James Webb Space Telescope
Optical Telescope Element / Integrated Science Instrument Module (OTIS) Cryogenic Vacuum Test

Part II: Thermal Analysis

Kan Yang

NASA Goddard Space Flight Center

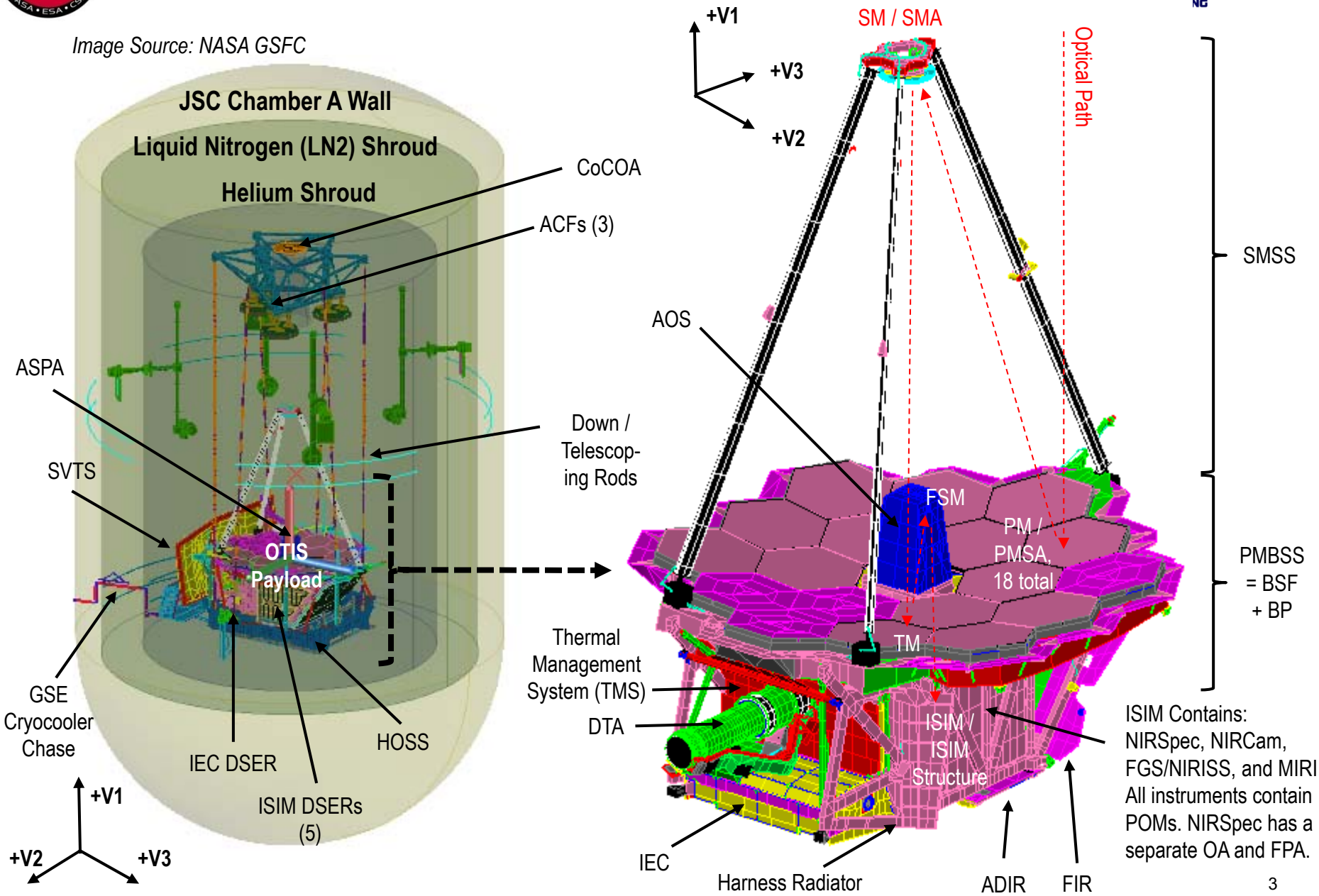
Overview

- **This lecture represents the second part of the JWST OTIS CV Test Lecture Series**
  - Part I: Thermal Architecture
  - **Part II: Thermal Analysis**
  - Part III: Preparations for Off-Nominal Events
  - Part IV: Lessons Learned

- **Objectives of this current lecture:**
  - Provide an overview of the OTIS CV test thermal model development
  - Describe the limits and constraints that drove pre-test planning and the development of the OTIS test methodology
  - Introduce the logic for optimizing the helium shroud profile by trading off between test time and hardware safety
  - Understand how our pre-test predictions compared with the actual hardware performance in the OTIS CV Test

