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Thermal Considerations for Reducing the Cooldown and Warmup Duration of the James Webb Space Telescope OTIS Cryo-Vacuum Test

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The James Webb Space Telescope (JWST), set to launch in 2018, is NASA's next-generation flagship telescope. The Optical Telescope Element (OTE) and Integrated Science Instrument Module (ISIM) contain all of the optical surfaces and instruments to capture and analyze the telescope's infrared targets. The integrated OTE and ISIM are denoted as "OTIS", and will be tested as a single unit in a critical thermal-vacuum test in mid-2017 at NASA Johnson Space Center's Chamber A facility. The payload will be evaluated for workmanship and functionality in a 20K simulated flight environment during this thermal-vacuum test. However, the sheer thermal mass of the OTIS payload as well as the restrictive gradient, rate, and contamination-related constraints placed on test components precludes rapid cooldown or warmup to its steady-state cryo-balance condition. Hardware safety considerations precludes injection of helium gas for free molecular heat transfer. Initial thermal analysis predicted that transient radiative cooldown from ambient temperatures, while meeting all limits and constraints, would take 33.3 days; warmup similarly would take 28.4 days. This paper discusses methods used to reduce transition times from the original predictions through modulation of boundary temperatures and environmental conditions. By optimizing helium shroud transition rates and heater usage, as well as rigorously re-examining previously imposed constraints, savings of up to three days on cooldown and up to a week on warmup can be achieved. The efficiencies gained through these methods allow the JWST thermal test team to create faster cooldown and warmup profiles, thus reducing the overall test duration and cost, while keeping all of the required test operations.

Nomenclature

AOS	= Aft Optical System
BP	= Backplane
BSF	= Backplane Support Fixture
CV	= Cryo-Vacuum
DSERS	= Deep Space Edge Radiation Sink
FGS	= Fine Guidance Sensor
FPA	= Focal Plane Arrays
FSM	= Fine Steering Mirror
GSE	= Ground Support Equipment
GSFC	= NASA Goddard Space Flight Center
IEC	= ISIM Electronics Compartment

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ISIM	= Integrated Science Instrument Module, which contains the Science Instruments (SIs)
JSC	= NASA Johnson Space Center
JWST	= James Webb Space Telescope
K	= Kelvin
L&Cs	= Limits and Constraints
MIRI	= Mid-Infrared Instrument
MLI	= multi-layer insulation
NASA	= National Aeronautics and Space Administration
NIRCam	= Near-Infrared Camera Instrument
NIRSpec	= Near-Infrared Spectrograph Instrument
OA	= Optical Assembly
OTE	= Optical Telescope Element
OTIS	= Optical Telescope Element and Integrated Science Instrument Module (OTE + ISIM)
PMSA	= Primary Mirror Segment Assembly
PMBSS	= Primary Mirror Backplane Support Structure (BSF + BP)
SAO	= Smithsonian Astrophysical Observatory
SI	= Science Instrument
SINDA	= Systems Improved Numerical Differential Analyzer
SLI	= single-layer insulation
SMA	= Secondary Mirror Assembly
SMSS	= Secondary Mirror Support Structure
SVTS	= Space Vehicle Thermal Simulator
TM	= Tertiary Mirror
W	= Watt

I. Introduction

THE James Webb Space Telescope (JWST) is NASA's next-generation space telescope and the successor to the Hubble Space Telescope. JWST (Figure 1) represents a collaboration among NASA, the European Space Agency (ESA), the European Consortium (EC), and the Canadian Space Agency (CSA), as well as partners in industry and academia. With four instruments in the near- to mid-infrared bands, JWST will provide scientists with unprecedented resolution to capture the formation of the first stars and galaxies in the universe as well as to directly image exoplanets. Slated to launch in 2018 via an Ariane 5 launch vehicle from Kourou, French Guiana, JWST will undergo a series of deployments before entering orbit at the Earth-Sun L2 Lagrange point, about 1.5 million km from Earth. A tennis-court-sized, five layer sunshield will protect the optical telescope and instruments from solar impingement, allowing for passive cooling to cryogenic temperatures before beginning its science mission.

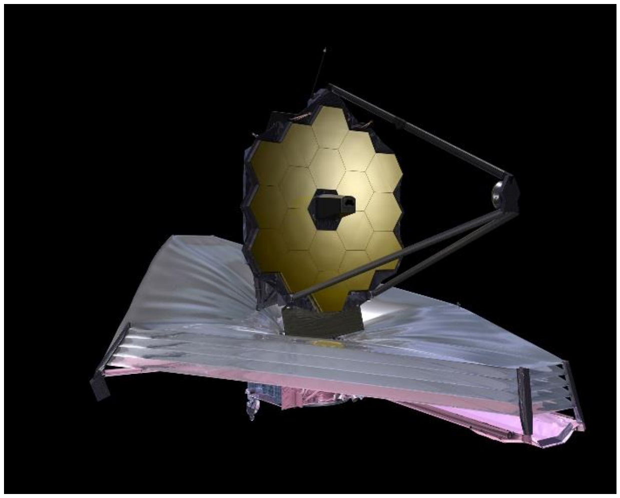

Figure 1. The James Webb Space Telescope

JWST is currently undergoing extensive environmental tests to verify its ability to withstand the harsh space environment, including system-level thermal vacuum tests to ensure that the observatory will achieve its design temperatures with the same thermal inputs as expected on-orbit. Due to its size, the entire deployed JWST cannot be thermally balanced or optically tested in any existing thermal-vacuum facilities; it will instead require optical and cryo-vacuum verification of separate subsystem-level assemblies before its final integration at Northrop Grumman Aerospace Systems in El Segundo, CA. Thermal analysis will be employed to show compliance with system requirements. The major system-level thermal vacuum tests include the spacecraft bus, the sunshield, and the OTIS cryo-vacuum (CV) test, which represents the culmination of the Optical Telescope Element (OTE) and the Integrated Science Instrument Module (ISIM) subsystem-level tests. Both OTE and ISIM have undergone a successful series of cryo-vacuum tests prior to OTIS: two Optical Ground Support Equipment (OGSE)[1] and one Thermal Pathfinder (TPF)[2] risk-reduction tests were performed at NASA's Johnson Space Center (JSC) for OTE; and three successive ISIM cryo-vacuum tests[3] were performed at NASA's Goddard Space Flight Center (GSFC) to verify instrument behavior in its intended flight environment. The OTIS CV test, taking place at the JSC Chamber A facility, will allow for end-to-end optical testing in the appropriate thermal environment for the combined assembly of optical telescope and instruments. The current work will discuss the design and implementation of the OTIS CV test and the considerations made to shorten the amount of transition time to cryogenic temperatures and back to ambient. The work will also explore in-depth the thermal analysis that has been performed to determine the most efficient cooldown and warmup profiles for the OTIS payload, with special attention given to not exceed any limits and constraints with margin.

II. Test Objectives

The OTIS CV test is a verification of the workmanship on flight hardware as well as a crosscheck of the assembled, integrated models. The thermal control objectives are fivefold: to achieve the correct on-orbit payload temperature levels and stability for optical, mechanical, and instrument tests; to predict and measure thermal balance test data for model crosscheck, both on ISIM and OTE components; to preserve hardware integrity upon transition to cryo-balance conditions and transition back to ambient temperatures by respecting all imposed limits and constraints; to achieve a workmanship thermal conductance assessment of the flight instrument heat straps; and to achieve timeline optimization by executing the OTIS CV cooldown and warmup in a time-efficient manner.

