Developing Controlled Conductive Boundaries for JWST Cryogenic Testing

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In 2017, the James Webb Space Telescope (JWST) underwent functional testing and optical metrology verification of the combined Optical Telescope Element and Integrated Science Instrument Module (OTIS) under cryogenic vacuum conditions in Chamber A at the Johnson Space Center. Maintaining flight-like thermal boundary conditions was a critical requirement for optical testing and required unique and challenging Ground Support Equipment (GSE) design solutions. Two such GSE systems, the Integrated Science Instrument Module (ISIM) Precool Straps and the Hardpoint Struts were direct conduction interfaces to the flight hardware. Hardware safety during cooldown required detailed design of their conductivity, and thermal balance testing required "zero-Q" (0-Q) heater implementation to bring the heat flow to zero, thereby cutting off these non-flight conductive links after operating temperatures were achieved. This paper describes the design considerations and approach implemented to achieve the required flight hardware cool down and return to ambient conditions, ensure flight hardware safety, and minimize the non-flight-like heat flows to or from the observatory during cryo-stable testing.

Nomenclature

A	= area
e	= emissivity
k	= thermal conductivity
L	= length
Q	= heat rate
T	= temperature
σ	= Stefan-Boltzmann constant
0-Q	= Zero-Q (i.e. no heat flow)
ADIR	= Aft Deployable ISIM Radiator
BSF	= Backplane Support Fixture
DSERS	= Deep Space Environmental Radiative Sink
E2E	= End-to-End
FGS	= Fine Guidance Sensor
FIR	= Fixed ISIM Radiator
GHe	= Gaseous Helium
GSE	= Ground Support Equipment
HOSS	= Hardpoint Offloader Support System
ISIM	= Integrated Science Instrument Module
JWST	= James Webb Space Telescope
LN2	= Liquid Nitrogen
MIRI	= Mid Infrared Instrument
MLI	= Multi-layer Insulation
MSA	= Microshutter Array
NIRCam	= Near Infrared Camera
NIRSpecFPA	= Near-Infrared Spectrograph Focal Plane
NIRSpec OA	= Near-Infrared Spectrograph Optical Assembly
OTIS	= Optical Telescope Element and Integrated Science Instruments Module
STE	= Specialized Test Equipment
STOP	= Strut Top (sensor location)

I. Introduction

The James Webb Space Telescope completed its cryogenic test late in 2017, and is now in final integration with the spacecraft bus and sunshield in preparation for launch. This was the final cryogenic-vacuum test of the Optical Telescope Element and Integrated Science Instruments Module (OTIS) and the critical objective was to verify the OTIS-level requirements in a flight-like environment. Figure 1 shows the test configuration of OTIS and several GSE

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subsystems in the test chamber. The thermal objectives for this test were to verify the flight hardware workmanship of the flight hardware and to collect thermal balance test data to validate the OTIS thermal model. For this thermal balance condition, a flight-like environment was required. Chamber A at Johnson Space Center was used to simulate the space environment of the telescope in flight. Chamber A supplies helium gas (GHe) to cool its high emissivity shrouds to simulate space as well as Deep Space Environmental Radiative Sinks (DSERS), and additional GHe lines for dedicated cooling of other specialized GSE.

Two meaningful differences between flight and test are the presence of Earth gravity and the budget impacts of test time. For a cryogenic vacuum test, the Ground Support Equipment (GSE) required to support the unit under test in a gravity condition can create a very different thermal boundary condition at the attachment locations. Depending n the objectives at each interface, the interfacing GSE could be designed as a high conduction path to cool the test article quickly, accelerating the testing schedule, or a low conduction path to keep heat flows and the structure temperature more flight-like. For the JWST OTIS test, the hardpoint struts and ISIM pre-cool straps were carefully designed to provide a balance between these two functions. Both of these thermal interfaces were designed with active control systems to reduce heat leaks to negligible quantities, to effectively zero (0-Q). This control helped manage payload temperatures through critical test phases, without compromising the test schedule through a combination of material selection, hardware geometry, heater control, and temperature measurement precision.

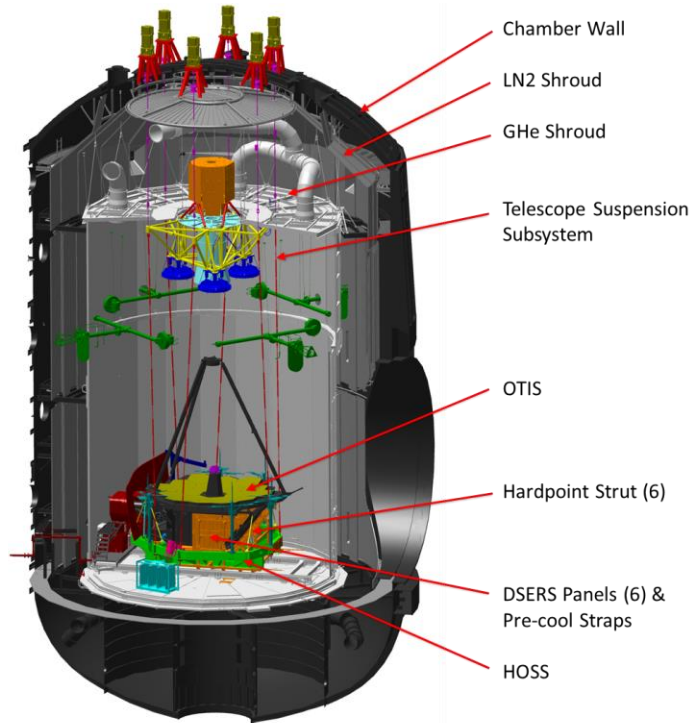


Figure 1. OTIS test configuration.

