

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

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In 2017, the combined Optical Telescope Element and Integrated Science Instrument Module (OTIS) of the James Webb Space Telescope (JWST) underwent functional testing and optical metrology verification under cryogenic vacuum conditions in Chamber A at the Johnson Space Center (JSC). Testing the infrared Science Instruments and OTIS optics below 50 K required an environment architecture that comprehensively controlled the temperature and energy path of every seam and penetration in the over 1100 m² of Chamber A helium shroud surfaces as well as the Ground Support Equipment (GSE) inside it. This paper outlines the design and implementation of thermal closeouts, thermal anchoring systems for electrical cables, and thermal control systems around room-temperature optical metrology equipment inside the helium shroud. It also details lessons learned from the repeated implementation and testing of these environmental control systems throughout the JWST Pathfinder test campaign.

Nomenclature

A	= Surface Area	GSFC	= Goddard Space Flight Center
ϵ	= emissivity	ISIM	= Integrated Science Instrument Module
Q	= Heat Rate	JSC	= Johnson Space Center
q	= Heat Flux	JWST	= James Webb Space Telescope
σ	= Stefan-Boltzmann constant	LN ₂	= Liquid Nitrogen
T	= Temperature	MIRI	= Mid-Infrared Instrument
ACF	= Auto-Collimating Flat (Mirror)	OTE	= Optical Telescope Element
ADM	= Absolute Distance Meter	OTIS	= OTE and ISIM
ADMA	= ADM Assembly	PG	= Photogrammetry
CPM	= Cryo-Positioning Metrology	PTE	= Pressure Tight Enclosure
GHe	= Gaseous Helium	SLI	= Single Layer Insulation
GSE	= Ground Support Equipment		

I. Introduction

LATE in 2017, the James Webb Space Telescope (JWST) Program completed a successful 100-day cryogenic vacuum test of the OTIS assembly, the integrated Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM) components, at the Johnson Space Center (JSC). The test achieved critical optical and thermal verification objectives for the telescope and infrared instruments that make up the cold half of the JWST Observatory: the hardware that will be on the side of the 5-layer shield opposite the sun. Specifically, the test achievements include verification of alignability and wavefront performance of the OTE components, end-to-end testing of the OTE and science instruments, thermal hardware workmanship verifications, and thermal balance test data gathering for model comparisons. As shown in Figure 1, these ambitious verification tests required hanging the 12x7x11-meter OTIS and numerous optical metrology GSE assemblies in JSC's 9-story vacuum chamber, called Chamber A, wrapping it in a dual-shroud system, and cooling it to flight-like temperatures.¹

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Considering that the thermal balance test required precise control of boundary heat leaks on the mW scale, and the optical and instrument tests required careful management of stray light entering the optical path, it was critical that the environment around the telescope be tightly controlled. The most demanding stray light requirements came from optical testing with the Mid-Infrared Instrument's (MIRI's) broadband imaging channel in its shortest wavelength filter which has a bandpass of 5-6.2 μm .² Note that MIRI covers a much wider range of 5-28 μm , but focus and alignment measurements for the OTIS test only required measurements in the shortest bandpass filter. The health of the instrument in its longer wavelength modes was confirmed using internal sources with the instrument's light-tight contamination control cover closed. Even these shortest MIRI wavelengths are, however, well within the emission spectrum of a black body at room temperature, as can be seen in Figure 2, which shows the spectral radiance for black body sources for temperatures between 200 K and 300 K. The stray light emitted by objects in this temperature range would have been intense enough to saturate the MIRI instrument and prevent optical testing and therefore had to be mitigated. A stray light analysis of the OTIS Test configuration indicated that levying a 70 K maximum temperature limit on all surfaces with a view to the optical path was safely conservative. Figure 3 adds a plot of spectral radiance for a 70 K source and is zoomed into the mid-infrared wavelength region with spectral radiance on a logarithmic scale. Comparison of the curves on that plot shows that a 70 K source produces 12 orders of magnitude less emission than a 300 K source.

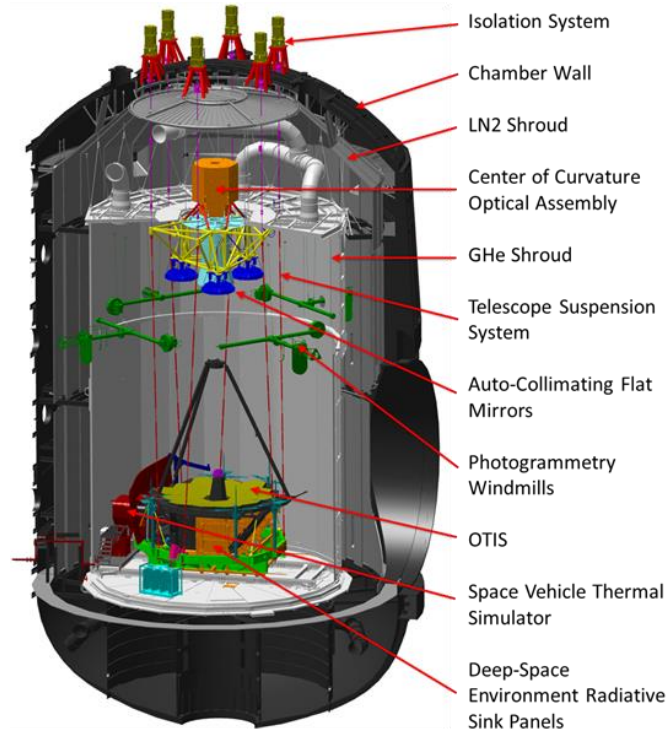


Figure 1. OTIS Test Configuration.