These thermal control objectives required the development of the OTIS CV thermal model, consisting of an integrated system-level model of the OTIS payload from Northrop Grumman Aerospace Systems (NGAS) with substantial inputs from NASA GSFC, detailed optical component models from Ball Aerospace Technologies Corporation (BATC), and a reduced GSE model, including the chamber and facilities, provided by Harris Corporation. The OTIS model was generated with Thermal Desktop and SINDA version 5.6, contains over 84,000 nodes, and typically requires more than a week of wall-clock time to run a simulated cooldown profile or warmup profile. The OTIS CV thermal model predictions are used to develop appropriate cooldown and warmup procedures employing the appropriate thermal control surfaces and methods to transition the OTIS payload from ambient to its cryogenic test conditions and back again. The model is also used to evaluate critical limits and constraints: those that may lack flight sensors to monitor real-time during the OTIS CV test may also be predicted pre-test to ensure that they will be met during transitions. Post-test, the OTIS CV thermal model will undergo selective test model correlation for engineering diagnostic purposes. However, there is no system-level flight model correlation effort planned: since the OTIS CV test will not be able to achieve a fully flight-like environment, the flight model validation will be the sum of the correlated component models, as discussed in the next section. If major inconsistencies are found in hardware behavior during the OTIS CV test versus pre-test thermal model predictions, the causes of these irregularities will be extensively peer-reviewed before any OTIS test results are used for flight model correlation.

III. Test Configuration

The OTIS payload encompasses all components of the observatory that lie above the plane of the sunshield. Figure 2 shows the OTIS payload in its test configuration at JSC; note the chamber coordinate system in V-coordinates. The optical path for the telescope element consists of light reflecting off of the 18 gold-coated beryllium Primary Mirror Segments comprising the Primary Mirror Segment Assembly (PMSA) and the Secondary Mirror Assembly (SMA) before entering the Aft Optics Subsystem (AOS), where it will travel from the Tertiary Mirror (TM) to the Fine Steering Mirror (FSM) and finally to the pick-off mirrors for each separate science instrument within the ISIM enclosure. ISIM (Figure 3) consists of four instruments mounted to the rigid composite ISIM structure: the Near-Infrared Camera (NIRCam), developed by NASA and the University of Arizona; the Near-Infrared Spectrograph (NIRSpec), a collaboration between the ESA and NASA; the Mid-Infrared Instrument (MIRI), jointly sponsored by ESA and the European Consortium, which is actively cooled to 6K; and the Fine Guidance Sensor (FGS), provided by the Canadian Space Agency. These instruments are powered and controlled by their electrical boxes mounted in the ISIM Electronics Compartment (IEC), a room-temperature enclosure which rejects its heat in the –V1 direction to space through a baffled radiator. A separate Harness Radiator rejects the bulk of the harness parasitic heat loads from IEC before they enter the cryogenic ISIM. The Near IR instruments reject heat to the radiators via high purity aluminum thermal links, while the MIRI instrument employs a radiator to control parasitic heat transfer from its kinematic mounts to the instrument.

The PMSAs and the AOS are mechanically supported by the Backplane (BP); while the ISIM is kinematically mounted to the Backplane Support Fixture (BSF). The combined BP and BSF form the Primary Mirror Backplane Support Structure (PMBSS), a large M55J composite truss shielded from its thermal environment with multi-layer insulation (MLI) and single-layer insulation (SLI). The Secondary Mirror is supported by three composite struts which deploy from the PMBSS, comprising the Secondary Mirror Support Structure (SMSS). The entire telescope assembly is interfaced with the flight spacecraft bus and sunshield via the Deployable Tower Assembly (DTA).