The 0-Q function of these GSE systems was essential to the success of the OTIS test thermal balance objectives: to verify system thermal workmanship, to provide test data to validate the thermal model, and to verify the science instrument heat loads within 10% of the model predictions. During thermal balance, the flight hardware was required to be in the operating temperature range, with small rate of change for both temperature and heat rate. To accomplish this quiescent test phase, the GSE interfaces needed to have heat flow error and stability down to values of single-digit milliwatts.

This paper provides design insight and test results discussion for the hardpoint struts and ISIM pre-cool straps; two of the more complicated thermal/mechanical interfaces to the flight hardware. Each system had challenging functional requirements that drove the hardware design and the thermal control to meet the optical, thermal, and schedule objectives of the OTIS test.

II. Hardpoint Struts

OTIS was supported on the Hardpoint Offloader Support Subsystem (HOSS) by six carbon fiber composite struts with MP35N flexures at the ends. The struts were arranged in a pseudo-kinematic configuration with two pairs of struts in a bipod arrangement on the -V3 end of the telescope and two struts in a monopod arrangement on the +V3 end, as shown in Figure 2. The mechanical connection to the flight hardware created a thermal path that only existed in the test configuration. Careful design of the hardpoint struts and flexures made them relatively low conduction, however, the remaining heat flow from the test article to the support structure would have created a non-flight-like gradient in the structure without further heat management.

The Hardpoint struts were designed to be extremely low conduction, also required augmentation to achieve the 2 mW (monopod struts) or 6 mW (bipod struts) heat leak required by the OTIS thermal test team. These requirements were applicable during the thermal balance tests. Within the +/- 6mW and +/- 2mW heat flow requirements, the OTIS thermal test team made an operational request that the heat flow was to be controlled as close as possible to 0 in the positive direction, meaning heat would only be flowing out of the payload and down the struts to the HOSS, rather than from the GSE to the payload. To provide this control, heater blocks containing cartridge heaters were designed to clamp to the bottom of each strut tube, shown in Figure 3. These heaters were termed 0-Q heaters as they were designed to heat the bottom of the strut to a temperature approximately equal to the saver plate, creating a zero heat rate (0-Q) interface.

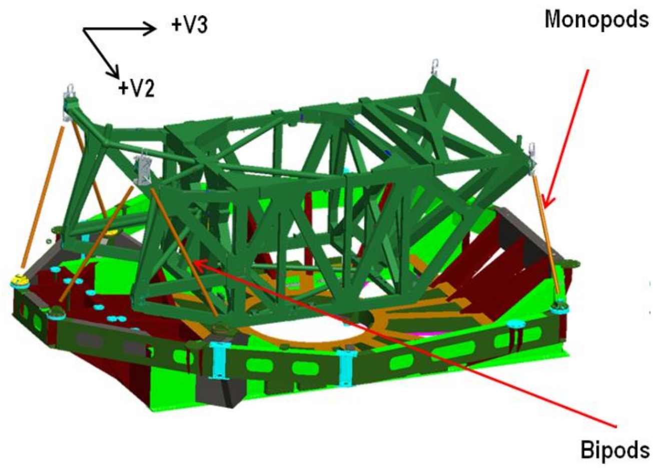


Figure 2. Hardpoint strut assemblies in OTIS configuration.

In addition to the active control provided by the 0-Q system, the struts were also covered with 25-layer multi-layer insulation (MLI) blankets from the base of the strut at the HOSS interface up to the saver plate. This blanket isolated the struts from the surrounding radiative environment, which may confound the 0-Q system and induce non-flight-like heat flows in the strut.

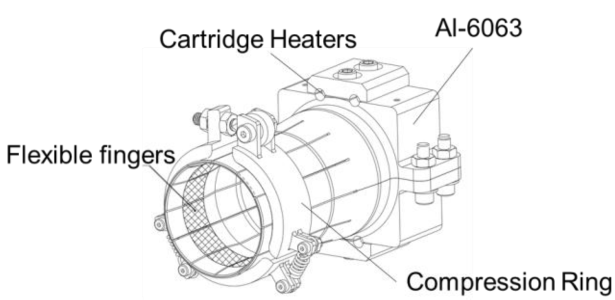


Figure 3. 0-Q Heater assembly.

The 0-Q heater itself faced several mechanical challenges. To reliably transfer heat from the heater cartridge to the strut, the interface needed to maintain clamping pressure at all times without inducing extra stress in the composite strut as the temperature changes. The strut locations and the heater design are shown Figure 2 and Figure 3. The heater-strut interface is a series of aluminum fingers that are clamped by a spring-loaded clamp. This arrangement ensures that clamp load is maintained as the composite strut and aluminum heater shrink at different rates while cooling. Aluminum tape was applied around the strut before installing the heater assembly to act as a thermal interface material and protect the composite strut outer resin layer from scratches.