Recap: Components in the OTIS CV Test

Image Source: NASA GSFC



Recap: Other Commonly-Used Acronyms

Acronyms:

- **GSE:** Ground Support Equipment (in contrast to "flight" equipment)
- **K:** Kelvin
- **L&Cs:** Limits and Constraints
- **LN2 / N2:** Liquid Nitrogen / Gaseous Nitrogen
- **ΔT or delta T:** Temperature Difference
- **Δt or delta t:** Change in time

Shorthand references:

- **"Gradients":** not used in context of temperature change per length, but rather in magnitude of the temperature difference, especially on large structures
- **"Harness":** electrical wire bundles
- **"Model":** specifically refers to the OTIS CV Test Thermal Model unless otherwise indicated
- **"Payload" or "OTIS":** refers to the entirety of the JWST OTIS system-level hardware assembly under test, as distinguished from the OTIS CV test
- **"Shroud":** specifically refers to the Helium Shroud unless otherwise indicated

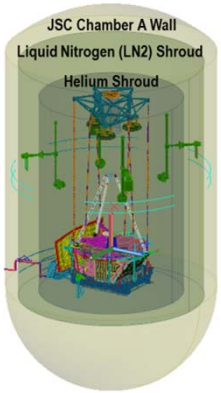
OTIS CV Test Planning: Pre-Test Thermal Analysis

- **The development of the OTIS CV Test Thermal Model was a multi-year process that required coordination between five separate organizations**
- **Pre-OTIS CV Test planning using this model encompassed the following scope of thermal analyses and produced the following deliverables:**
  - Cooldown and Warmup studies to establish timelines
    - » Full transient cooldown and warmup within all specified limits and constraints
    - » Temperature stability estimation and time required to reach stability criterion
    - » Handoff of model results for stray light, thermal distortion, and stress analyses
  - Timeline optimization against OTIS payload sensitivity
  - Prediction of temperatures and heatflows during cryo-balance for ISIM and OTE, and validation that steady-state test requirements can be met
  - Mapping of flight and test thermal sensors to OTIS thermal model
  - Analysis of off-nominal thermal conditions in OTIS CV test
  - Incorporation of correlated model parameters on a case-by-case basis from previous subsystem-level CV testing: ISIM Cryo-Vacuum Test, Core 2 Test, and Thermal Pathfinder test

OTIS CV Test Thermal Model: A System-Level Integration of Subsystem-Level Deliveries

Reduced GSE Model from Harris Corp.

Chamber / LN2 Shroud / Helium Shroud Dimensions from NASA JSC Chamber A Facilities Team



Secondary Mirror Model used Ball Aerospace Detailed Thermal Model for tracking gradients / transient behavior

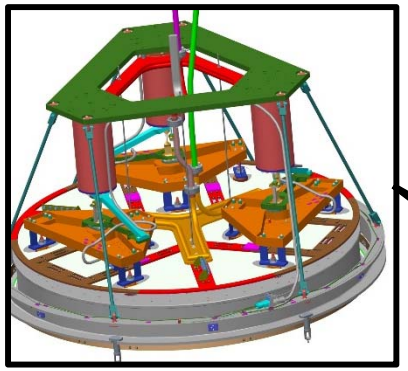
Select PMSA Models used a "Detailed" Geometric Representation from Ball Aerospace to better track gradients / mirror transient behavior

Ball Aerospace AOS Source Plate Assembly Model

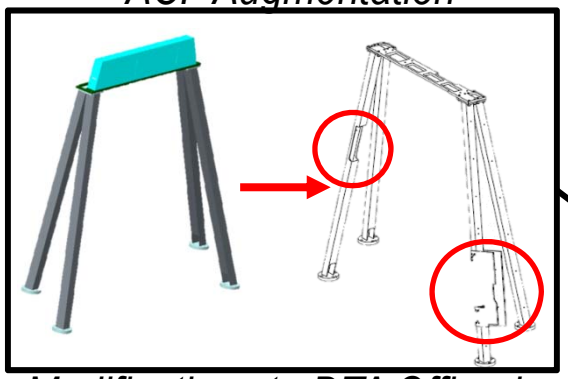
Northrop Grumman Corporation Detailed Flight OTIS Model

Image Source: NASA GSFC

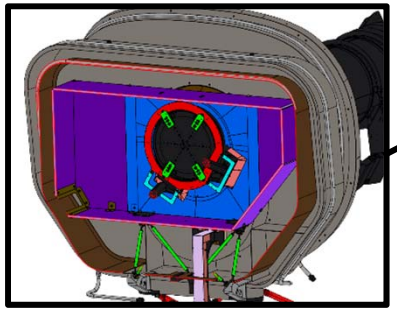
GSE Thermal Updates and Modeling for the OTIS CV Test