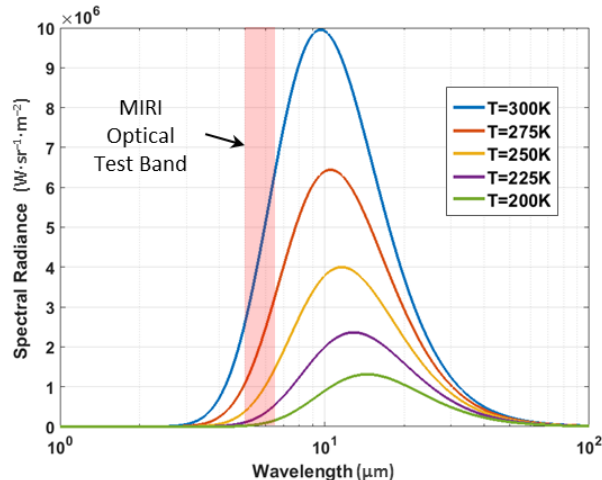


Figure 2. Black Body Spectral Radiance for 200-300 K sources as a function of wavelength.

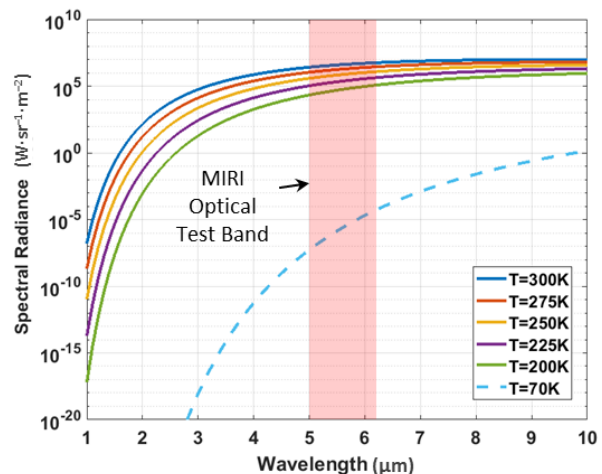


Figure 3. Black Body Spectral Radiance for 200-300 K and 70 K.

The Apollo-era Chamber A of JSC's Space Environment Simulation Laboratory³ was built with a shroud cooled by liquid Nitrogen (LN_2), which along with an attached tank farm housing over 100-thousand gallons of LN_2 , ensures an approximately 90 K boundary. The JWST Program designed a gaseous Helium (GHe) shroud and installed it within

that heritage LN₂ shroud. When fed by the attached GHe train capable of rejecting approximately 20.4 kW, the GHe shroud could provide a controllable 20 K test boundary.⁴ In the OTIS test, this 20 K boundary not only shielded the optical test configuration from stray light well within the 70 K requirement, but also provided the radiative cooling background necessary to achieve the thermal balance test objectives.

At the cryo-stable configuration shown in Figure 4, the LN₂ shroud was removing over 66 kW of parasitic heat, and the GHe shroud was removing an additional 2.5 kW.³ These heat rejections, however, assume that the shrouds have constant properties and temperatures and are energy-tight cylindrical bodies. In reality, both shrouds have numerous penetrations. The hanging configuration in Figure 1 shows mechanical hardware penetrating the shrouds, but excludes the numerous cutouts for the electrical, fluid, and instrument access required to control and monitor the flight and GSE systems during test. These penetrations required management to ensure that:

- Direct viewfactors from the chamber wall into the GHe shroud were eliminated.
- Direct viewfactors from the LN₂ shroud into the GHe shroud were minimized.
- Use of reflective (non-black or specular) surface finishes in view of the optical path was minimized.
- All surfaces within view of the optical path were less than 70 K.

Closeouts for these penetrations were typically designed as single layer insulation (SLI) attached to the GHe shroud with a high emissivity surface facing into the GHe shroud and a reflective surface facing out to the warmer LN₂ shroud. As the goal of these closeouts was to reduce both parasitic heat loads and stray light, it was not only critical that the closeout mechanically block the path the energy would take, but that the closeout itself not reradiate excessive heat. Per Equation 1, reradiated heat flux from an SLI closeout surface to the 20 K test environment (q_{rerad}) is governed by the Stefan-Boltzmann Equation as a function of the temperatures (T), and emissivity (ϵ).