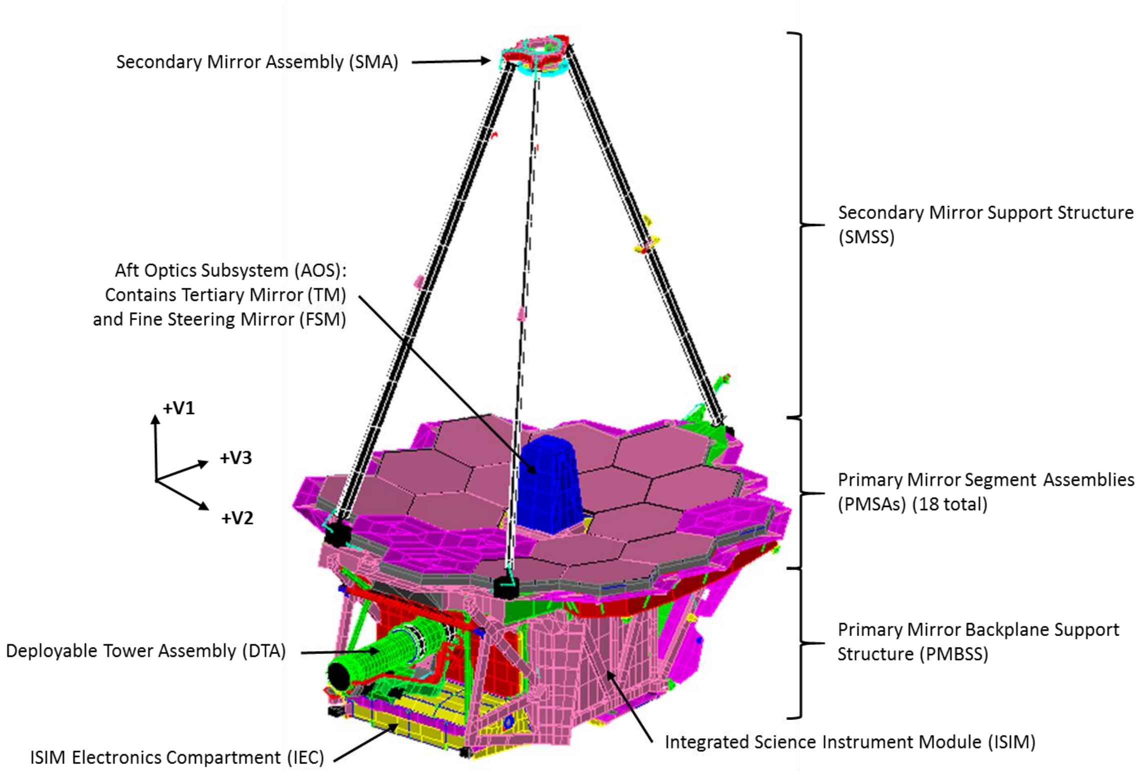

Figure 2. The OTIS Payload

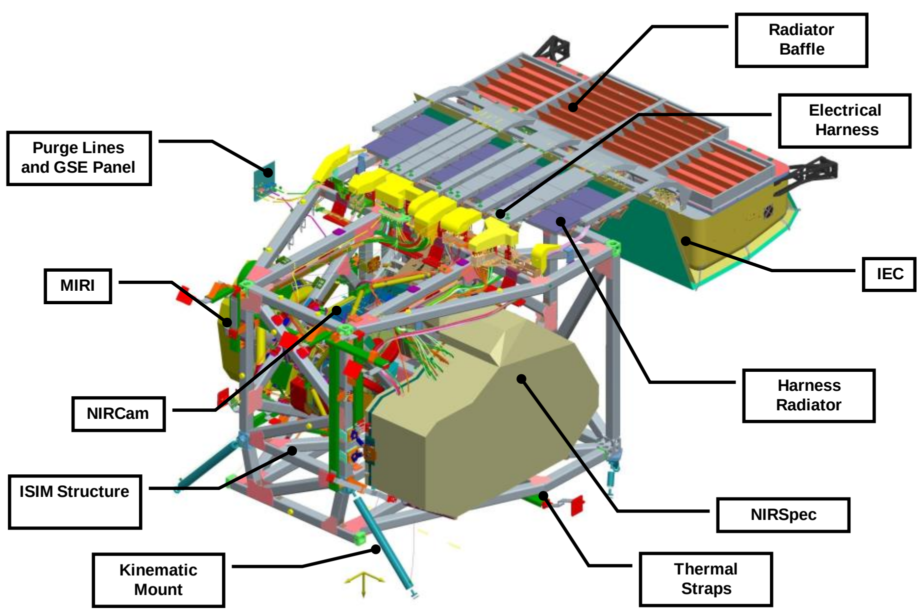

Figure 3. The Integrated Science Instrument Module and Electronics Compartment

The JSC Chamber A, a 16.8m diameter x 27.4m high thermal-vacuum test facility, was modified extensively to accommodate the OTIS payload described above and simulate a flight-like thermal environment[4]. Figure 1Figure 4(a) shows the OTIS test payload mounted within a successive series of shrouds within the JSC Chamber to provide the correct ambient thermal environment: the outermost wall being the ambient temperature pressure vessel; the middle shroud flowing liquid nitrogen at 90K during cryo-balance conditions; and the innermost shroud flowing gaseous helium at 20K. The gaseous helium from the refrigerator that cools the innermost shroud (identified as "Train 3") can be distributed to 16 zones through a valve system. The helium shroud uses seven zones, and the remaining nine zones are plumbed to various Ground Support Equipment (GSE). As all of the gaseous helium within the shroud originates from a single refrigerator, the gas inlet temperature delivered to all zones is the same. Some zones additionally have line heaters to fine-tune the temperatures reaching their respective GSE.

Harris Corporation developed the suite of thermal Ground Support Equipment (GSE) inside the helium shroud, as shown in Figure 4(b), to provide the correct OTIS payload thermal boundaries. The Space Vehicle Thermal Simulator (SVTS) was developed to provide the correct thermal heat loads of the JWST spacecraft and harness interfaces, with the interior "hub" region temperatures being directly controlled via heaters to simulate a flight-like environment, in the absence of the flight spacecraft bus and sunshield. Extending in the V1/V2 plane from the "hub" which closes out to the flight DTA, a truncated Layer-5 (L5) sunshield simulator allows for a flight-similar temperature gradient to form radiating from the SVTS. However, it was decided to not actively heat the L5 simulator since the shape of this sunshield layer would not approximate its shape in flight due to 1-g loading, and therefore would not simulate the correct flight-like heat loads or radiative views. Mounted on frames from the helium shroud floor, a series of Deep Space Environment Radiators (DSERs) consisting of extremely high emissivity radiator surfaces provide localized cold sinks for both the ISIM enclosure and IEC, and allow for separate radiative control of these components. A GSE helium chase interfaces the spacecraft from below the SVTS and provides MIRI with active cooling from a GSE cryocooler. Finally, the OTIS payload itself is supported on the stainless steel Hardpoint and Offload Support Structure (HOSS) through a series of hardpoint struts interface the BSF at the –V3 and +V3 ends. The HOSS is helium-cooled and suspended from the ceiling of Chamber A. Other support equipment, such as the Center of Curvature Optical Assembly (CoCOA), Auto-Collimating Flats (ACFs), and Photogrammetry Cameras (PGs) do not have an immediate thermal function, but rather are used to conduct optical testing of the OTIS payload. The Aft Optics Subsystem Source Plate Assembly (ASPA), separately developed by BATC, is mounted on the OTIS payload Aft Optics Subsystem forward bulkhead and generates the sources for optical testing.

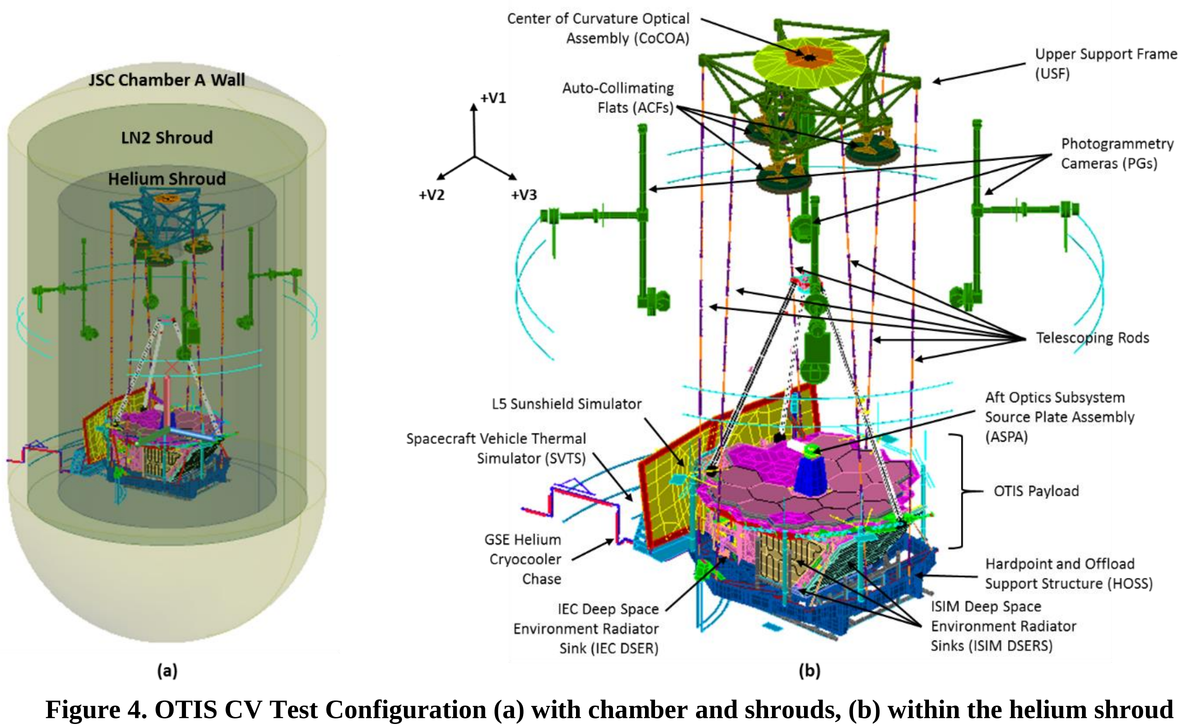

Figure 4. OTIS CV Test Configuration (a) with chamber and shrouds, (b) within the helium shroud

The OTIS payload requires further non-flight-like modifications to accommodate ground test equipment. In flight, high-purity Aluminum heat straps are used to transport heat from the science instruments inside ISIM to their respective radiators on the Fixed ISIM Radiator (FIR) and Aft Deployable ISIM Radiator (ADIR) sub-assemblies. To accelerate the cooldown of the instruments in the OTIS test when approaching cryo-balance temperatures, additional ISIM GSE "pre-cool" heat straps are attached to the flight heat-strap radiator interfaces, allowing for additional conductive heat flow out to a GSE helium line when radiation heat transfer becomes less effective at low temperatures.

Heat transfer from these pre-cool straps are made adiabatic ("zero-Q'd") as the payload approaches and achieves thermal balance conditions. Extensive changes are made to the MIRI cryocooler line to accommodate the GSE cryocooler. The flight IEC is also subjected to multiple changes to accommodate test hardware: flight vents on the +/-V2 sides of the IEC are removed to allow the IEC enclosure to vent its contaminants through a GSE sequestration duct to a scavenger plate; flight radiator baffles which directionally reject heat to space from the IEC are also removed for better view to the IEC DSER; nesting blanket tunnels are fabricated between the IEC DSER and the IEC radiator to prevent the warm IEC temperatures from being a stray-light source to the OTE optics; and the outer conformal shield which helps to thermally isolate the IEC from the rest of OTIS is replaced on the V2 and –V3 sides with a GSE version to accommodate the struts holding the IEC in gravity loading. In addition, the flight stray light "bib" structure between the spacecraft bus and the –V3 end of the BSF is replaced with a GSE equivalent to accommodate the offloader for the DTA. Finally, a flight lightshield around the SMA assembly is removed and various cutouts are made in the insulation around the PMSAs to accommodate optical test targets for the PG system. Due to these modifications, a true flight-like thermal balance for the entire OTIS system is not achievable in the OTIS CV test.