A. Calculating Heat Flow

The heat flow into the payload was calculated across the flexure at the top of the strut, using the Strut Top sensor (STOP) and the saver plate sensor (SAVER_P) shown in Figure 4. This location was chosen to perform the heat flow calculation against requirements due to its discrete conduction path and small radiative area, which limits the error in the heat flow calculation caused by heat loss or gain in the flexure between the sensors, and its proximity to the telescope. The heat flow is calculated as:

$$Q = \frac{kA}{L}(T_{Saver} - T_{STOP}) \tag{1}$$

In the above equation, k is the thermal conductivity of the flexure as a function of the average temperature of the flexure. The $\frac{A}{L}$ term is a constant determined from the mechanical drawing for the flexure. T_{Saver} is the temperature of the saver plate as calculated by the average of the primary and redundant temperature sensors. T_{STOP} is the temperature of the top of the strut.

This heat flow calculation is conservative, because while the temperature sensors are located on the saver plate and composite tube, Equation (1) uses only the flexure conductivity. Figure 5 illustrates the flexure (in green) and the difference between the actual sensor locations and the assumed sensor locations used in the heat flow calculation. Equation (1) ignores the additional thermal resistances of the bonding adhesives, fittings, threaded connections, and contact resistances between components. On the lower end of the flexure, heat must conduct axially through the strut, then diametrically through the composite strut body and the threaded insert that accepts the flexure. On the payload side of the flexure, heat must conduct along the invar saver plate then through the spherical flexure interface before it reaches the assumed sensor location.

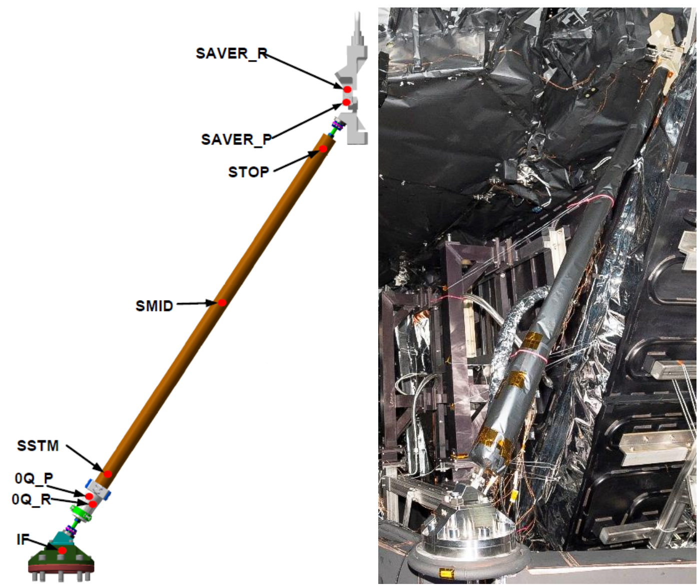


Figure 4. Hardpoint Strut and 0-Q Assembly Telemetry Locations.

When MLI blankets are very thick, they have the potential to act as parallel heat paths to add to the conduction across an interface. In this thermally-sensitive design, a thermal short across the flexure to the interface would make the heat flow calculation incorrect, and yield lower values than reality. To mitigate this potential heat path, the strut blankets were placed such that they shielded the strut flexure, but stopped short of the saver plate to ensure there was no contact to neither the saver plate nor flexure, and could not be a conductive path. Additionally, a gap between the inner layer of the blanket and the strut can result in "tunneling" of radiated energy axially along the tube. To reduce tunneling risk, the inner layer of MLI was bare Kapton which absorbs the axial radiated heat transfer.

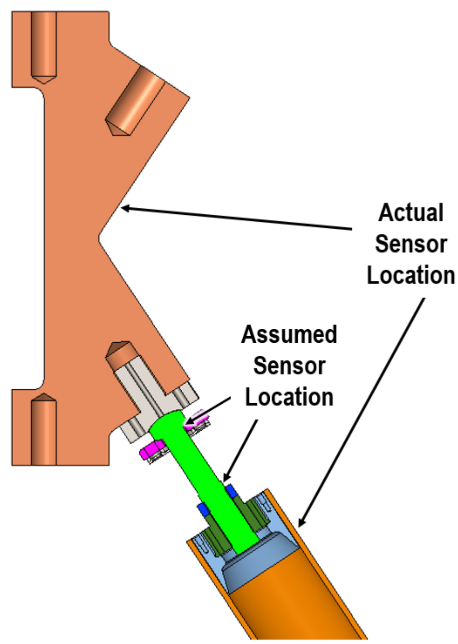


Figure 5. Strut-Saver Plate Flexure and sensor locations

B. Cooldown and Cryo-stability

The saver plates and struts were allowed to passively cool during cooldown with the assistance of the conduction path through the GSE strut. The 0-Q heaters were activated once the monopod saver plates reached 65K, on 8/5. Critical thermal distortion testing was in progress when the bipod saver plates reached 65K, so the 0-Q activation was delayed until 8/12, when the optical test completed. After the 0-Q heaters were activated and the conduction path along the strut removed, the saver plates isothermalized with the flight Backplane Support Fixture (BSF) structure and experienced a minor increase in temperature. For the duration of cooldown after 0-Q activation and cryo-stability the saver plates were cooled along with the BSF structure.

