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

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Introduction to JWST

- James Webb Space Telescope (JWST) is NASA’s next-generation space telescope
  - Collaboration between NASA, ESA, European Consortium, CSA, and partners in industry and academia
- With four near-to-mid IR instruments, JWST will provide scientists with unprecedented resolution to study:
  - First light and reionization
  - Assembly of galaxies
  - Birth of stars and protoplanetary systems
  - Exoplanets and origins of life
Introduction to the OTIS CV Test

- The Optical Telescope Element and Integrated Science Instrument Module (OTIS) Cryo-Vacuum (CV) Test is a critical part of the environmental test campaign for JWST
  - Due to the size of JWST, the entire observatory cannot be thermally balanced or optically tested in existing facilities
  - Two large subsystem-level thermal vacuum tests are planned (OTIS and Spacecraft Bus/Sunshield) for optical and cryo-vacuum verification

- The thermal control objectives of the OTIS CV test are to:
  - Achieve simulated on-orbit payload temperatures for optical, mechanical, and instrument tests
  - Predict and measure thermal balance data for model crosscheck
  - Preserve hardware integrity in temperature transitions i.e. meet all limits and constraints (L&Cs)
  - Assess thermal conductance of flight instrument heat straps
  - Achieve timeline optimization on payload cooldown and warmup
OTIS Test Configuration

- Center of Curvature Optical Assembly (CoCOA)
- Auto-Collimating Flats (ACFs)
- Upper Support Frame (USF)
- Photogrammetry Cameras (PGs)
- Telescoping Rods
- Aft Optics Subsystem Source Plate Assembly (ASPA)
- OTIS Payload
- Hardpoint and Offload Support Structure (HOSS)
- ISIM Deep Space Environment Radiator Sinks (ISIM DSERS)
- L5 Sunshield Simulator
- Spacecraft Vehicle Thermal Simulator (SVTS)
- GSE Helium Cryocooler Chase
- IEC Deep Space Environment Radiator Sink (IEC DSER)

JSC Chamber A Wall
LNG Shroud
Helium Shroud
OTIS CV Critical Components: OTE

DTA: Deployable Tower Assembly
IEC: ISIM Electronics Compartment
ISIM: Integrated Science Instrument Module, contains:
- Near-Infrared Camera (NIRCam)
- Near-Infrared Spectrograph Optical Assembly (NIRSpec OA) and Focal Plane Assembly (NIRSpec FPA)
- Fine Guidance Sensor (FGS/NIRISS)
- Mid Infrared Instrument (MIRI)
OTIS CV Critical Components: ISIM
OTIS Thermal Control Hardware

- FSM Flight Baseplate Contamination Control Heater
- ISIM Contains Multiple Flight Bench and Trim Heaters
- ISIM GSE Precool Strap zero-Q heaters for cryo-balance
- ISIM GSE Precool Straps controllable through individual helium zone
- TM GSE warmup Bench Heater
- DTA Wagon Wheel GSE Heaters maintain DTA base at 295K
- MIRI GSE Cryocooler operated similar to ISIM CV testing
- GSE IEC DSER controllable through individual helium zone
- GSE HOSS Cooled through helium line
- ISIM DSERS (+V2, -V2, +V3, -V1, Harness Radiator GSE DSERS) in one Helium zone

Red: Heater Controlled
Blue: Helium Controlled
The OTIS CV Test Thermal Model is a combination of four separate models:

- OTIS Payload Thermal Model from Northrop Grumman Aerospace Systems (NGAS)
- Detailed Optical Component Thermal Models from Ball Aerospace Technologies Corporation (BATC)
- GSE and Chamber Thermal Models from Harris Corporation
- OTIS CV test-specific modifications from NASA Goddard Space Flight Center

Thermal Desktop/SINDAF, ~84000 nodes, >1 week wall-clock time for transient run

Used to develop appropriate cooldown and warmup procedures while keeping within L&Cs (over 90 Thermal-specific)
 Drivers for OTIS CV Thermal Control in Transition Periods