IV. Baseline (Initial) Thermal Simulations of OTIS CV Cooldown and Warmup

A baseline cooldown and warmup case was previously developed given the thermal constraints which govern the OTIS payload. The limits and constraints (L&Cs) consist of absolute temperature constraints, rate constraints, and gradient constraints. The principal control "knobs to turn" are the helium shroud and DSERS temperature transition rates, and heater operations. These were controlled by model logic such that no constraints were broken during the transition periods. The baseline cooldown and warmup profiles for the major components on OTIS are shown in Figure 5 and Figure 6. Figure 7 and Figure 8 show the compliance of the OTIS payload in cooldown and warmup to its major gradient constraints by comparing the temperature difference between the maximum and minimum thermal nodes within each component as a percentage of its specified constraint. The baseline cooldown time is 33.3 days to reach cryo-balance, the start of which is defined when the PMBSS average temperature achieves the stability criterion of 27 mK/hr sufficient to begin optical testing. The baseline warmup time is 28.4 days to warm all payload optics above 285K.

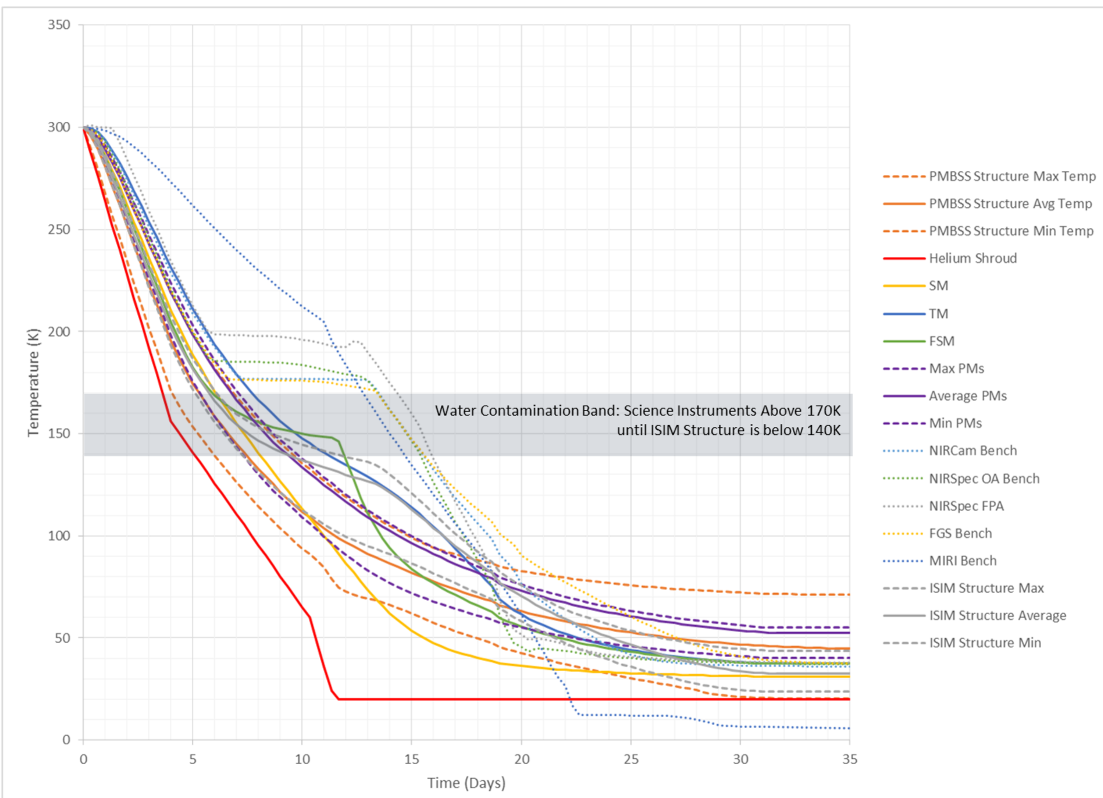

Figure 5. Baseline Cooldown Curve for OTIS CV Test

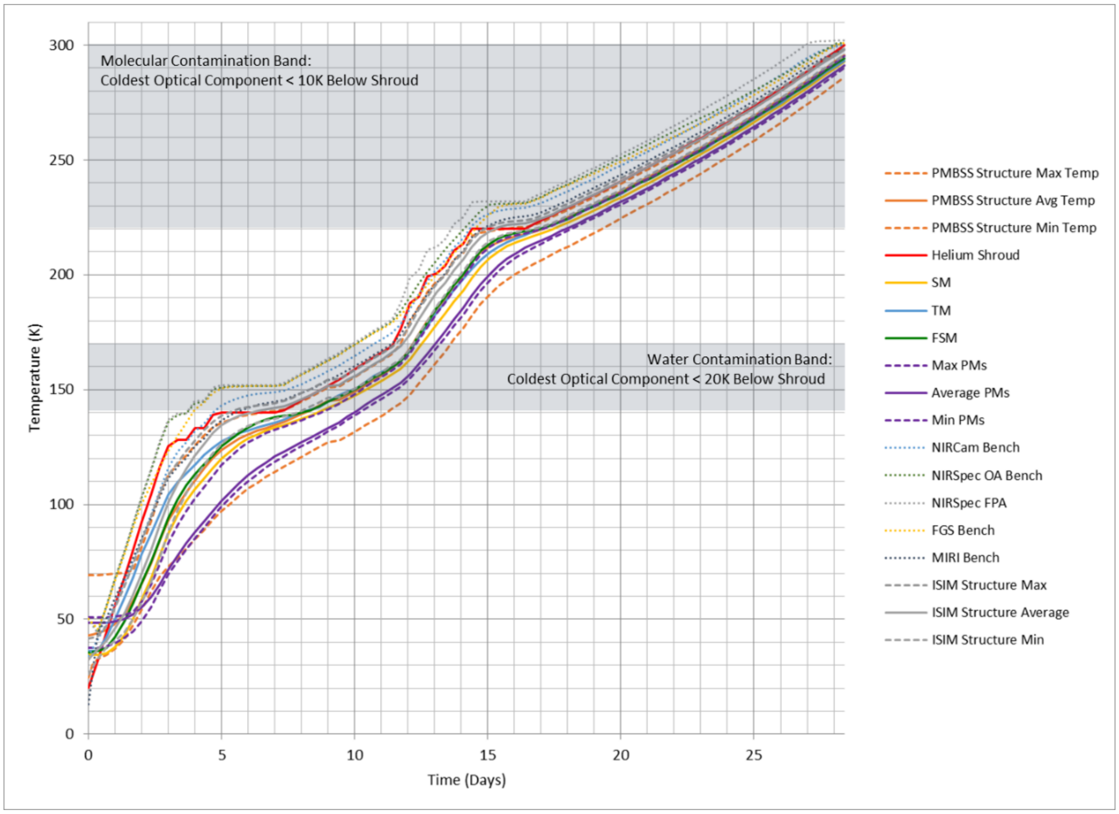

Figure 6. Baseline Warmup Curve for OTIS CV Test

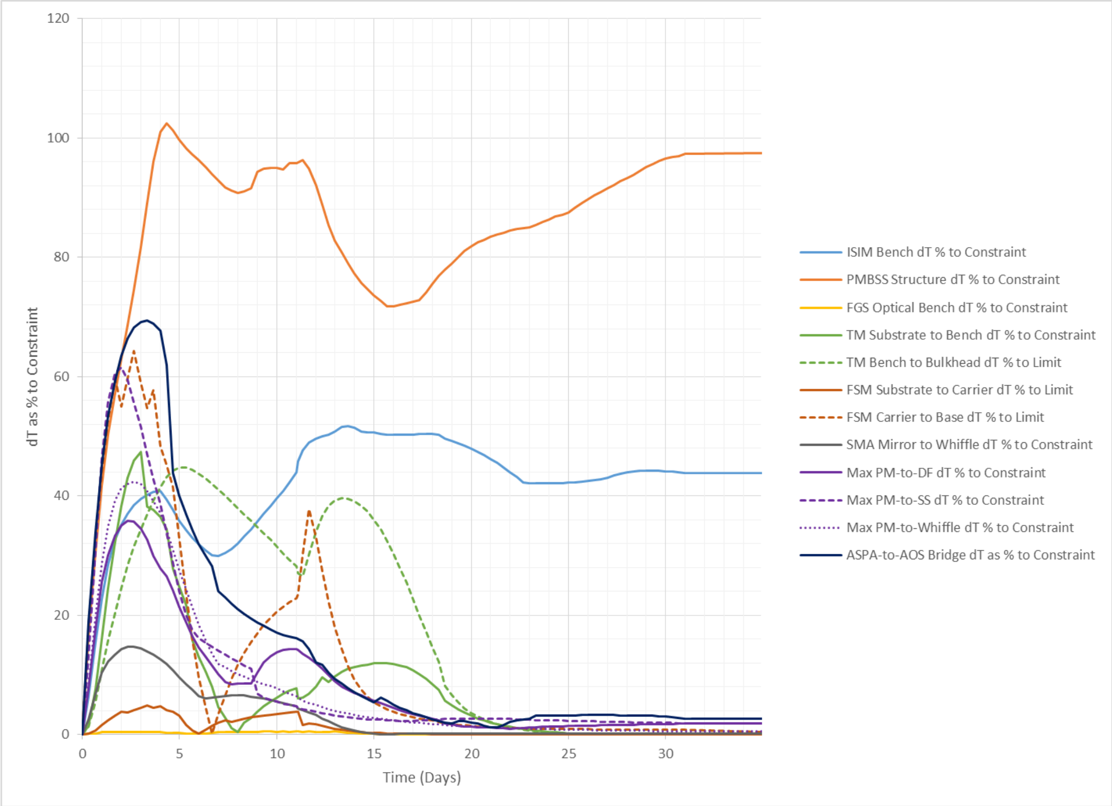

Figure 7. OTIS CV Test Cooldown Component Max-Min delta-Ts as Percentage to Gradient Constraint

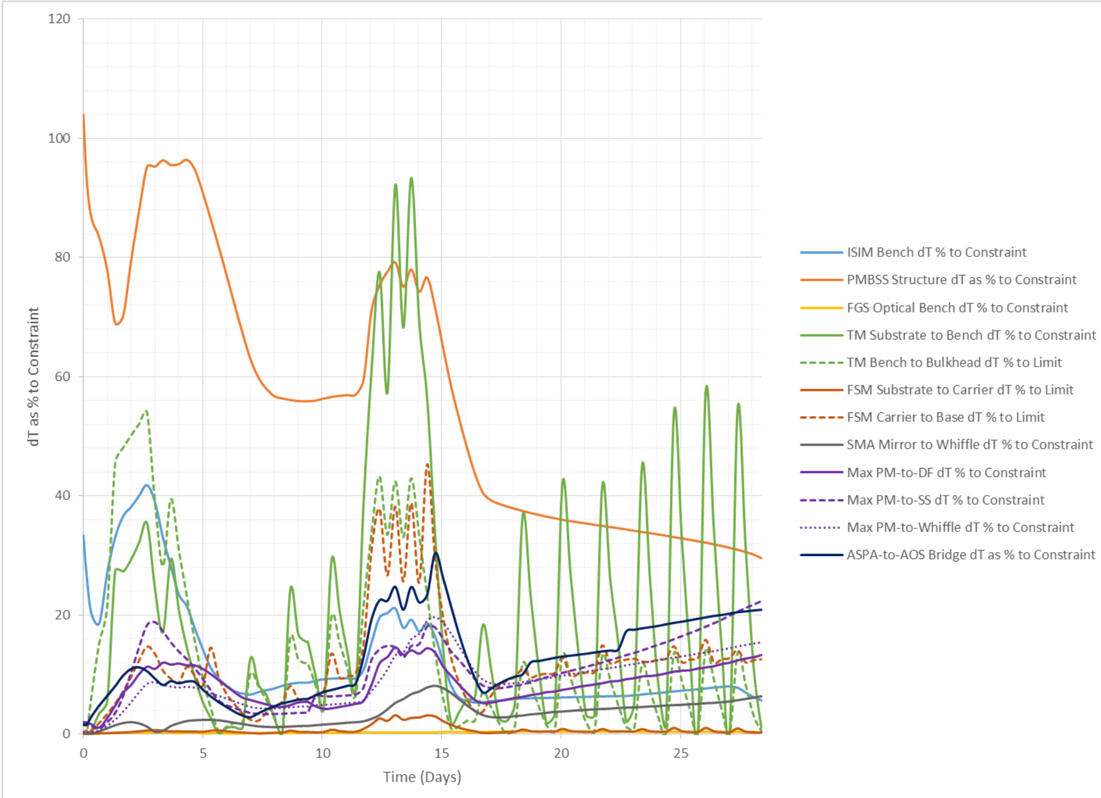

Figure 8. OTIS CV Test Warmup Component Max-Min delta-Ts as Percentage to Gradient Constraint