$$q_{rerad} = \epsilon \sigma (T_{SLI}^4 - T_{GHe}^4) \quad (1)$$

To calculate the SLI equilibrium temperature (T_{SLI}) requires performing a radiative energy balance on the closeout material taking into account the radiative boundary temperature and emissivity of both the warm and cold (GHe) sides of the closeout. This reduces to the emissivity-weighted temperature average provided in Equation 2.

$$T_{SLI} = \left(\frac{\epsilon_1 T_{Warm}^4 + \epsilon_2 T_{GHe}^4}{\epsilon_1 + \epsilon_2} \right)^{\frac{1}{4}} \quad (2)$$

Equations 1 and 2 can be used to estimate a typical closeout equilibrium temperature of approximately 50 K assuming emissivities for aluminized Kapton (ϵ_1) facing out to the LN₂ shroud and Black Kapton (ϵ_2) facing in to the GHe shroud. This temperature meets the requirement for successful optical testing and equates to an approximately 90% reduction in the total heat flux that would pass through from the LN₂ shroud if the penetration area were not closed out. As will be seen in Section II, most closeouts were designed with several layers to further reduce the temperature of the surfaces facing the GHe shroud and the net heat rate through the penetration.

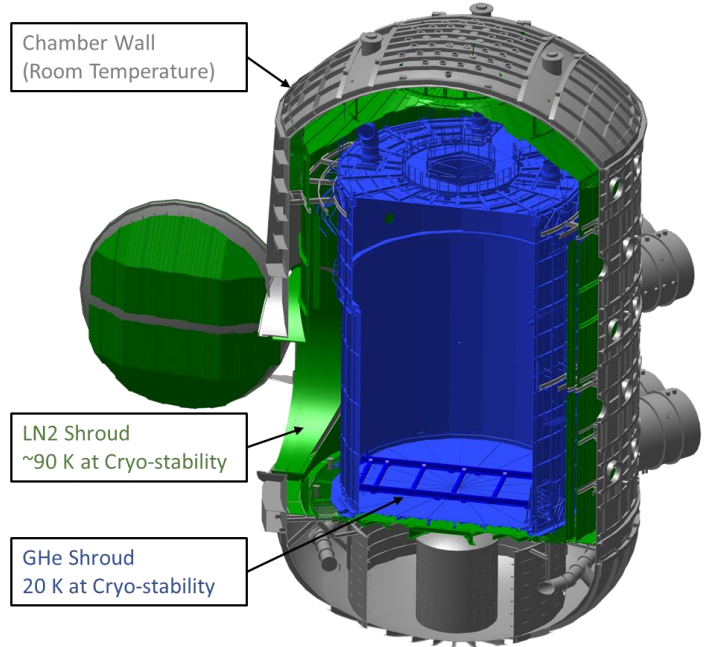


Figure 4. Chamber A Shroud Configuration noting Cryo-stable temperatures.

After the more specific closeout conversation in Section II, Sections III and IV present thermal and stray light control methods for the other GSE heat and light sources that penetrated the GHe Shroud in the OTIS Test configuration.

II. GHe Shroud Penetration Closeouts

Management of the numerous GHe shroud penetrations required varying design complexity based on the configuration of interfacing or penetrating hardware. The following sections separate the detailed discussion of stationary penetrations from penetrations designed to accommodate motion.

A. Stationary Penetrations

In terms of managing stray light, the penetrations in the GHe shroud without relative motion due to cryo-shift, dynamics, or hardware operations were both the largest in terms of area, and the easiest to address. The majority of these locations were holes or gaps designed into the GHe shroud for integration activities. Often, such openings were small areas required for metrology or integration access that could be covered up completely after those activities. At most of these locations, fixed hardware assemblies were designed to completely close out the opening in the shroud. A few, however, required an extra insulation layer to ensure light tightness. One example of this configuration is the Clamshell Assemblies which supported the ACF GHe Lines through the GHe shroud ceiling as shown in Figure 5. A simple encapsulating layer of black Kapton, aluminized on the top surface, closed out any gaps in that bolted assembly. The largest example of a stationary penetration is the gap between the rolling doors of the GHe shroud and its fixed walls. Once the OTIS assembly was rolled into the chamber and suspended, these doors were closed to complete the GHe shroud cylinder, but this rolling action required a gap between the stationary walls of the cylinder and these movable doors. A single layer Kapton sheet was installed across that gap with vented edge-taping to cut down the direct viewfactor to from the LN2 Shroud without over-constricting airflow.