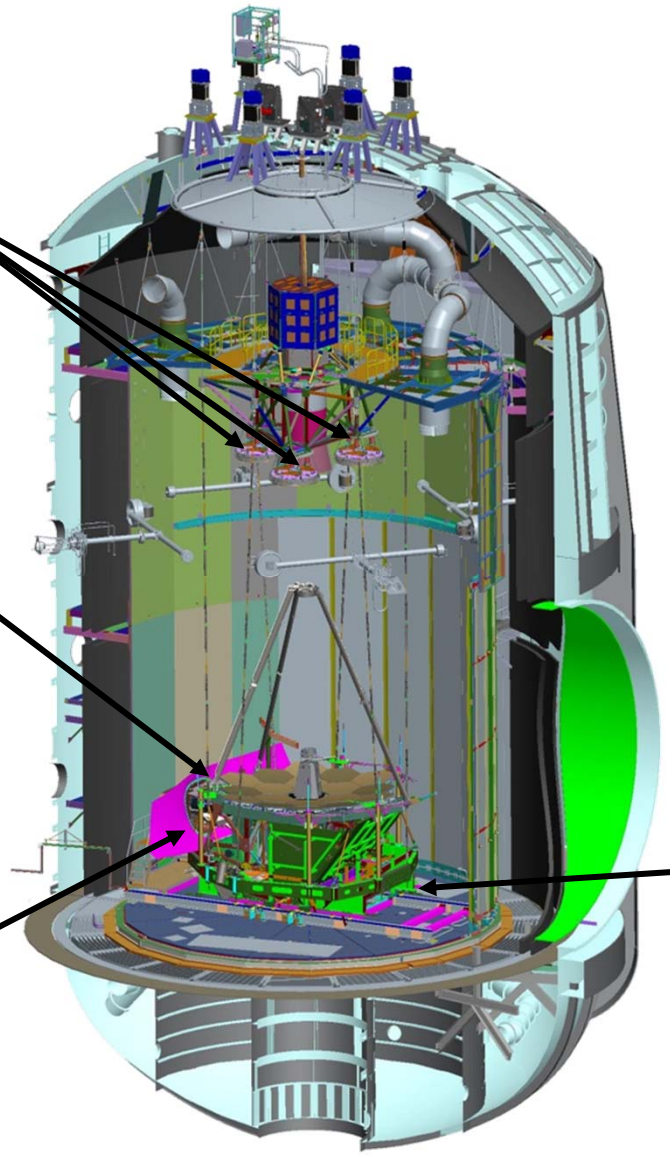
ACF Augmentation

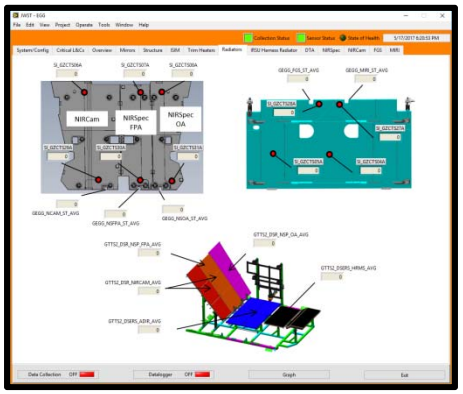


Modifications to DTA Offloader

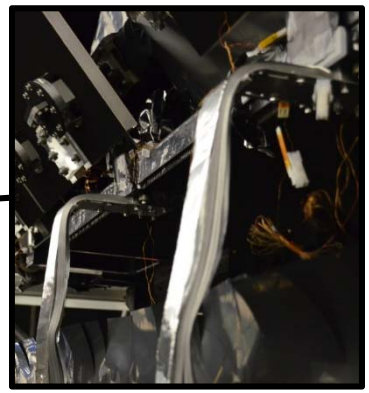


SVTS MLI Modifications





Harris Thermal Test Set (TTS) and Eclipse Graphical Generator (EGG) Systems

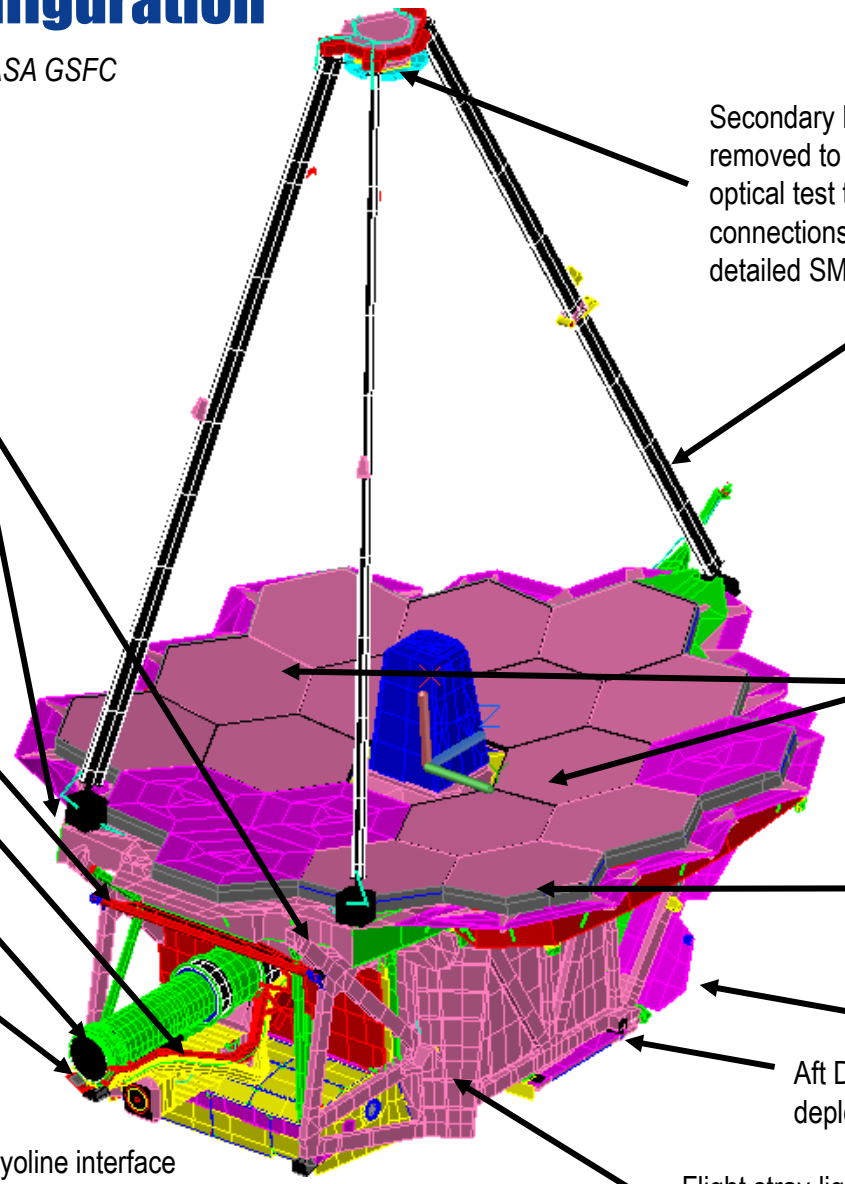


ISIM Pre-Cool Straps

Modifications to Flight OTIS Model to Match CV Test Configuration

+V1
+V3
+V2

Image Source: NASA GSFC



Secondary Mirror Assembly: Flight Lightshield removed to reflect test configuration with optical test targets, mirror mount and harness connections changed to accommodate detailed SM model

Detailed payload Secondary Mirror Support Structure model added to simulate mechanism deployment heater operations

GSE "Saver Plate" interfaces modeled to correctly capture heat transfer from OTIS to offloading structure (HOSS)

NG stray-light bib structure replaced with GSE bib to match test configuration