The bulk thermal mass of the OTIS payload and its radiative heat transfer to the helium shroud is the main driver for schedule in cooldown, as seen in Figure 5. At the beginning of cooldown, the helium shroud rate has a large impact on the cooldown rate of the OTIS payload itself. However, past day 5 of the cooldown curve, the temperature difference between the helium shroud and bulk payload average (as represented by the PMBSS average) is sufficiently large that further increases in the delta T causes little additional change to the rate of radiative heat transfer from the payload. This is seen on the PMBSS average, PMBSS max, TM, and PM behavior, which asymptotically reach their final cryo-balance temperatures by day 35, but mostly do not mirror the helium shroud profile shape. The science instrument cooldown is governed by its contamination constraints: when the ISIM structure temperature is between 170K and 140K, it can outgas water. The contamination constraint requires the critical optical and detector elements in the science instruments to be held via heaters above 170K until the composite tubes of the structure are below 140K, so that the instruments do not become collectors for moisture. After the ISIM structure cools below 140K at day 11, the MIRI cryocooler is turned on, as seen in the inflection of MIRI cooldown rate at this time. Once the MIRI bench reaches the temperature range of the other SI benches, by day 12.6, the science instruments all “step down” within 5K of each other through the water contamination band through a successive series of lower heater setpoints. Nearing cryo-balance, the near IR SIs do not show the same asymptotic behavior as the OTE mirror components because: (a) the thermal conductivity of the flight thermal links to the radiators increases by nearly an order of magnitude from ambient to 40K; (b) the pre-cool straps artificially cool and “overdrive” the radiators to maximize the delta T between instruments and radiators. When the near IR SIs reach their operational temperatures, a zero-Q heater is utilized on each pre-cool strap to make each pre-cool strap adiabatic, allowing a true thermal balance to the payload instruments and radiators..