Figure 6 shows the activation and tuning of the monopod (MHP) and bipod (BHP) strut 0-Q system. The 0-Q control was semi-automated, the test set computer set the heater setpoint based on a user supplied offset from the current Saver Plate temperature every 2 minutes. This offset was used to compensate for the gradient along the strut length from the top flexure location to the heater location at the bottom of the strut. At the start of the 0-Q process, the initial offset was chosen based on data from the Thermal Pathfinder development test and the strut gradients at the time. A conservative estimate of -8K offset was chosen for all the Bipod struts, this left room for at least one offset adjustment to be made without fear of overshooting the saver plate. Once the initial -8K offset was sufficiently stable, the offset was changed to -5 for all the Bipods. After stabilizing, the temperature gradient across the strut flexure was calculated for both the -8 and the -5 offsets. A linear fit was made for each pair of points, to estimate a heater offset that would drive the flexure gradient to zero. Given this estimate, the next offsets for each strut were chosen to land on the trend line at approximately 1/3 of the current measured flexure gradient. This process was repeated several times until the flexure gradient was within the acceptable range as defined by the heat flow requirements. These adjustments to the offset are apparent when comparing the number of steps required to reach the specification limits between the monopod struts and bipod struts in Figure 6.

Once the heat flow was stable and within requirements, changes in heat flow due to activities outside of the strut-saver plate system such as operation of warm optical equipment were managed by the thermal engineer using small changes in offset based on previous change data and engineering judgement.

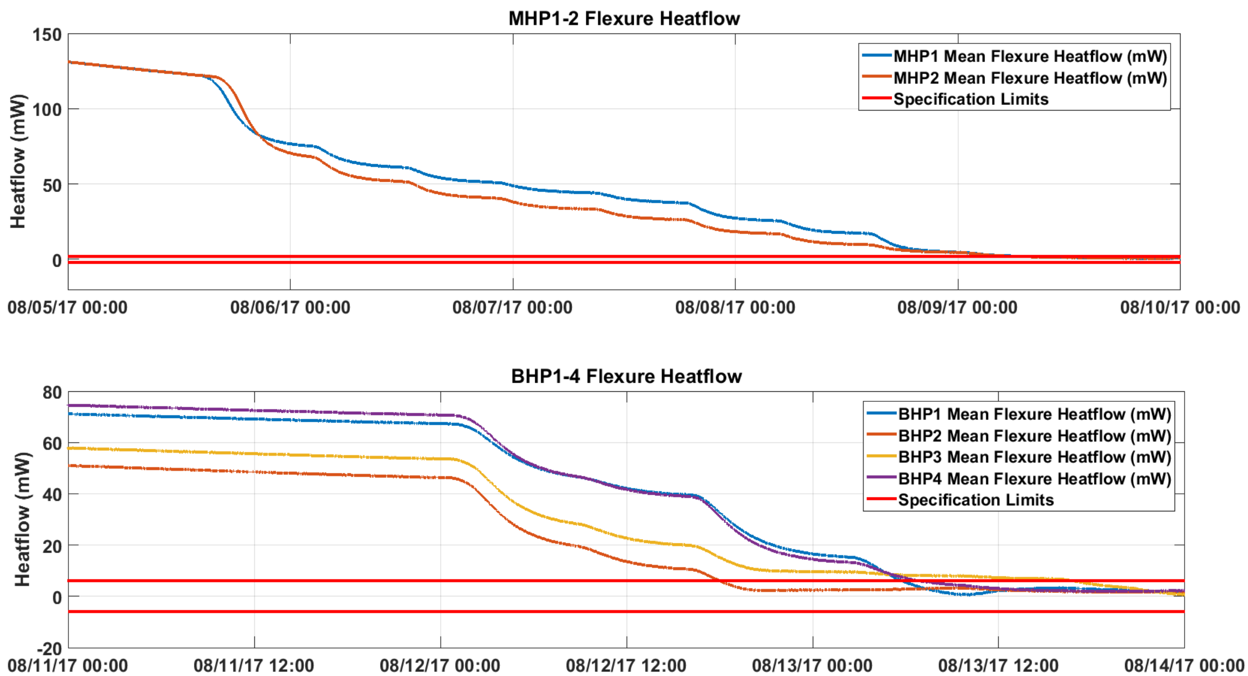


Figure 6. Hardpoint struts heat flow during 0-Q tuning for bipods (BHP) 1-4 and monopods (MHP) 1-2.

III. Precool Straps

A significant difference between the flight and testing environments was the cooldown timeline. After the hardware temperatures cool below 100K, the radiative heat transfer off the surfaces greatly diminishes, due to the T4 term in the heat transfer equation:

$$Q_{radiation} = e\sigma A\left(T_{\text{Radiator}}^4 - T_{\text{Space}}^4\right) \tag{2}$$

Figure 7 shows a representation of the drop-off in the contribution to the heat flux as the temperature drops down below 100K. At that point, the heat contribution is 98% less than at 300K. In the flight condition, this is not a concern due to the time it takes for the observatory to reach its L2 destination. However, for a thermal vacuum test, an accelerated cooldown was desired to optimize schedule and cost. This helps to reinforce the point that some contribution of conduction, even if it is small at room temperature, can become a significant mode of heat transfer at cryogenic temperatures. The science instruments are nested and thermally isolated behind the primary mirror array, and are thermally coupled to cryogenic radiators with a view to space. In the OTIS test, DSERS were used to simulate this space view. As the temperatures decreased, the radiators heat rejection decreased, with the temperature rate slowing down dramatically before reaching the approximate target temperature of 40 K. The ISIM pre-cool straps are a GSE subsystem that was used to assist the cooldown as the radiative mode of heat transfer became ineffective by using a GHe flow line as a cold sink.