OTE and IEC harnesses on DTA attached to GSE SVTS

DTA base held at room temperature to simulate spacecraft boundary

IEC Changes:

- Various Thermal-structural component GSE replacements
- Heater setpoints modified for ground testing
- -V2 GSE vent cover
- +V2 vent tied to contamination sequestration duct

Hingeline GSE Clamps between backplane center structure and wings added to simulate test supports for gravity loading

Stray-light frill cutouts for primary mirror optical test targets added to match OTIS test configuration

ISIM precool straps attached to flight radiator interfaces

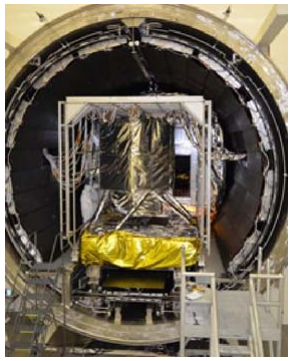
Aft Deployable ISIM Radiator (ADIR) only deployed 1 degree due to GSE interference

GSE cryoline interface between GHe Chase and flight cryoline for MIRI instrument

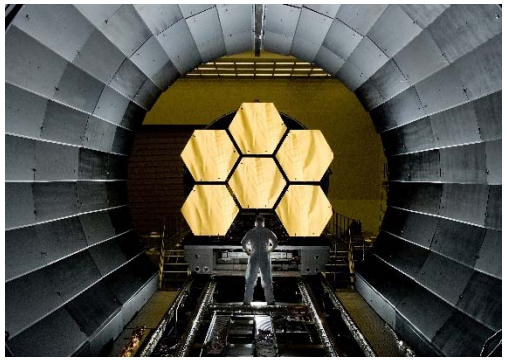
Flight stray-light Batwings partially deployed due to GSE interference