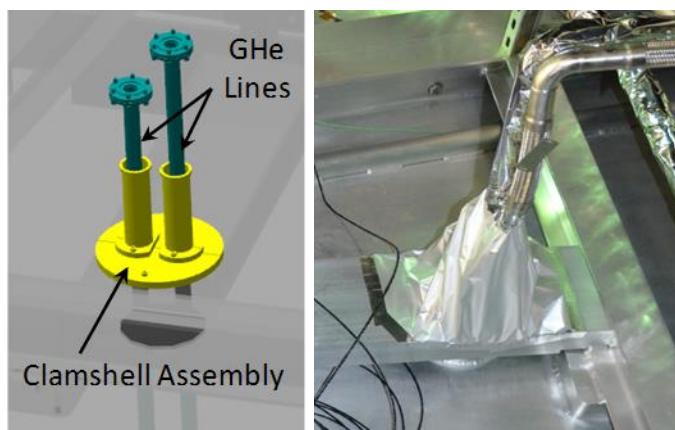


Figure 5. ACF Clamshell Assembly CAD View and As-Installed View with Insulation Closeout

Some stationary penetrations were purpose-built into the GHe shroud wall assembly to allow cables, fluid lines, and other GSE access to the interior of the GHe Shroud. These aluminum penetration boxes were designed with at least one 90-degree angle to negate direct views into it. The openings on both sides of the boxes were closed out with insulation as additional stray light barriers. On the back side of the shroud, a weighted Kapton blanket was installed with a tape seam only on the top so that it could move freely to ensure airflow during chamber pump-down and repress. The internal opening was covered with black Kapton taped to the penetration box sides and draped over the hardware exiting the box such that any energy leak was directed down to the shroud floor.



Figure 6. Down Rod Closeout

B. Movable Penetrations

The OTIS test configuration imposed unique boundary closeout challenges stemming from relative motion due to cryo-shift, dynamic isolation requirements, and GSE metrology operations. The range of motion from these sources could be relatively large, often as much as 2 inches in the vertical and 1 inch in the lateral directions. Stray light closeouts installed in several locations were designed with special features and in multiple parts to accommodate these motions. Examples at the Down Rod penetrations and Photogrammetry (PG) boom penetrations are provided in this section to demonstrate the accommodations made for passive and active motion.

The Down Rods penetrated the GHe shroud ceiling at 6 locations via 15-inch holes in the shroud ceiling plates with 5-inch-tall collars welded at the perimeter. Since these Down Rods carry the entire load of the hanging test system to the Isolators, they also passed through holes in the LN₂ shroud and present an open path for room temperature energy to enter the GHe shroud. A light-tight baffle and closeout shell system, shown in Figure 6, was devised to completely block that energy path while providing flexibility to minimize the dynamic coupling between the GHe

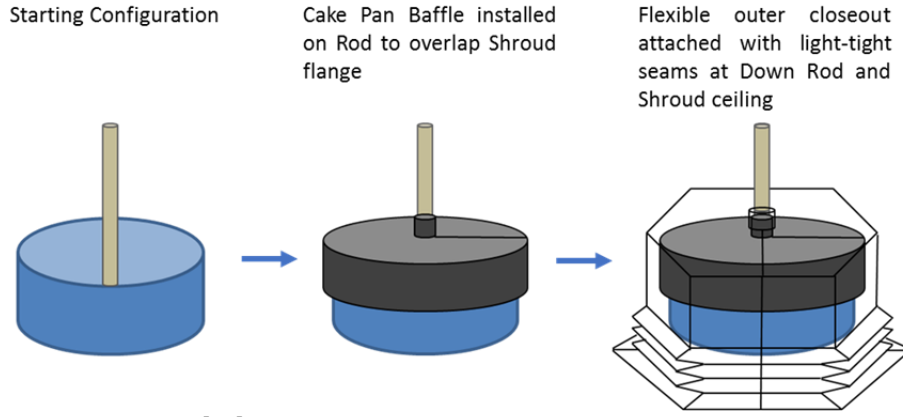


Figure 7. Down Rod Closeout Components

shroud and the hanging test configuration. As depicted in Figure 7, this two-part system started with a Kapton (black facing down into the GHe shroud, aluminized facing up) cake pan baffle stiffened with stainless steel wire that attached to the Down Rod and was both vertically long and radially large enough to overlap the shroud collar with room for relative motion. Once the cake

pan baffle was attached to the rod, an oversized Kapton (bare Kapton facing in, aluminized facing out) closeout was installed with light-tight seams at the Down Rod and at the shroud ceiling panel. This closeout was built of straight panels stiffened with wire, and connected to an accordion-style folded band at the bottom which accommodated motion in all directions. The use of thin material (1-2 mil), oversized dimensions, minimal stiffening frames, and intentional folding allowed these closeouts to achieve light-tightness while minimizing dynamics impacts.

The PG system was comprised of 4 windmill assemblies whose support structures penetrated the LN₂ shroud to mount to the chamber wall and whose rotating booms penetrated the GHe shroud. The opening in the GHe shroud for each boom, roughly 0.28 m², would be a direct path for energy from the room temperature chamber wall and 90 K LN₂ shroud into the GHe shroud. The heat flow through these openings, if unaddressed, can be estimated at 935 mW per boom, or a total of 3,743 mW for all four, using the Stefan-Boltzmann formula in Equation 3 if the following assumptions are made: the LN₂ volume temperature is 90 K, and the volume inside the GHe shroud is a black body ($\epsilon=1$) at 20 K.