In warmup, contamination constraints are the main schedule driver. When the helium shroud and payload are between 140K and 170K, the composite structure outgasses water and therefore presents a contamination risk for the optics. Similarly, from 220K to ambient temperatures, there is a molecular contamination risk. To prevent the optics from becoming a collector, a constraint was established by the contamination control engineers to require the coldest optical surface to be no colder than 20K from the helium shroud in the water contamination band, and 10K in the molecular contamination band. This necessitated helium shroud “holds” at both 140K and 220K, before each respective contamination band, for the mirrors to isothermalize to the required delta-T to the shroud before moving through each temperature regime. The helium shroud rate through these regimes are completely driven by the helium shroud-to-mirror deltas: the environment only moves as quickly as the slowest optical surface. In the baseline warmup plan, the coldest PM was the driver for schedule. The SIs, similar to how they were operated in the previous ISIM CV tests at NASA GSFC, use their flight contamination control heaters to lead the helium shroud through the entirety of warmup. This ensures that they will not collect any contaminants transitioning from cryo-balance to ambient temperatures.

As seen in Figure 7 and Figure 8, the major gating item for payload constraints in the OTIS CV test is the delta-T constraint for the PMBSS structure. The PMBSS structure has a delta-T limit of 42K imposed over the entire structure, as specified by the mechanical subsystem. Radiative heat transfer with the helium shroud is the dominating factor for driving PMBSS gradients, and therefore the only practical method to control this gradient is to adjust the rate of temperature change of the helium shroud itself. In cooldown, by reducing the rate of the helium shroud temperature, the least thermally massive components of the structure, which comprise the "PMBSS min" temperature on the plot, have a less-cold sink to radiate to and therefore cool more slowly, reducing the delta-T between PMBSS maximum and minimum temperatures. As a result, the helium shroud transitions from a 1.5 K/hr rate to a slower 0.63 K/hr rate between days 4 and 10.3 of the cooldown (Figure 5) to mitigate exceedances of this constraint. However, even with this slower rate, there is still a slight exceedance in Figure 7 between days 4 and 5 when the PMBSS reaches 103% of its delta-T constraint. In warmup, as seen in Figure 6, the short plateaus of the shroud profile between days 3 and 5 and 12 and 14.5 are also to prevent the PMBSS from exceeding its delta-T constraint when the shroud temperature is changing quickly between contamination bands. In warmup, the shroud temperature control is more successful in preventing exceedance of the PMBSS gradient allowable than during cooldown.

V. Modified Cooldown and Warmup Profiles to Accelerate Transitions

Due to the high daily operational costs of the OTIS CV test and project schedule pressures, a study has been undertaken to optimize the overall test duration by reducing the test transition duration from the baseline predicted cooldown time of 33.3 days and warmup time of 28.4 days . OTIS payload hardware safety concerns precluded the use of helium gas injection for free molecular heat transfer to accelerate transition times, as employed in the previous OGSE and TPF tests. Therefore, in a purely radiative environment, schedule optimization can only be achieved via modulating helium shroud rates and heater usage, as well as reexamining the gating constraints with the mechanical and contamination control teams.

An optimization code was developed in the form of a feedback loop for helium shroud control in the OTIS thermal model. Logic computing the critical limits and constraints for the payload has been added to the model, and this logic is executed each timestep to provide real-time monitoring of the thermal behavior of components against their allowable values. If no constraints are exceeded in that timestep, then the helium shroud is allowed to proceed with transitioning in cooldown or warmup at the maximum rate of 1.5 K/hr, as preset by the TPF risk-reduction test. However, if the delta-T or rate of any component exceeded its constraint plus margin, then the helium shroud temperature will hold constant for that timestep. Thus, over the entire cooldown or warmup simulation, a fully optimized helium shroud cooldown or warmup curve can be generated for a given set of limits and constraints. On a microscopic level, this profile shows near-instantaneous changes of helium shroud rate per a timestep size of 30 seconds to mitigate constraint violations. This is an ideal profile and such level of control is not achievable on the hardware itself. However, the instantaneous shroud rate changes calculated by the model can be approximated by long-term steady shroud transition rates. For example, to satisfy the water band contamination constraint in warmup and maintain a 20K delta-T from coldest optical surface to helium shroud, the optimization code may allow the shroud to increase in temperature by 0.0125 K over first 30 seconds (corresponding to the rate of 1.5 K/hr), then detect that the coldest optical surface has violated the constraint. For the next five 30-second cycles, the helium shroud will hold constant at that temperature until the coldest optical surface is compliant with the constraint, after which it will increment again and wait until the coldest optical surface is compliant again. While instantaneously, this is a stepwise helium shroud profile, macroscopically, a constant rate of 0.25 K/hr is established and used for the test.

A further study was undertaken to determine the amount of cooldown time savings that could be achieved in a "best case" scenario, where the helium shroud instantaneously transitions from ambient temperatures to cryo-balance temperatures at 20K. The helium shroud and DSERS inlets were held at a cold sink of 20K while the payload and supporting GSE started from an initial temperature of 290K. The cooldown results show that in this bounding scenario, the PMBSS stability criterion which denotes the end-of-cooldown can be established in 30.3 days, only a savings of three days. This confirms that the cooldown of the OTIS CV payload is mostly determined by the bulk thermal mass of the payload and its capacity for radiative heat transfer. It is fairly independent of the helium shroud rate especially when the shroud cools to an arbitrarily cold sink with respect to the payload temperature. The bulk of schedule savings in the OTIS CV test transitions can only be achieved in the warmup phase, not the cooldown phase.

In the original baseline warmup, the greatest hindrances to accelerating the payload transition were the restrictive PMBSS gradient constraints and contamination constraints. PMBSS initially had a constant 42K point-to-point delta-T constraint imposed over the entire composite structure, which vastly outpaced other constraints as the gating item. In talks with the OTIS mechanical team, it was decided to submit specific thermal analysis results at various points in cooldown and warmup for revised stress analysis. These temperature contours represented the worst-case OTIS payload temperature contours and were scaled up further by 50% for margin. The Smithsonian Astrophysical Observatory (SAO) coordinated the mapping of these thermal contours to the finite element models used by Orbital ATK. Upon renewed analysis, it was found that the stresses at various times during cooldown and warmup were acceptable beyond the original constraint. Therefore, a new temperature-dependent constraint has been developed which relaxes the original allowables from 42K to 52-86K in cooldown, and 52-78K in warmup. Furthermore, the thermal team coordinated with the contamination control team to relax the helium shroud-to-coldest optical surface constraint which was slowing payload transition in the 140-170K and 220K-ambient contamination bands. In the Thermal Pathfinder test, the contamination control team developed an experiment on warmup to examine the amount of contaminants collected on surfaces lagging the shroud temperatures by approximately fixed amounts. Each contamination collection tray was designed to lag in increments of 10K, up to 50K colder than the helium shroud temperature. From the TPF test results, it was shown that a 30K lag with a margin of 6K was acceptable to prevent contamination of the mirrors. This relaxation of the constraint allows for faster transition rates to be pursued during these contamination bands.

