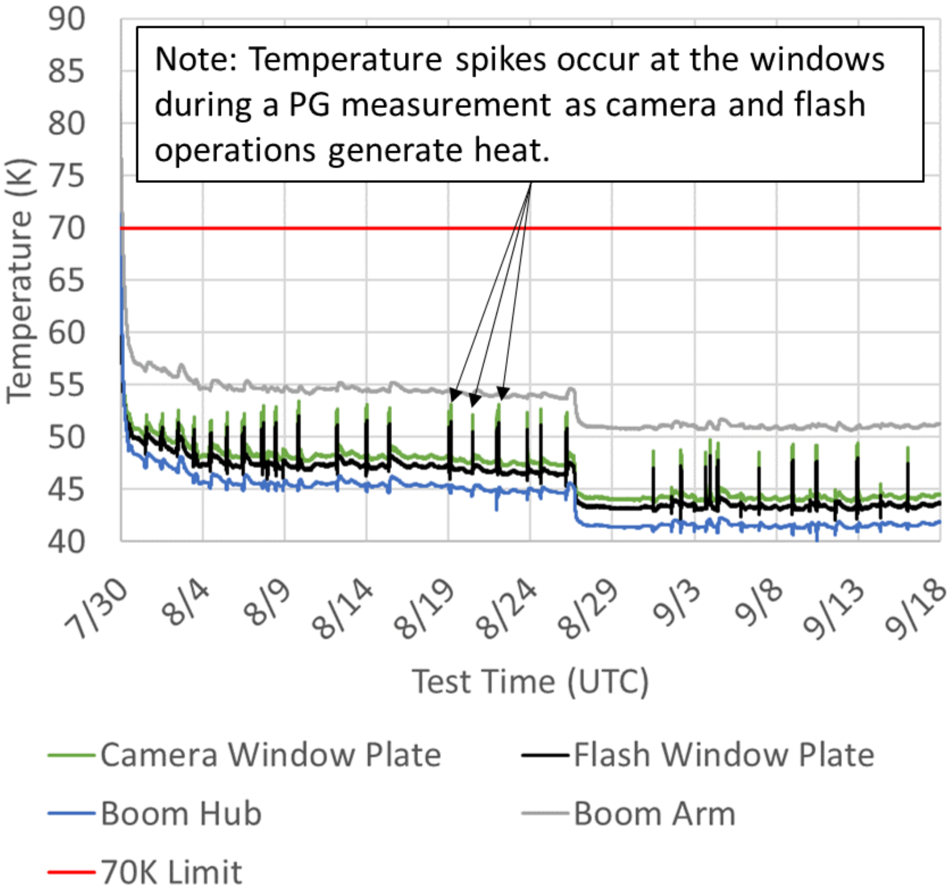
Test Equipment Thermal Management

- **Room temperature and pressure metrology systems were required inside the optical test environment.**
- **The most complicated of this was a set of four camera and flash Photogrammetry units suspended in the test cavity**
- **An active thermal management system was required to both manage the temperature and pressure sensitive hardware and maintain a cold exterior. It was designed with:**
  - A blanketed pressure tight enclosure purged with dry nitrogen
  - A windowed thermal shield actively cooled with helium
  - Active cooling of the boom and other external components



CPM Test Results

- **All actively-cooled components achieved temperatures below 52 K at cryostability.**
- **The dual-window system with IR coatings was effective.**
    - No heat signatures detected by radiometers, calorimeters, or optical test images.
- **Operation of the units did result in additional heat generation, but the GHe flow was adequate to remove it.**



Lessons Learned

- **Five commissioning and Pathfinder development tests provided opportunity to experiment with closeout materials and configurations and verify with test data. Observations of note are:**
  - Over numerous cryo-cycles, pinholes can form in thin sheet materials, especially where motion from cryoshift or pressure changes occur.
  - Rigorous closeout designs with flexible features are more likely to survive multiple cryo-cycles at locations with moving parts
  - Light-tight seams can be achieved using polyimide tapes with acrylic adhesives, but CTE mismatch can cause tape lifting.
    - Aluminum foil tape with acrylic adhesive can be a good way to make tape seams to solid surfaces more robust.
  - Developing a rigorous thermal instrumentation plan is critical in large cryogenic vacuum tests.
    - Secondary instruments looking for environment heat/light leaks

Summary

- **The JWST OTIS test, the largest cryogenic-vacuum optical test to date, was successfully completed in 2017.**
- **Stray light and thermal control of test boundaries provided an 1100 m^2 environment that was dark and cold enough to successful test the flight infrared instruments by:**
  - Meticulously managing every gap, cutout, and penetration in the shroud.
  - Rigorously designing test equipment that had to be inside the shroud, including cables.
  - Providing extensive thermal telemetry and control systems and precisely controlling them during the test.

Acknowledgments

- **JWST is a collaborative effort involving NASA, industry partners, the European Space Agency, the Canadian Space Agency, the astronomy community and numerous principal investigators.**
- **OTIS cryo-vac test GSE hardware design, integration, and execution was carried out under the JWST contracts NNG11FD64C with NASA's Goddard Space Flight Center and NNG15CR64C with ATA Aerospace.**
- **Special thanks to:**
  - Randy Kimble and the NASA GSFC stray light team for assistance with chamber closeout verification
  - Wes Ousley and Mike DiPirro for cryogenic design oversight
  - The entire JWST thermal community for their contributions and collaboration to the success of this hardware and the OTIS test