$$Q = \epsilon \sigma A (T_{LN_2}^4 - T_{GHe}^4) \quad (3)$$

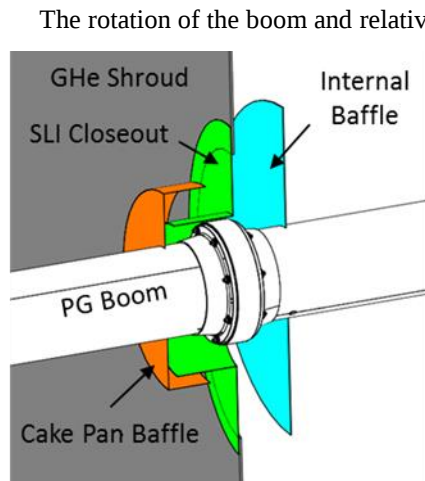


Figure 8. PG Closeout Configuration

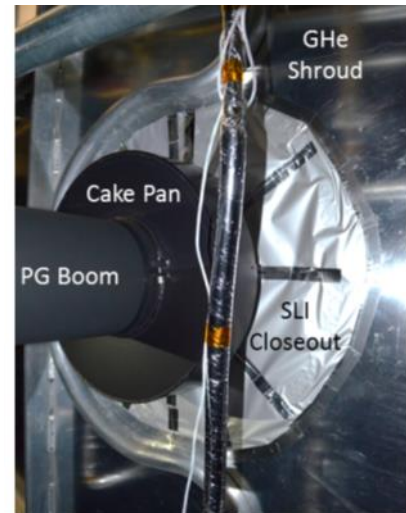


Figure 9. PG Closeout on Outside surface of GHe Shroud

The rotation of the boom and relative motion due to cryo-shift restricted the design of the closeout to that of a multi-part baffle system with features that interlocked without touching in a design similar to the Down Rod closeouts described previously. As shown in Figure 8, an oversized aluminum cake pan baffle was mounted to the rotating boom on the exterior of the GHe shroud so that it overlapped with a wire-stiffened Kapton (black facing in, aluminized out) closeout attached to the GHe shroud. On the interior of the GHe shroud, another aluminum baffle attached to the boom overlapped the SLI closeout. A sketch of the complete interlocking baffle arrangement is shown in Figure 9. Assuming a 50 K SLI Closeout temperature, Equation 2 can be used to estimate that each of the 4 SLI Closeouts reradiate 94 mW into the GHe shroud volume. The Internal

Baffle ensures that this reradiated energy, and the multi-bounce energy that makes its way through the Cakepan/SLI Closeout baffling, will reflect back to the GHe shroud ensuring that all energy paths have at least one 20 K surface in their paths before entering the optical path.

III. Thermal Anchoring of Cables

In addition to flight-like routing and control of all flight harnesses, the OTIS test configuration also required managing cables for the 164 GSE heaters and 964 GSE telemetry sensors. The stringent thermal balance and optical test requirements described in Section I required that the cables enter the GHe shroud with external temperatures below 70 K, and ideally below an objective of 50 K, to minimize stray light in the optical path. Achieving this temperature required numerous thermal anchoring locations along the cables' routes from the room-temperature penetration plates at the chamber wall, through the LN₂ shroud, and around the GHe shroud wall to penetration boxes. The comprehensive cable anchoring plan was comprised of four distinct components:

- A. LN₂ shelves to support the cables through holes in the LN₂ shroud and thermally clamp them to that 90 K surface.
- B. GHe shelves to support the cables around the perimeter of the GHe shroud and thermally clamp them to that 20 K surface at each of the multiple shelves along the way.
- C. Aluminum foil tape-tab anchoring on the final column of GHe shelves before the penetration box into the GHe shroud.
- D. Weighted connector stands inside the GHe shroud to provide conductive link to its 20 K floor.