- Structural Limitations and Constraints (L&Cs), as well as thermal mass of payload, are main driver for schedule in cooldown
  - Structural L&Cs consist of absolute temperature constraints, rate constraints, and gradient constraints
- Contamination Constraints are main driver for schedule in warmup
  - Component-to-component ΔT requirements in water (140K-170K) and molecular (220K-ambient) contamination bands, where composite OTIS structure is most likely to outgas water and organic molecules, which present contamination risk to optics
- Principal “knob to turn” to prevent violation of constraints is Helium Shroud and DSERs transition rate
  - Helium shroud provides effective control of gradients at beginning of cooldown, but past day 5, temperature difference between the helium shroud and bulk payload average is sufficiently large that larger ΔT causes little additional change to the rate of radiative heat transfer from the payload.
  - In warmup, slower helium shroud temperature transition rate allows for all contamination constraints to be met by maintaining appropriate ΔTs between components
Full Test Profile
Baseline Cooldown Profile

ISIM instruments are held above 170K during contamination hold until ISIM composite structure stops outgassing water.

Initial cooldown rate for most components determined by helium shroud profile.

Lower shroud transition rate to control PMBSS structure gradients.

Towards end of cooldown, payload cooldown profile does not mirror shroud cooldown profile (shroud is now an arbitrarily cold sink).

Conductive straps to helium line used to accelerate ISIM transition cold: this conductive interface is made adiabatic when steady-state is reached.

Water Contamination Band: Science Instruments above 170K until ISIM Structure is below 140K.
Baseline Warmup Profile

In water contamination band, coldest optical surface cannot be >20K colder from helium shroud temperature. Shroud transition rate adjusted to maintain this constraint.

All ISIM instruments have contamination control heaters to accelerate their transition in warmup. These are powered to keep ISIM above helium shroud temperature in entirety of warmup.

Helium shroud hold at 140K to isothermalize shroud and optics to required ΔT (20K) before entering water contamination band.

Helium shroud hold at 220K to isothermalize shroud and optics to required ΔT (10K) before entering molecular contamination band.

In molecular contamination band, coldest optical surface cannot be >10K colder from helium shroud temperature. Shroud transition rate adjusted to maintain this constraint.
Baseline Cooldown $\Delta T$s as % to Constraint

Slower shroud transition rate between days 4 and 10.3 of cooldown (1.5 K/hr to 0.63 K/hr) prevents exceedance of PMBSS structural constraint in cooldown.

All other constraints are maintained by shroud rate required by gating schedule item (PMBSS structure gradient).
Baseline Warmup $\Delta T$s as % to Constraint

Short shroud holds allow for control of PMBSS and Tertiary Mirror component structural $\Delta T$s during warmup.

Shroud contamination holds at 140K and 170K also allow for large reduction in PMBSS $\Delta T$s as temperatures isothermalize.

Peaks in TM component $\Delta T$s caused by operation of TM heater in warmup.
Schedule Optimization Study

- Due to high daily operational costs of OTIS CV test, a study was undertaken to reduce OTIS CV payload cooldown and warmup transition times
  - In purely radiative environment, schedule optimization can only be achieved with modulating helium shroud/DSER rates and heater usage, and reexamining all gating L&Cs
  - PMBSS structural constraint reviewed with mechanical team: new stress analysis showed that previous point-to-point structural ΔT constraint was too conservative. A new temperature-dependent constraint was developed which precluded need for helium shroud rate slowdown in baseline curve
  - Contamination constraint re-examined: previous constraint for optics-to-helium shroud ΔT was too conservative based on results from previous Pathfinder test. New allowables are 40K for both contam. bands
  - Overdriving of shroud temperatures and GSE boundaries also considered
- Optimization code was developed in the form of a feedback loop for helium shroud/DSER control in cooldown and warmup
  - Model calculates payload performance against all critical L&Cs per timestep, providing real-time monitoring of thermal behavior of components against allowable values
    - If no constraints exceeded, helium shroud/DSERs allowed to proceed at max. rate of 1.5 K/hr
    - If ΔT or rate of any component exceeded constraint + margin, the helium shroud/DSERs temperature will hold constant for that timestep
  - While this produces a stepwise shroud profile at a microscopic level, on a macroscopic level this produces the constant shroud rate needed to maintain this constraint
Modified Cooldown Profile