Subsystem Model Heritage

- **Payload**
  - AOS: correlated to subsystem-level testing at Ball Aerospace[1]
  - IEC: correlated to subsystem-level testing at NASA GSFC[2]
  - ISIM: correlated to ISIM CV testing[3,4]
  - PM and SM: correlated to segment assembly testing at Ball Aerospace[5]
  - PMBSS Structure: correlated to tests at NASA MSFC's X-Ray Cryogenic Facility (XRCF)[6]
- **GSE**
  - Harris thermal simulators, mechanical support hardware, metrology systems: correlated to individual subsystem-level tests and system-level testing at Thermal Pathfinder[7,8,9]



CoCOA Test at NASA MSFC



PM EDU Test at NASA MSFC



ISIM CV Testing at NASA GSFC



Core 2 Test at NASA GSFC



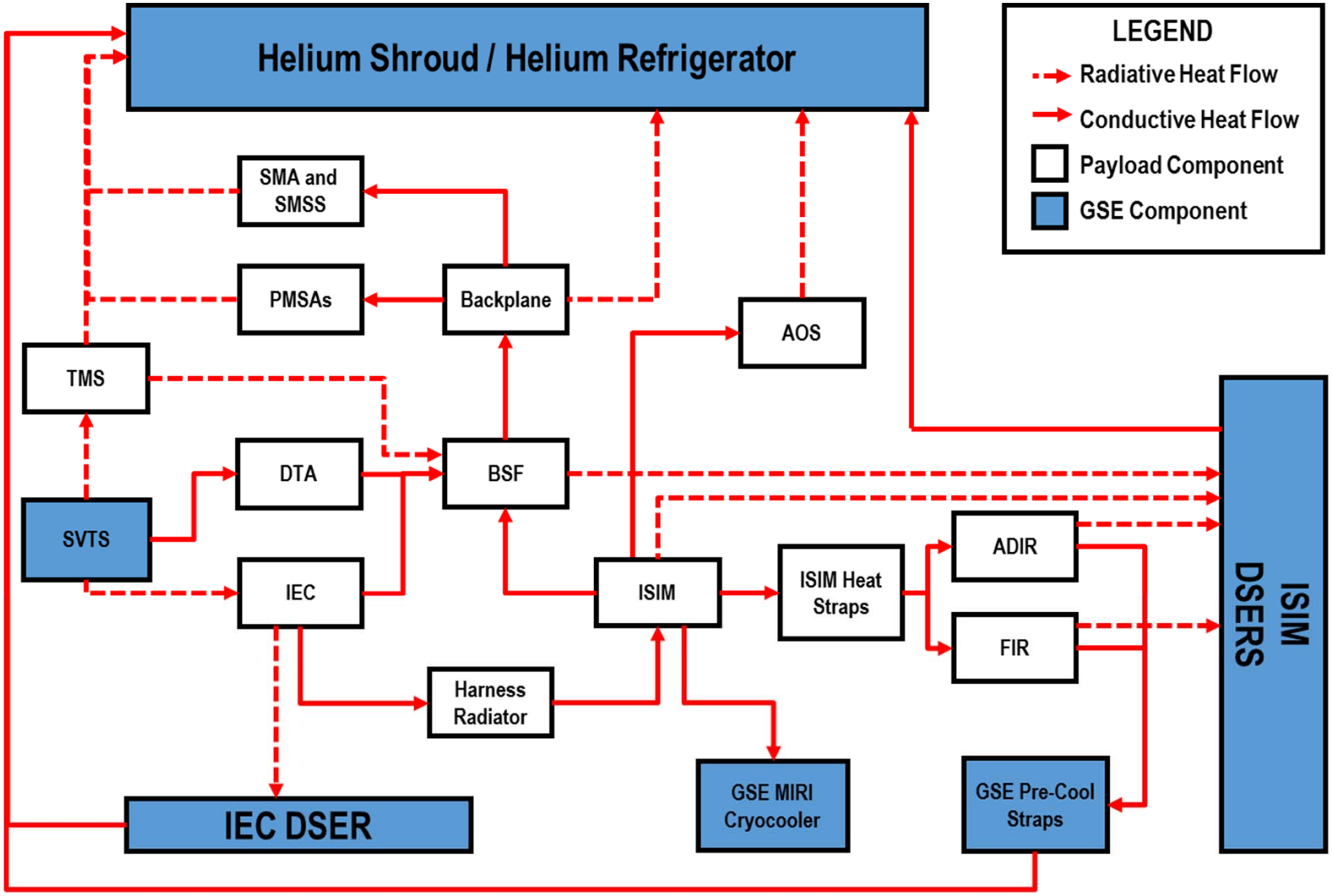
Thermal Pathfinder at NASA JSC

Image sources: NASA/JWST

Model Verification

- **Northrop Grumman "Math Model Guidelines" document**
  - All subsystem models designed to this guideline
    - » Recurring reviews to assess model status / ensure compliance
  - For Thermal Model, defines coordinate systems, mass and thermal dissipation conventions, boundary conditions, model size/numbering/naming
- **Crosschecks for OTIS system-level model accuracy**
  - Flight separate model crosschecks are performed with incoming flight and flight test correlated models that constitute the main OTIS payload model