As the instruments reached their target temperatures, heaters on the pre-cool strap assemblies were used to prevent the heat from continuing to flow down through the strap by warming the strap to eliminate the temperature gradient. When this temperature gradient is reduced, the heat conduction is stopped and thereby "zeroed the Q."

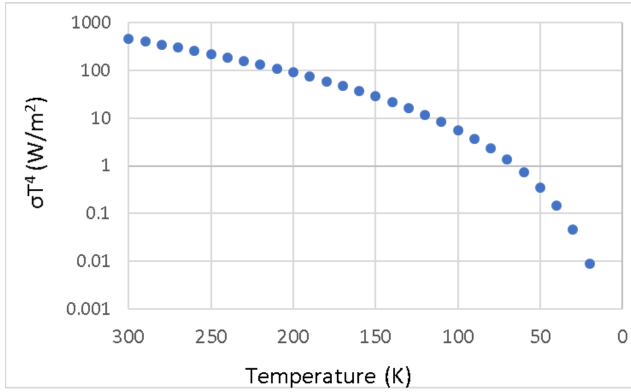
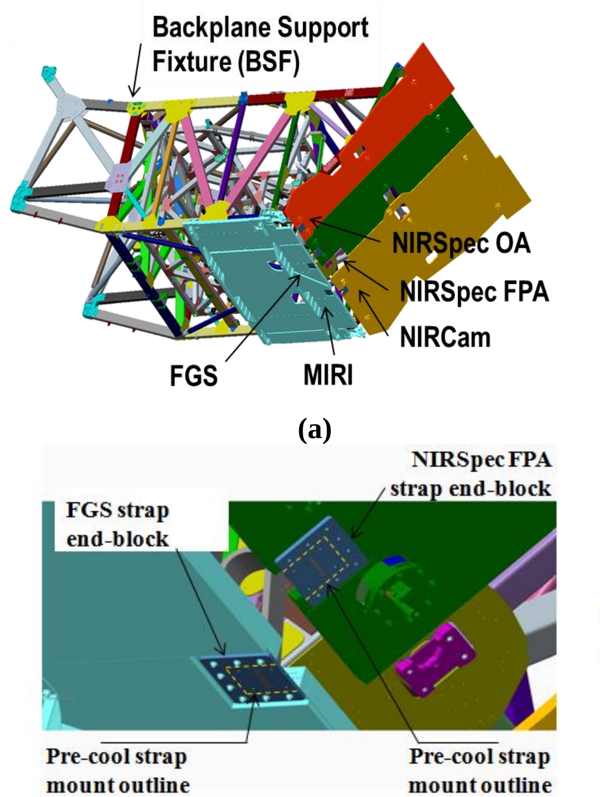


Figure 7. Potential radiative energy versus temperature.

The pre-cool straps conductively interface at one end to the DSERS panels, a high emissivity GSE radiator heat sink for OTIS which are shown in Figure 1. These DSERS panels are actively cooled by GHE and act primarily as a heat sink for the ISIM radiators, but also support the pre-cool strap assemblies. The other ends of the pre-cool straps attach to the radiator end of the ISIM heat strap. Attachment features for the pre-cool straps were baselined into the flight strap design early in the program to accommodate the pre-cool concept anticipated at OTIS. The design is common across all 5 pre-cool straps, irrespective of the instrument each attaches to. These instruments are the NIRCam, NIRSpec FPA, NIRSpec OA, FGS and MIRI. Figure 8 (a) shows an OTIS view which includes the Backplane Support Fixture (BSF), ISIM frame, Fixed ISIM Radiator (FIR), and the Aft Deployable ISIM Radiator (ADIR). Figure 8 (b) shows the NIRSpec FPA and FGS cooling blocks, with the pre-cool strap interface area indicated by the dashed lines. Three of the pre-cool straps interface to the straps on the FIR radiator and are supported by the +V3 DSERS panel, and two of the pre-cool straps interface to the straps on the ADIR radiator and are supported by the ADIR DSERS panel.

The pre-cool strap assembly attached to the flight locations by a flexible, high purity aluminum strap. The design was required to accommodate the relative motion between OTIS suspended in the chamber for optical testing and the fixed DSERS, to provide vibration isolation, as well as provide conductance to the 0-Q heater and the heat sink. On the other end (GSE side) of the flexible strap, the pre-cool mount attached to the backside of the DSERS panels which acted as a sink to GHe. The pre-cool strap assembly components are shown in Figure 9. The flexible strap was bolted to a stainless steel heater connector plate (pink), which was connected to the 0-Q cartridge heaters, which served as a prime and redundant heat source. The 0-Q heater connected to the DSERS panel by a heater isolator (yellow), a stainless steel support which ensured positive heater control. The supplemental cooling line (blue) was welded to a stainless steel plate (green), and served as the primary cold sink for the heat flow from ISIM during test cooldown only. A stainless steel heat throttle (gray) was designed to ensure the proper conduction path from the GHe line to the flexible strap, which balanced the goals of effective heat transfer for cooldown, while keeping parasitic heat



(b)

Figure 8. (a) OTIS view with flight heat straps highlighted and (b) interface locations outlined.

losses low during the 0-Q mode at cryo-stability. The GHe plate and tubing was supported off the DSERS panel by a low conduction G10 isolator (orange). To cut down on the radiative heat loss from the assembly, both the DSERS mounted components as well as the flexible strap were wrapped in a VDA surface finish Single Layer Insulation (SLI).