Expansion of PMBSS structural gradient allowable permits shroud to maintain constant 1.5 K/hr through entirety of cooldown; this allows payload to cool at fastest radiative rate possible.

Due to faster shroud rate, ISIM can end its decontamination phase two days sooner from ISIM structure reaching 140K earlier.

Water Contamination Band: Science instruments above 170K until ISIM Structure is below 140K.

PMBSS structure reaches optical testing stability criterion (which denotes end of cooldown) three days sooner than baseline.

Total Time Reduction: 3 Days
Modified Warmup Profile

Due to relaxed $\Delta T$ requirements before entering water and molecular contamination bands, time needed to hold shroud and wait for components to isothermalize is now shorter.

Total Time Reduction: 6.8 Days
Faster shroud transition rate now exacerbates structural ΔTs over other components.

Expansion of PMBSS structural gradient allowable permits PMBSS to maintain below constraints despite faster shroud transition rate.

Modified Cooldown ΔTs as % to Constraint
Expansion of PMBSS gradient allowables removes need for short shroud holds to control PMBSS gradient: shroud can move at 1.5 K/hr when outside contamination bands.
Summary and Conclusions

- JWST OTIS CV Test is a workmanship test for the OTIS payload before its final integration with the spacecraft bus and sunshield.
- A modeling study was undertaken to optimize the OTIS payload cooldown and warmup transition times for this test. The following table summarizes the major modifications made and their impacts on test schedule:

<table>
<thead>
<tr>
<th>Major Modification to Baseline</th>
<th>Time Impact on Cooldown</th>
<th>Time Impact on Warmup</th>
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<tbody>
<tr>
<td>Expansion of PMBSS structural gradient constraint to a larger allowable ΔT via stress analysis</td>
<td>Reduction of Helium shroud cooldown time by 4 days, reduction of total cooldown time by 3 days</td>
<td>Removal of shroud plateau time spent to mitigate PMBSS gradient, savings of 0.6 days</td>
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<tr>
<td>Relaxation of Helium shroud-to-coldest optical surface allowable ΔT constraints in water and molecular contamination bands</td>
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<td>Reduction of time in 140K shroud plateau and water contamination band by 1 day, reduction of time in 220K shroud plateau and water contamination band by 4 days</td>
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<td>Other changes: Driving of Helium shroud to 310K at end-of-warmup, overdriving of GSE heater setpoints</td>
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<td>Reduction of time spent at end-of-warmup by 1.2 days</td>
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- Baseline times: 33.3 Days cooldown, 28.4 days warmup. Modified transition times after optimization study: 30.3 days cooldown, 21.6 days warmup. Total time savings: 9.8 days.
Acknowledgments

The authors would like to thank the following individuals who made invaluable contributions to the content and analysis presented here:

- Brian Comber, *Genesis Engineering Solutions, Inc.*
- Randy Franck, Rusty Schweickart, and Denny Teusch, *Ball Aerospace Technologies Corporation*
- George Harpole and John Pohner, *Northrop Grumman Aerospace Systems*
- Keith Havey, Jesse Huguet, and Clint Travis, *Harris Corporation*
- Angelique Davis, *Edge Space Systems*
- Sang Park, *Smithsonian Astrophysical Observatory*
- Paul Cleveland, *Energy Solutions Inc.*