    - » NASA GSFC maintains separate flight model in different thermal analysis software than Northrop Grumman model for crosscheck
  - OTIS system crosschecks performed by analysts working independently on the same model to verify model accuracy:
- **OTIS CV thermal model version releases and thermal results provided to other subsystems for their model analyses: thermal distortion model, structural model for stress analysis, optical stray light model**
- **Post-test "calibration" of thermal model to OTIS CV test data; enhancement of flight model with test results**

Heat Flows on the OTIS Payload



Driving Parameters for OTIS Test Methodology (1 of 2)

- **One of the primary objectives for the OTIS CV Thermal Test Model was to develop the methodology for cooldown and warmup of the OTIS payload while ensuring payload safety and optimizing test time**
- **For ensuring payload safety, the OTIS CV Test needed to consider all 92 separate thermal limits and constraints (L&Cs) during all test phases:**
  - These can be divided into four general categories
    - » Absolute temperature limits
    - » Structural gradient or temperature difference (ΔT) requirements
    - » Rate requirements
    - » Contamination control requirements

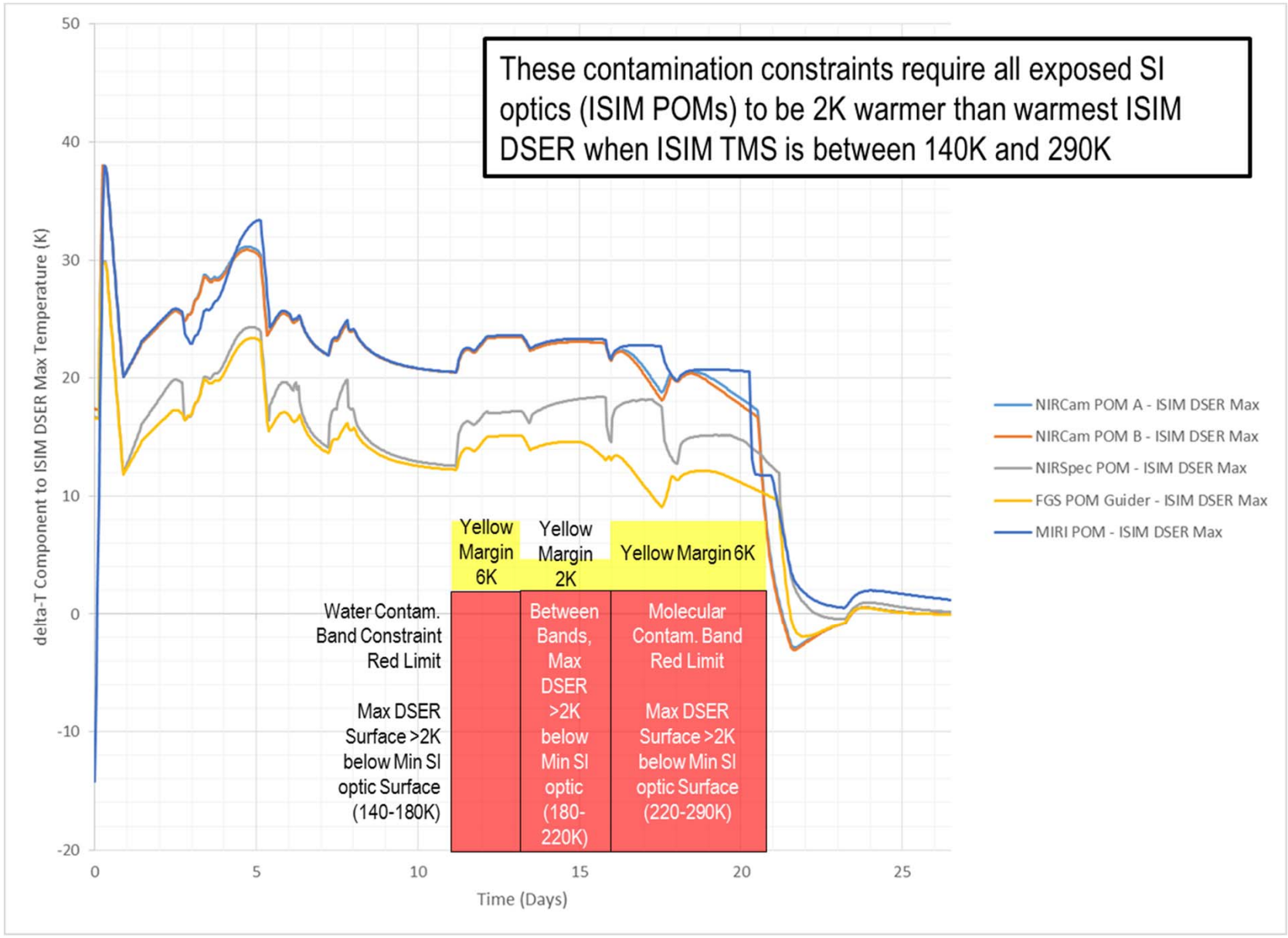
Driving Parameters for OTIS Test Methodology (2 of 2)