All five pre-cool straps are supplied with GHe through the JSC facility Zone 8, with flow being sequential through NIRCam, NIRSpec FPA, NIRSpec OA, FGS, and to MIRI. The 0-Q function of the straps was performed by shutting down the GHe flow, and using the 0-Q heater to drive the gradient across the flexible strap to zero. This gradient was measured by the "interface" temperature on the flexible strap at the end block connected to the flight radiator, minus the "junction" temperature of the flexible strap end block connected to the heater connector plate. The pre-cool strap design, with both heater and cold sink components allowed for it to remove heat, add heat, and cut off heat flow to the flight radiators.

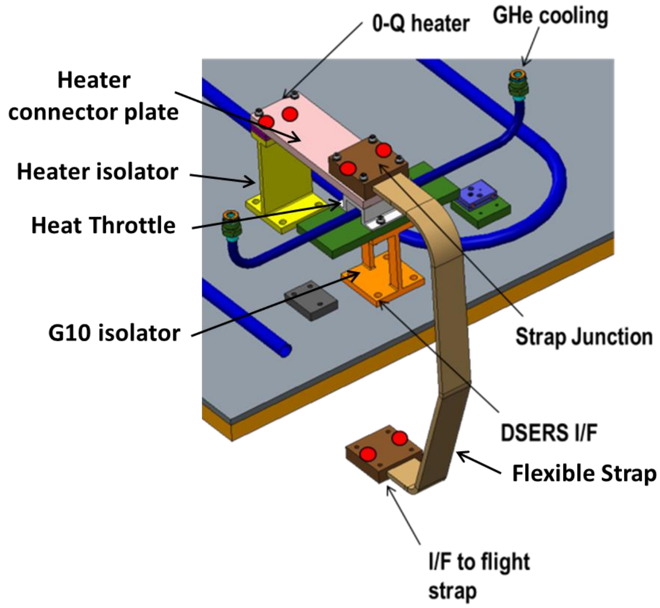


Figure 9. Pre-cool assembly attachment to DSERS panel.

A. Cooldown Performance

The cooldown approach for the pre-cool straps was to passively cool down without GHe flowing until the ISIM instruments cooled to below the contamination sensitive temperature range, which is <160K. GHe flow to the pre-cool straps was started on 7/24/2017, so that the instruments could be assisted in the cooldown by the conductive link from the pre-cool straps. While the pre-cool straps were cooling, the ISIM instrument benches temperatures were monitored as they cooled to the nominal operating temperatures. As each instrument bench temperature reached its contamination-constrained temperature or operating temperature, the pre-cool strap 0-Q heaters were powered to drive the temperature gradient across the flexible strap to zero. To do this, the automated heater control was set up for the pre-cool straps to automatically make the heater setpoint equal to the interface sensor on the strap near the radiator, plus an offset to account for the temperature change from the heater to the strap junction. Throughout the test, the offsets were adjusted as necessary to achieve the test heat flow goals.

Figure 10 shows the cooldown from 7/13 to 8/23/2017, showing temperatures on the left axis, and pre-cool strap gradients on the right. During the ambient checkout activities that occurred until 7/21, the chamber cooled due to the LN2 flow to the scavenger panel assemblies. As the shroud started the formal GHe cooldown, the pre-cool straps had temperature gradients that had the junction temperature greater than the interface temperature. This was attributed to the radiator starting to cool radiatively to the DSERS panels before the GHe flow was opened to the pre-cool straps. Once the GHe flow for Zone 8 was started, the junction temperature on the pre-cool straps cooled below the temperature of the radiator interfaces, pulling heat out of the science instruments. The GHe flow was opened on 7/24 by moving the flow valve to 50% open. Throughout cooldown, the ISIM bench heaters were used to control the instrument cooldown, including a temperature hold which ended on 8/2, to operate within structural and contamination control constraints.