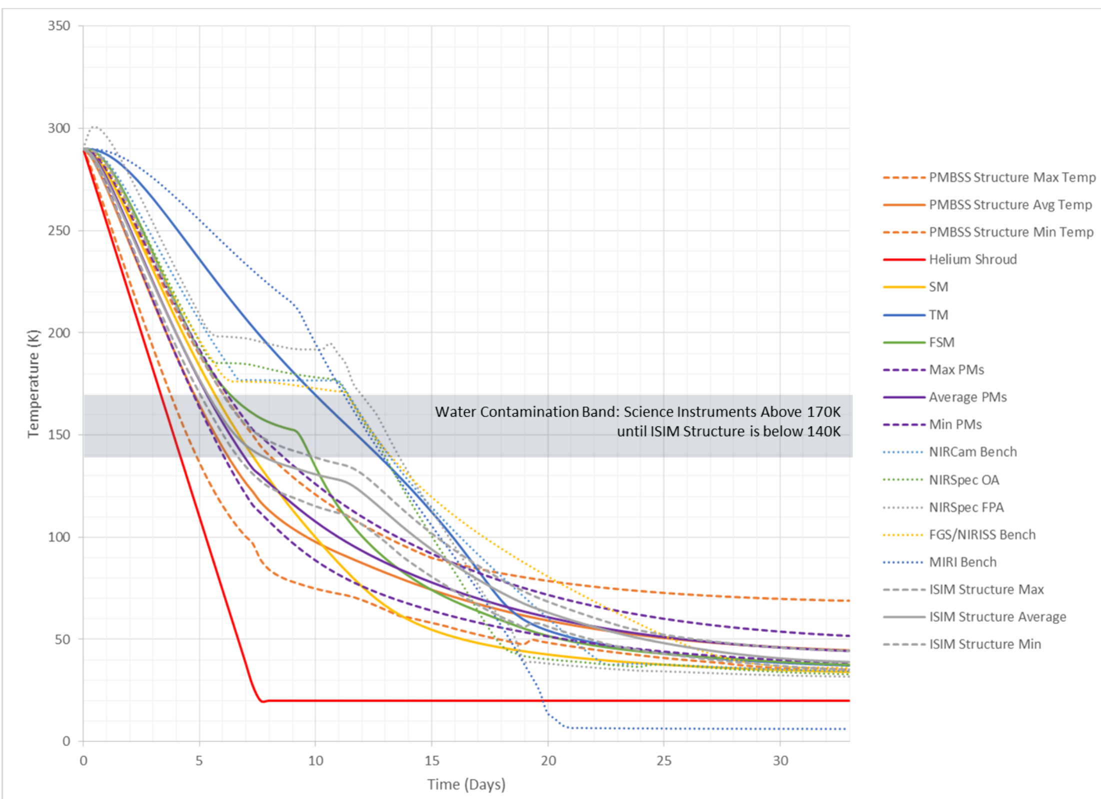

Figure 9. Accelerated Cooldown Curve for OTIS CV Test

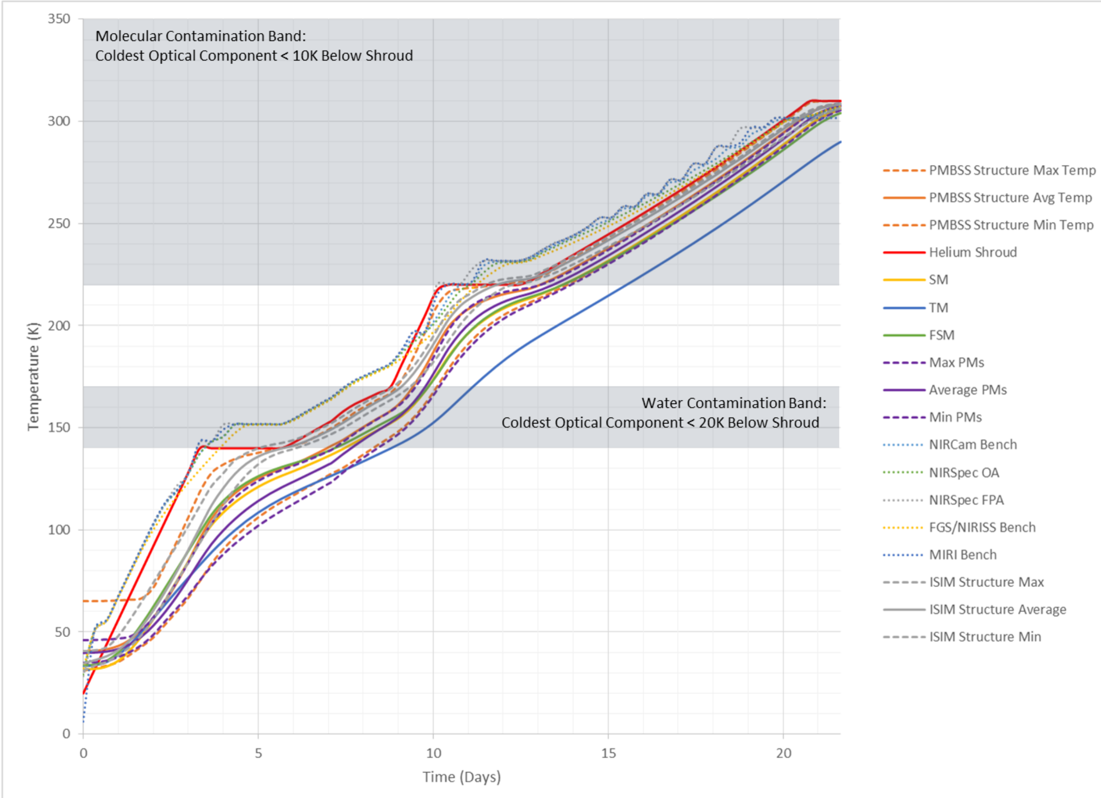

Figure 10. Accelerated Warmup Curve for OTIS CV Test

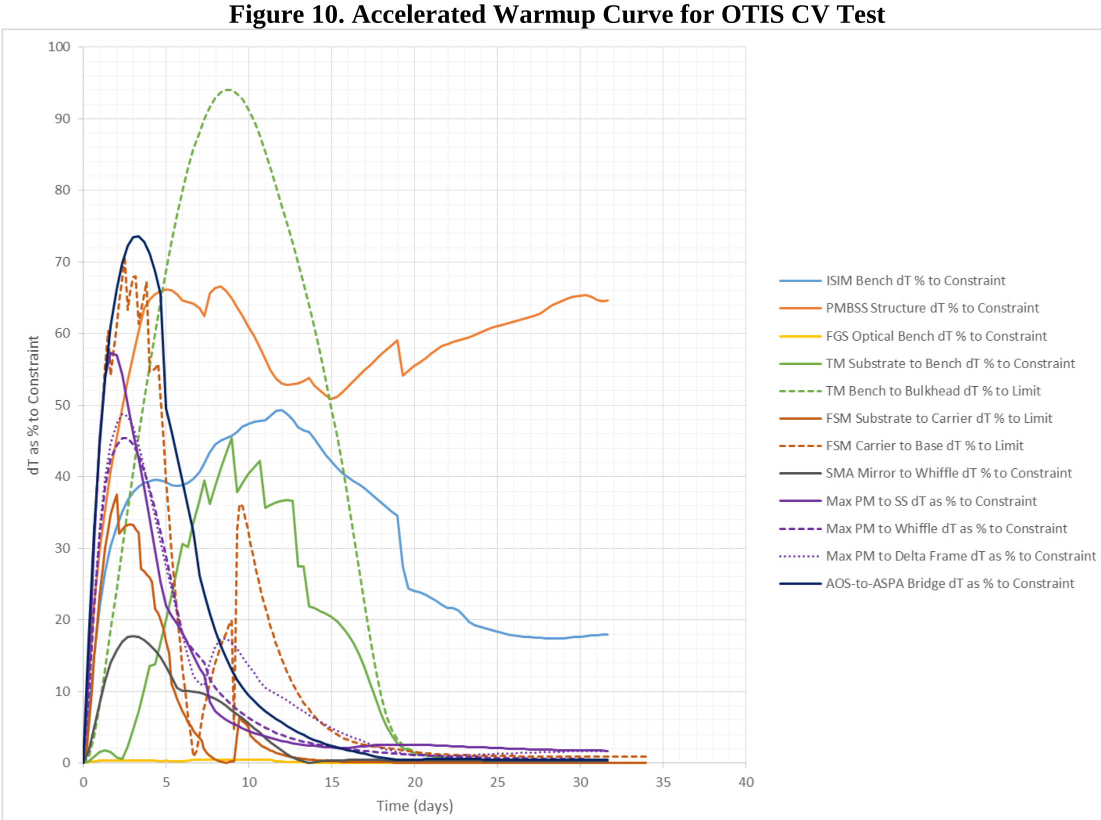

Figure 11. Accelerated Cooldown Component Max-Min delta-Ts as Percentage to Gradient Constraint