- **Additionally, the following items needed to be addressed:**
  - Margins for all test hardware to ensure that action was being taken to avoid limits and constraints well before the constraint was violated
  - Heater control logic for each ISIM instrument, the FSM and the TM: these needed to reflect the actual hardware installed, as well as control to avoid any limit and constraint violations
  - MIRI GSE cryocooler logic: needed to reflect the actual function and stage transitions of the hardware to capture the correct temperatures on the MIRI cryocooler line and MIRI optical bench
- **The overall goal of OTIS thermal analysis is to achieve a thorough understanding of the driving parameters for payload temperature transition, which "knobs to turn" we have, and when to use them to avert hardware damage**

Contamination Control Limits and Constraints

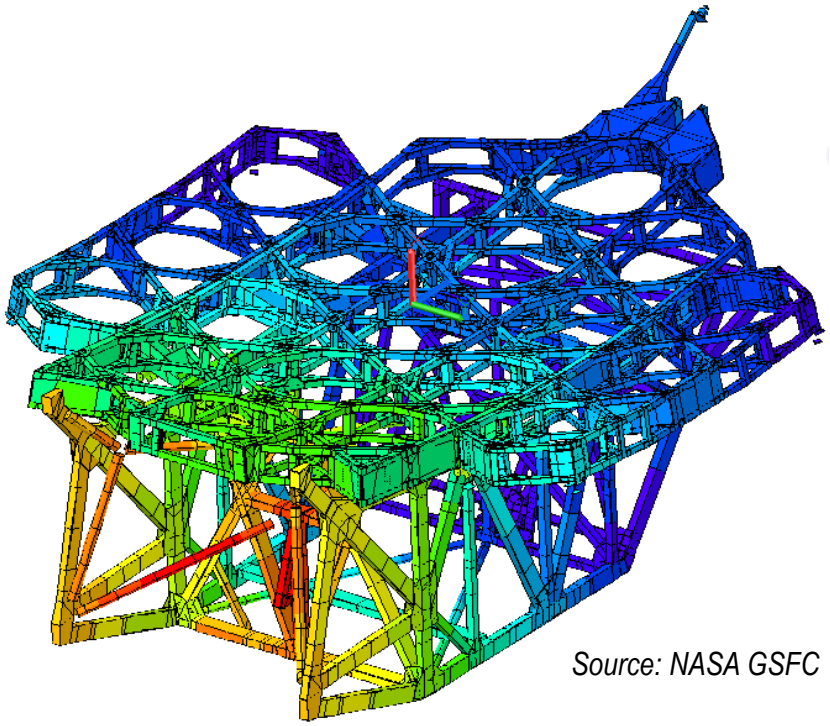
- **Since OTIS has a composite truss frame, at 140-170K water is emitted from the composite structure, and at 220-285K molecular contaminants are released**
  - The sensitive optical components (18 Primary Mirrors, Secondary Mirror, Tertiary Mirror, Fine Steering Mirror, ISIM Pick-Off Mirrors) are at risk of being contaminated unless they are kept warmer than the surrounding structure
  - A plan was developed with the contamination control team to actively heat ISIM and FSM mirrors above environment during cooldown and warmup
  - Helium shroud and DSER warmup rates were also controlled to prevent a large ΔT from forming between environment and primary / secondary / tertiary mirrors
- **In cooldown, an ISIM contamination avoidance phase was used, keepingall instruments above 170K until ISIM structure stopped emitting water below 140K**
- **In warmup, both active heater control and shroud rate were used to keep all components within contamination constraints at temperature ranges for water emission and molecular contaminant emission**