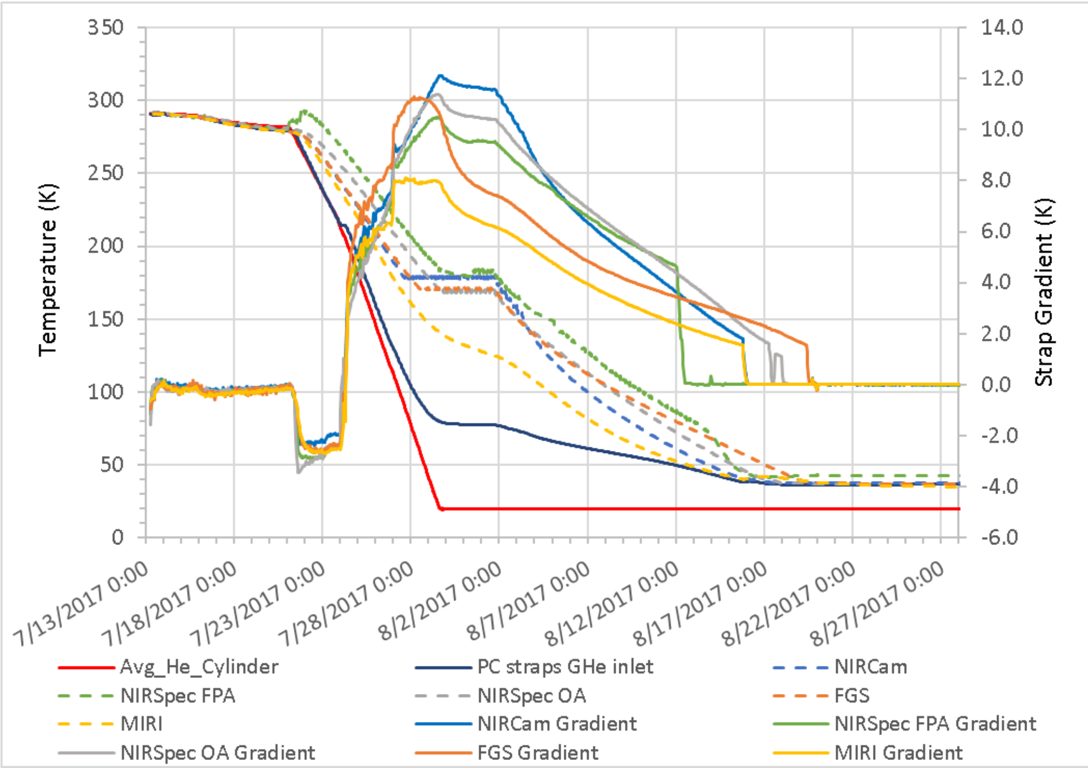


Figure 10. Cooldown profile for ISIM benches (dashed) and pre-cool strap gradient.

On 8/11 the NIRSpec FPA pre-cool strap 0-Q heater was enabled to stem the heat flow from the instrument down the strap, to reduce risk of overcooling the instrument. The next instruments to start the 0-Q heaters were the MIRI and NIRCam on 8/15, then the NIRSpec OA instrument on 8/17. After turning on the NIRSpec OA 0-Q function when the instrument reached 40.0K, it was decided to let the instrument cool another degree before performing 0-Q, where the strap gradient was minimized. The FGS strap was the last one to 0-Q, which started on 8/19 after the instrument cooled below 38.0K.

B. Cryo-stability and Thermal Balance

For the cryo-stable and thermal balance portion of testing, GHe flow to zone 8 was gradually closed, while adjustments to the heater setpoint feedbacks were made. These adjustments during the period were typically setpoint offset changes of 0.05K to 0.025K. The measured heat flows for the duration of cryo-stability and thermal balance are shown in Figure 11. For much of the test phase, the heat flow was small, but from 9/7 to 9/12 the payload thermal team requested the pre-cool strap heaters be used to push the radiator interfaces up to 40K so that the ISIM instruments could measure the End-to-End (E2E) thermal conductance for each of

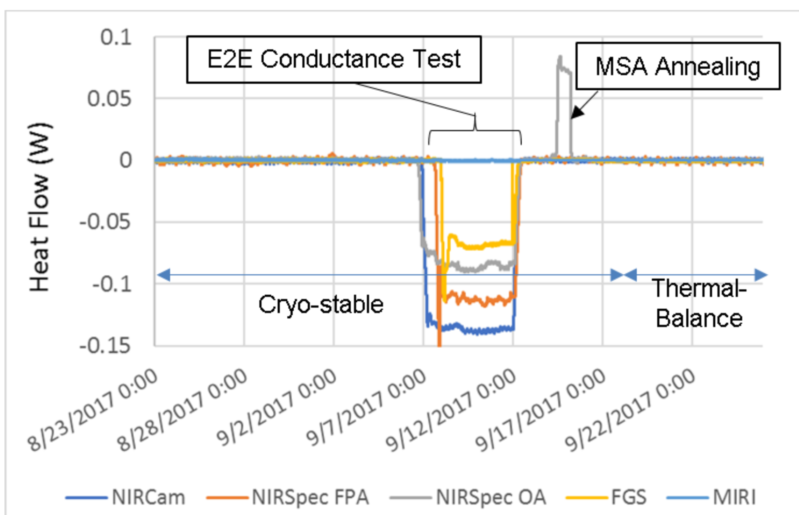


Figure 11. Measured heat flow through pre-cool straps for cryo-stable and thermal balance period.

the flight heat straps. During this E2E testing, the NIRSpec FPA and FGS had a spike in heat flow as the instrument heaters were adjusted for the test. On 9/14, the NIRSpec OA heat strap began to remove heat while the other pre-cool straps were in the 0-Q mode. This was due to the NIRSpec Microshutter Array (MSA) annealing, a planned OTIS test step. This increased the temperature at the pre-cool interface black by about 1.1K. No effort was made to stay in the 0-Q mode during this annealing process, and when it was complete, the temperature at the interface cooled back down and returned to the 0-Q process. The use of the pre-cool straps for E2E flight testing was not anticipated, but became a critical capability in verifying the flight heat strap conductances between the instruments and radiators.

A closer look at the periods where the goal was to 0-Q the straps is shown in Figure 12, by modifying the scale from Figure 11. All 5 of the straps have heat flows near 0W, with some spikes in heat flows, with it most prominently shown on the NIRSpec FPA strap. During testing, it was found that this periodic signature was due to the instrument system heater power and dissipation. Attempts to correct for the spike in heat flow, would be detrimental to the other direction as it oscillated between its maximum and minimum dissipation through the strap to the radiator.