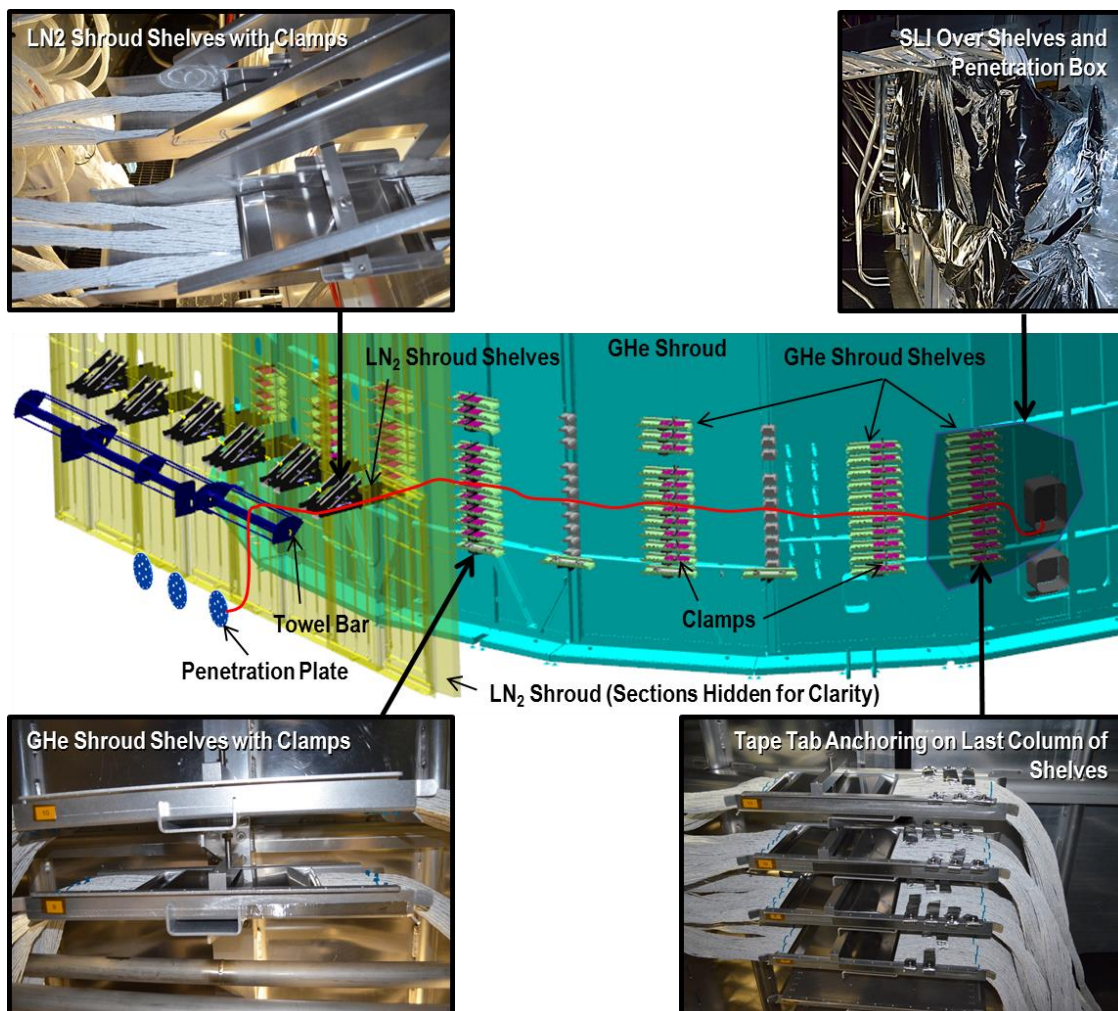


Figure 10. GSE Cable Thermal Anchoring Hardware Outside GHe Shroud.

The first three of these components were outside the GHe shroud and are shown in Figure 10. Supporting the cables on aluminum shelves conductively tied to the shrouds not only kept them out of the way of operations behind the shroud, but also provided a meaningful cooling path when combined with clamps on every shelf. The length of the routing path behind the GHe shroud was also beneficial to pulling heat out of the cables as the relatively high emissivity of the cable materials radiatively coupled to the shroud. As the cables approached the penetration box, however, it was more critical both to provide a final extra conductive interface and to radiatively decouple them from the 90 K black LN₂ shroud. As shown in the top and bottom images on the right side of Figure 10, the final shelf on the GHe shroud was augmented with conductive aluminum foil tape tabs on every wire of every cable bolted down to the shelf. A layer of double-aluminized Kapton was attached to the GHe shroud and allowed to drape over that final column of shelves and the penetration box to shield the assembly from the LN₂ shroud.

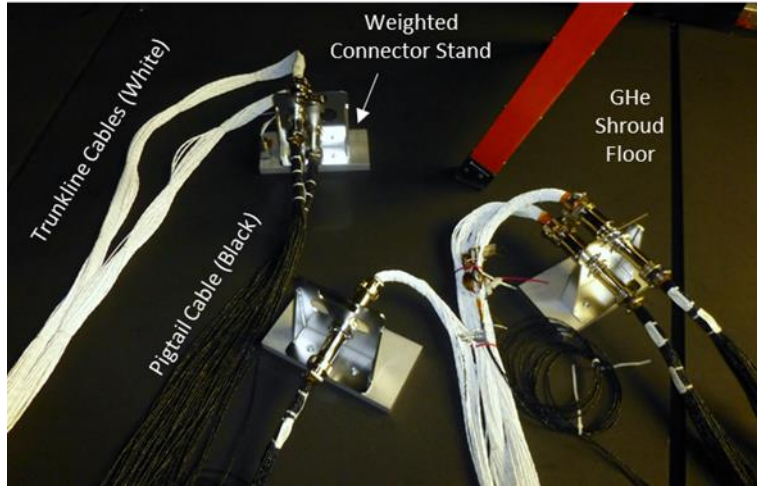


Figure 11. Cable Routing Configuration Inside the GHe Shroud.

After exiting the penetration box inside the GHe shroud, these cables, referred to as “trunklines,” were routed on the GHe shroud floor, as shown in Figure 11, to Weighted Connector Stands where they mated to black “pigtail” cables which broke out the cable bundles into the individual connectors required to mate with the devices installed on

the test hardware. The trunkline cables were designed conservatively long, and all the extra length was coiled on the floor inside the GHe shroud. This additional contact and radiation area inside the shroud resulted in further cooling of the cables.