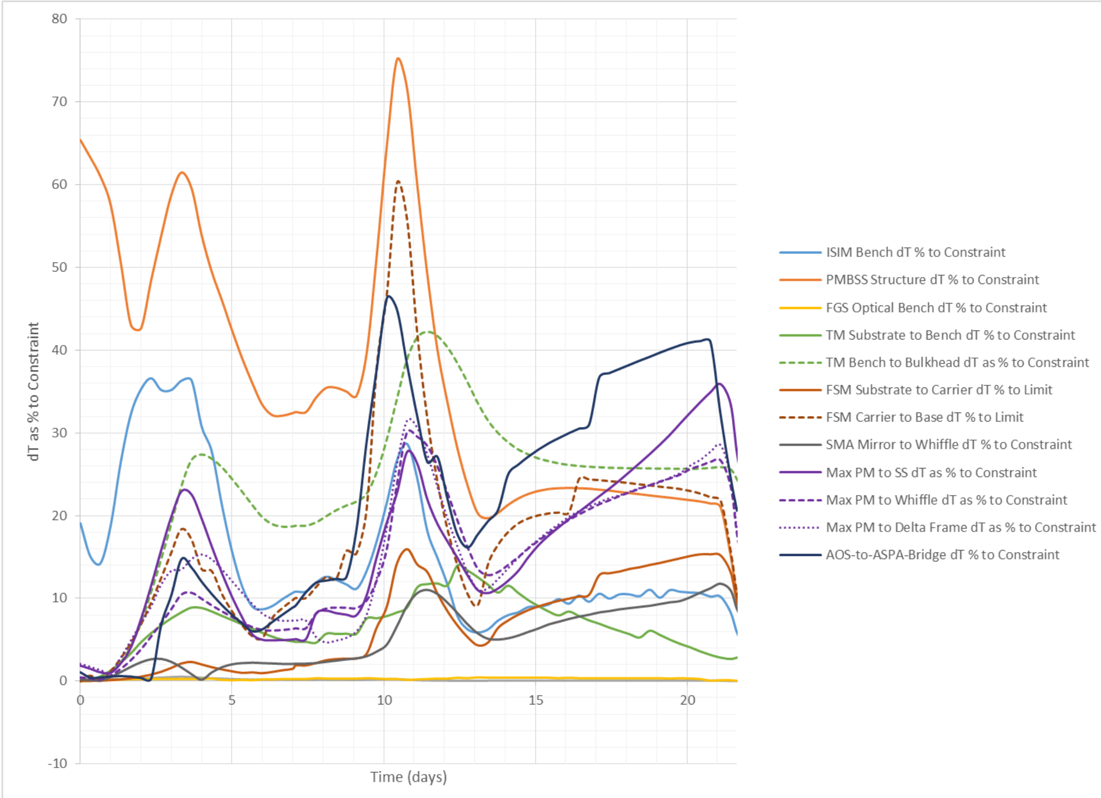

Figure 12. Accelerated Warmup Component Max-Min delta-Ts as Percentage to Gradient Constraint

Finally, modification of GSE heater setpoints were considered to accelerate the cooldown and warmup transitions. In cooldown, reduction of the radiative load on the payload is implemented via reduction of the boundary heaters in the core region: the DTA base heater was reduced from 295K to 265K; the SVTS "hub" heaters which simulate flight radiative heat loads were brought colder; the box powers in the IEC were reduced when the boxes were not in use. These were returned to their flight-like boundaries with enough time to reach thermal stability before the start of the cryo-balance phase. In warmup, the DTA base heater was raised to 310K and the SVTS hub heaters were brought warmer to contribute heat to the payload's radiative environment. The shroud was allowed to drive to 310K to provide a warmer radiative source for the coldest optics. Additionally, a series of heaters are added for the "saver plates" which comprised the GSE interfaces for the BSF structure. The effect of these is twofold: to prevent conductive heat loss from the payload through the offloader struts to the HOSS, which is relatively massive and lags during warmup, and to add more radiative heat around the OTIS payload's extremities, especially in the interest of warming the coldest PMs. The results generated from the helium shroud optimization code, as well as inclusion of the relaxed payload constraints and changes in payload boundary temperatures during transitions, are shown in Figure 9 for cooldown and Figure 10 for warmup.

In the new accelerated cooldown profile, the expansion of the PMBSS gradient allowable permits the shroud to cool down with the maximum rate of 1.5 K/hr from ambient to 20K without violating the PMBSS gradient constraint. The faster initial cooldown of the PMBSS also accelerates the cooldown of the ISIM structure, causing it to dip below 140K at day 10 rather than day 12 in the baseline case. As a result, the SIs are allowed to end their decontamination phase two days sooner and begin stepping through the water contamination band. The cooldown of the most thermally massive components are still fairly independent of the shroud temperature when the shroud becomes an arbitrarily cold radiative sink. However, the removal of the slower shroud rate period from day 4 through 10.3 as seen in the baseline case allows the overall OTIS payload to cool at the fastest radiative rate possible, achieving the PMBSS cryo-balance stability criterion of 27 mK/hr by day 30.3. In Figure 11, the delta-Ts to the constraints have changed significantly due to the expansion of the PMBSS allowable. The gating items are now the AOS Forward Bulkhead-to-ASPA Bridge delta-T through the first five days of cooldown, and the TM Bench-to-Bulkhead through the next 10 days, before the PMBSS gradient resumes as the gating constraint. The large increase of the TM Bench-to-Bulkhead gradient in comparison with the baseline case is a result of the faster shroud profile: whereas the previous reduction in shroud rate to control the PMBSS gradient also had the effect of reducing component-to-component temperature differences inside the TM assembly, the faster shroud rate now results in a large delta-T between the TM components. This is equivalent to the time savings calculated by the bounding shroud temperature case discussed earlier, and represents the greatest possible time savings on the OTIS payload in cooldown: three days.

Figure 10 shows that optimizing the warmup profile results in much larger time savings than cooldown. Expansion of the contamination constraint in the water and molecular contamination bands prove the greatest benefit for schedule, as the duration spent in contamination bands decrease due to the relaxed delta-T requirement between the helium shroud and coldest optic temperatures. The expansion of the PMBSS constraint in warmup also eliminates the need to perform short shroud plateaus to control PMBSS gradient. Therefore, when the shroud is outside of the contamination bands, it can warm at its maximum rate of 1.5 K/hr. In Figure 12, it is seen that the all of the delta-Ts are exacerbated by the periods of rapid shroud increase before the water contamination band and between the water and molecular contamination bands. However, the PMBSS constraint is still the gating item through much of the warmup phase. The overall time needed for warmup in this accelerated case is 21.6 days, a time reduction of 6.8 days from the baseline case.

VI. Conclusion

The JWST OTIS CV test will be a workmanship test for the OTIS payload before its final integration with the spacecraft bus and sunshield. Thermal model simulation respecting all existing limits and constraints determined that the baseline test cooldown and warmup durations would be 33.3 and 28.4 days, respectively. Due to the high costs of running the OTIS CV test at JSC, emphasis was placed on schedule reduction through moderating environmental controls and expanding limits and constraints while respecting hardware safety. Through optimization, time savings of 3 days on cooldown and 6.8 days on warmup can be achieved, allowing for a total thermal transition schedule savings of 9.8 days.

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