For the times between 8/23 and 9/6 and from 9/17 to 9/24, the measured heat leakage performance for each strap is listed in Table 1, with values in mW. The heat leakage was determined by:

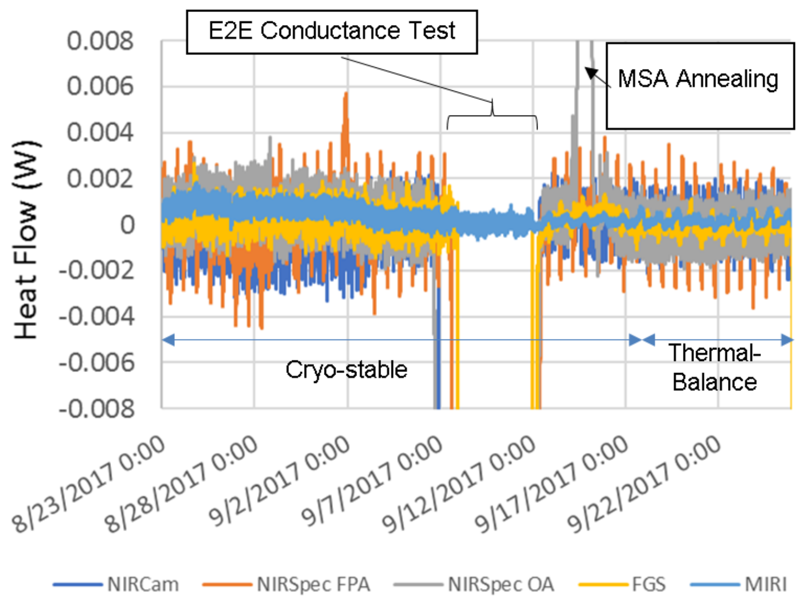


Figure 12. Pre-cool strap measured heat flow for cryo-stable and thermal balance periods (zoomed in from Figure 11).

$$Q_{leak} = k_{strap} \frac{A}{L} \left(T_{radiatorI/F} - T_{junction} \right) \tag{3}$$

In this calculation, a positive heat flow implies the heat was flowing from OTIS through the pre-cool straps, while a negative heat flow implies heat was flowing from the pre-cool 0-Q heater up through the straps and into OTIS. This table gives the average heat leakage measured, the maximum, minimum, and the standard deviation (over 20 days of cryo-stability and thermal balance). The final column is the potential heat leakage due to the uncertainty in the temperature measurement. In the Thermal Pathfinder test, each of the Cernox sensor pairs were calibrated at stable periods to determine the precision (bias) and random errors.

Table 1: Pre-cool strap heat leakages from cryo-stable and thermal balance including uncertainty.

	Average Heat Leak (mW)	Maximum Heat Leak (mW)	Minimum Heat Leak (mW)	Standard Deviation (mW)	Heat from temp. uncertainty (mW)
NIRCam	-0.39	1.95	-2.85	0.82	1.84
NIRSpec FPA	-0.08	5.70	-4.24	1.31	2.13
NIRSpec OA	0.29	2.75	-1.58	0.71	2.89
FGS	0.18	2.03	-0.84	0.45	1.68
MIRI	0.47	1.29	-0.22	0.33	3.02

The pre-cool strap data shows that on average, the heat leak was below 0.5 mW, which satisfies the requirement. However, the NIRSpec FPA strap had the largest range as it oscillated. It stayed below 5 mW of heat leakage, with a standard deviation in values of 1.3, which helps to show how variable it was. Contrasting it to the MIRI strap, which did not show the oscillations like the NIRSpec FPA, it had always been below 1.5mW of heat leakage, and had a small standard deviation of 0.33. This demonstrates that the pre-cool straps were more capable of performing the 0-Q functions when the heat flowing down the ISIM heat straps to the radiators was constant.

IV. Lessons Learned

Prior to the OTIS cryogenic-vacuum test, the commissioning tests that used the "Pathfinder" test unit (an engineering model) was essential to first operate the GSE and STE in a test environment, prior to the introduction of flight hardware. These tests allowed for the characterization of the thermal hardware, demonstrating the capabilities and responsiveness to all phases of test. In all, these lessons can be compiled into 3 categories:

1. Engineering models or interface simulators are very beneficial to ensure the hardware can be integrated and tested in a similar environment for the critical thermal vacuum test. The ISIM thermal simulators were GSE hardware in the Thermal Pathfinder test that were used to mount the pre-cool straps to in lieu of OTIS, and simulated OTIS heat loads for the pre-cool straps to remove and 0-Q against. This commissioning test burned down risk and demonstrated the strap capabilities.
2. Communication between test teams, organizations, and disciplines is crucial for a successful test. Assumptions should not be made that a change to one system will not affect or be noticed on another. Simple forewarnings can go a long way to prevent missed events or potential limit violations and instead the anticipation of the change can prevent overcorrecting an impulse to the system.
3. Any durations for sensor calibrations or heater control (Proportional, Integral, Derivative) parameters should be scheduled into the test timeline and planned for. These measurements or adjustments can become critical for measuring heat flows, or operating the hardware in test with the flight hardware. Allocating the time and performing these activities within the environment they will be tested at is essential.

V. Conclusion

Specialized thermal GSE was critical in the successful execution of the JWST OTIS test campaign. The pre-cool straps enabled an accelerated cooldown of the ISIM hardware to meet the test timeline, while being able to stem the heat flow during the critical thermal balance period to a few milliwatts of heat leakage. The hardpoint strut 0-Q heaters used at the main structural offloading support points to OTIS successfully managed heat flow out of the backplane support fixture. By zeroing the gradient across the flexure to the flight hardware, the heat leakage was minimized to values less than 6 mW for the bipods and 2 mW for the monopods. The 0-Q systems described here successfully met their requirements and provide guidance to future cryogenic missions seeking to manage the energy balances and accelerate schedules during ground testing.

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