To monitor the performance of these cable anchoring schemes, three telemetry sensors (Lakeshore DT670 diodes) were installed on individual wires of two trunkline cables inside the shroud. Two sensors were installed on cables where they exited the penetration box, and a third was installed on a cable near its Weighted Connector Stand. The data from these sensors for cooldown and cryostability are plotted in Figure 12 and show that the cables were below 50 K where they entered the GHe shroud. They continued to cool as they routed along the Shroud floor and achieved temperatures below 35 K at the Weighted Connector Stands where

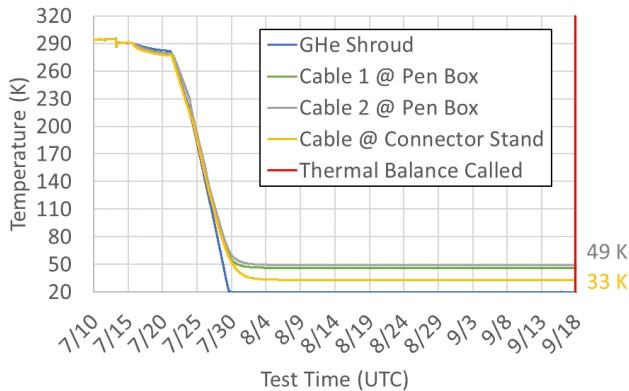


Figure 12. Cable Temperatures Measured during OTIS Cool Down and Cryostability with Thermal Balance Data Enumerated.

they mated with the pigtail cables. Radiometers and calorimeters provided by NASA’s Goddard Space Flight Center (GSFC) were also used to provide independent non-contact temperature measurements and look for heat leaks; they found no warm sources near the penetration box or routed cables.⁵

IV. Thermal Control of Optical Ground Support Equipment

Views from the LN₂ shroud or chamber walls were not the only potential source of mid-infrared radiation or undesirable heat loads within the GHe cavity. The Cryo-Positioning Metrology (CPM) system was a GSE metrology system responsible for spatial measurements of the test configuration and comprised of a set of four room temperature, atmospheric pressure cameras mounted on the PG windmill assemblies discussed in Section II B and a fifth similar assembly that housed an Absolute Distance Meter (ADM) on a fixed mounting structure. The room temperature and pressure electronics in these assemblies were housed in pressure tight enclosures (PTEs), purged by active nitrogen

flow, and enveloped in both active and passive thermal and stray light control systems. Each PTE was covered in 30-layer blanket, then surrounded by a black, GHe-cooled enclosure. In the case of the PGs, this GHe cooling extended along the full length of the windmill assemblies and the counterweight opposite of the PTE that balanced the assembly. This configuration is demonstrated with an exploded view of the Thermal Desktop model of a PG assembly in Figure 13.

As the electronics inside these PTEs were intended for optical metrology, windows were integrated into the PTEs and thermal shields. If these optical glass windows were left uncoated, their infrared transmission would exceed stray light and thermal requirements. To address this, custom coatings were applied to the dual-window systems that allowed visible light necessary to the instruments' functions to enter and exit the assemblies but did not transmit the longer infrared wavelengths. The windows in the thermal shield were also conductively tied to a GHe-cooled aluminum cold plate to ensure that the external window surfaces would be cold enough to ensure they were not thermal or stray light sources themselves. Reference 6 describes the PG system and window design in more detail.

Temperature sensors were installed on the window-housing cold plates, the actively cooled boom and counterweight assemblies, and the thermal shields of each assembly to monitor temperatures, but the window temperatures themselves could not be directly measured. Temperature data for the actively-cooled components of PG Windmill #3, the last in the serial GHe cooling line, and thus the warmest, is plotted in Figure 14. Similarly, the ADM Assembly (ADMA) external temperatures are plotted in Figure 15. The temperature data indicates that all actively cooled components, and even the ADMA blankets were below the 70 K limit. Additionally, radiometers pointed at the PG systems throughout the OTIS Test detected no unacceptable heat leaks.⁵ Finally, and most importantly, the

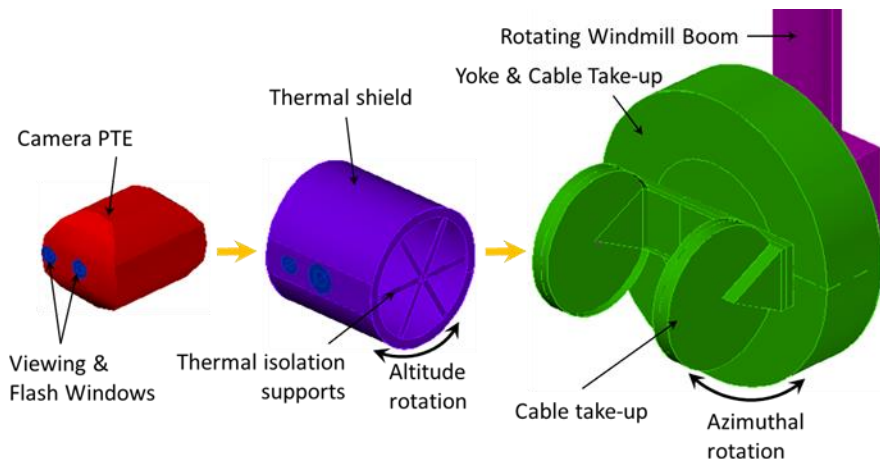


Figure 13. PG Exploded View (Thermal Model Geometry) Showing Hardware Configuration and Critical Thermal Management Features.

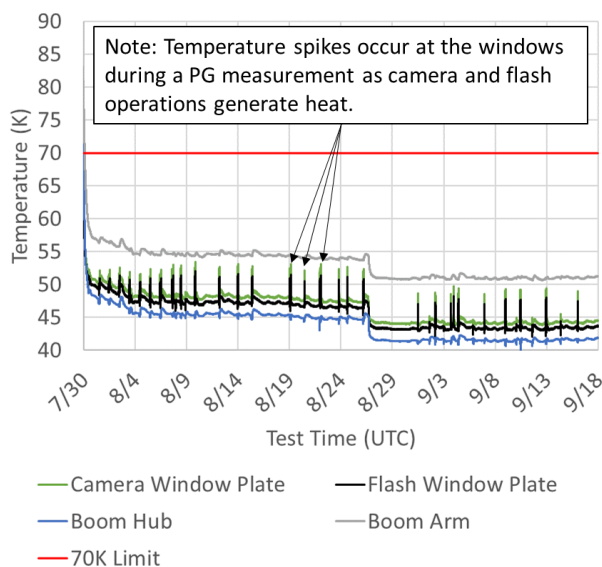


Figure 14. PG Windmill 3 External Temperatures during OTIS Cryostability

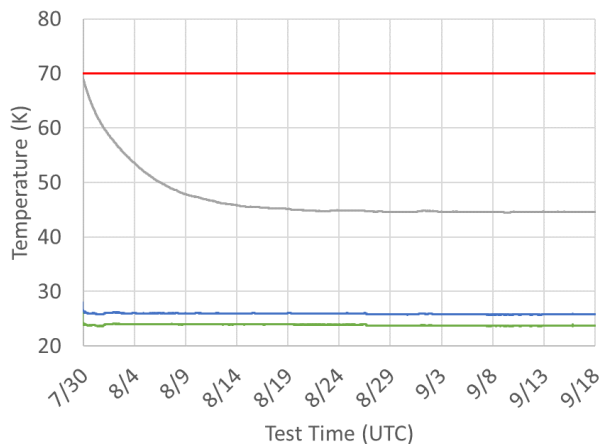


Figure 15. ADMA External Temperatures during OTIS Cryostability

flight instrument tests were all successful -- clearly indication that these thermal and stray light measures were adequate.

V. Lessons Learned Summary

The JWST OTIS ground test campaign included a progression of five commissioning and “Pathfinder” cryo-vac tests leading up to the final flight-hardware verification test.⁶ This extensive suite of development tests allowed for experimentation with closeout configurations, material selections, and attachment methods while also providing some insight into material degradation through numerous cryo-cycles. Four observations of specific note are:

1. When submitted to numerous cryo-cycles, single layer Kapton and Mylar materials can develop pinholes which are only visible when the surface is back-lit in a lights-out test. These pinholes were noticed more frequently in closeouts of large area (greater than 0.1 m²) where effects of billowing motion likely occurred during chamber pumpdown and repress or where chamber air-flow currents were more turbulent.
2. When closing out penetrations where dynamic and cryo-shift relative motions are expected, baggy, unshaped, single layers of material may be adequate to achieve light-tightness, but more rigorous designs with intentionally flexible features are far more likely to survive multiple cycles.
3. Kapton tapes with acrylic adhesives can maintain light-tight seams at temperatures below 20 K, but material coefficient of thermal expansion mismatch in some configurations was found to cause lifting due to strain in the tape material. When tape was used to support Kapton or Mylar closeouts on the aluminum shroud surfaces, the seams were found to be much more robust when a layer of aluminum foil acrylic tape was used to add structural integrity to the seam before being covered with an emissivity-matching over-tape.
4. Developing a robust thermal instrumentation plan is critical to the success of large cryogenic tests. Multiple systems may be needed to rigorously interpret test results. The extensive OTIS test telemetry systems were complimented with radiometers and calorimeters to better understand radiative boundaries and look for stray light/heat leaks.

VI. Conclusion

The OTIS Test environment was successfully managed to achieve the mission-critical verification tests of the JWST telescope and instrument systems. Meeting the stray light and thermal requirements of a cryovac test with infrared instruments on the scale involved was an audacious feat and required a collaborative effort. This success was realized through precise control of the LN₂ and GHe shrouds by the JSC Chamber A facility, rigorous design of GSE systems, and dedicated attention to detail in addressing every square inch of the GHe shroud boundary. It is anticipated that the GSE and closeout designs proved in this test campaign will inform future space telescope ground testing, and that the success of this OTIS Test milestone will spur the JWST Observatory on to great scientific discoveries.

Acknowledgments

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