Sample Thermal Model Predictions Against One Contamination Constraint



Structural Limits and Constraints (1 of 2)

- **To maintain structural integrity and prevent any unacceptable stresses from forming in structural joints and members, PMBSS and ISIM structures both have L&Cs defining allowable ΔTs across any two points**
  - For both structures, this was the result of structural model analysis with predicted thermal gradients and cryo-cycle testing of bare composite structure assemblies
  - ISIM structure ΔT requirement remained constant
  - PMBSS ΔT requirements varied based on temperature and if the structure was warming or cooling
    - » Especially challenging to manage given the large ΔTs between heat sources and sinks inside the helium shroud, as well as reliance on passive control to maintain structural gradients

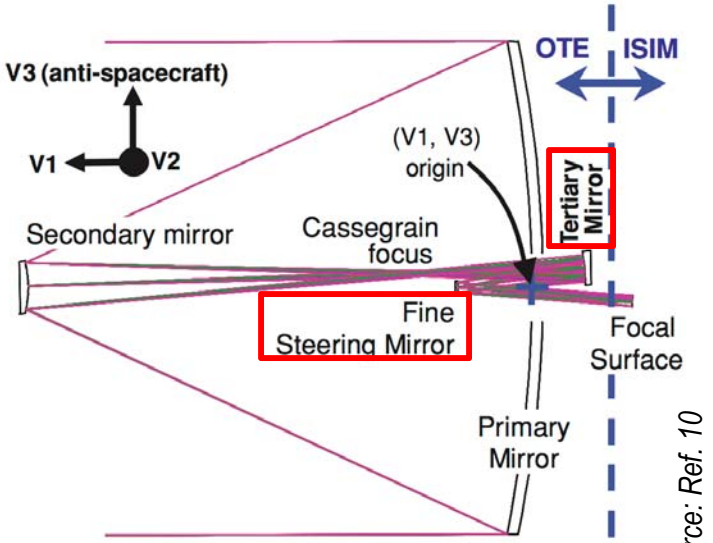


Source: NASA GSFC

Cryogenic steady-state temperature distribution on PMBSS composite truss structure

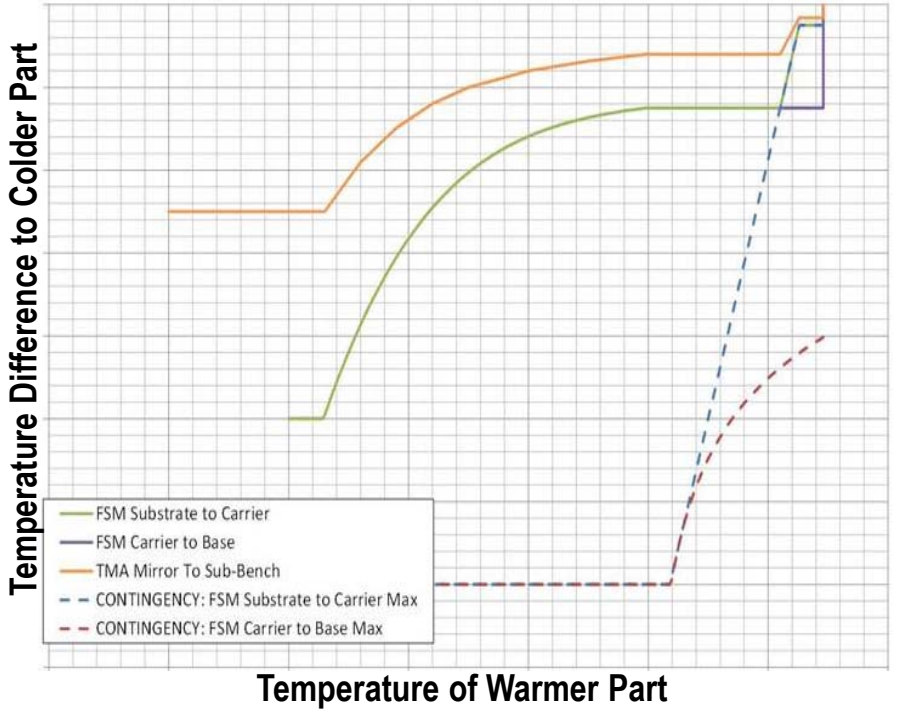
Structural Limits and Constraints (2 of 2)

- **For mirror assemblies, there are temperature-dependent ΔT requirements between components for structural integrity and to prevent optical distortion**
  - Violation of limitations on optical components can result in increased surface figure error, resulting in degraded observatory optical performance
  - Violation of constraints can cause stress in mirror substrates
    - » Results in permanent deformation of mirror surface performance



Source: Ref. 10

Position of the TM and FSM in the JWST Optical Design

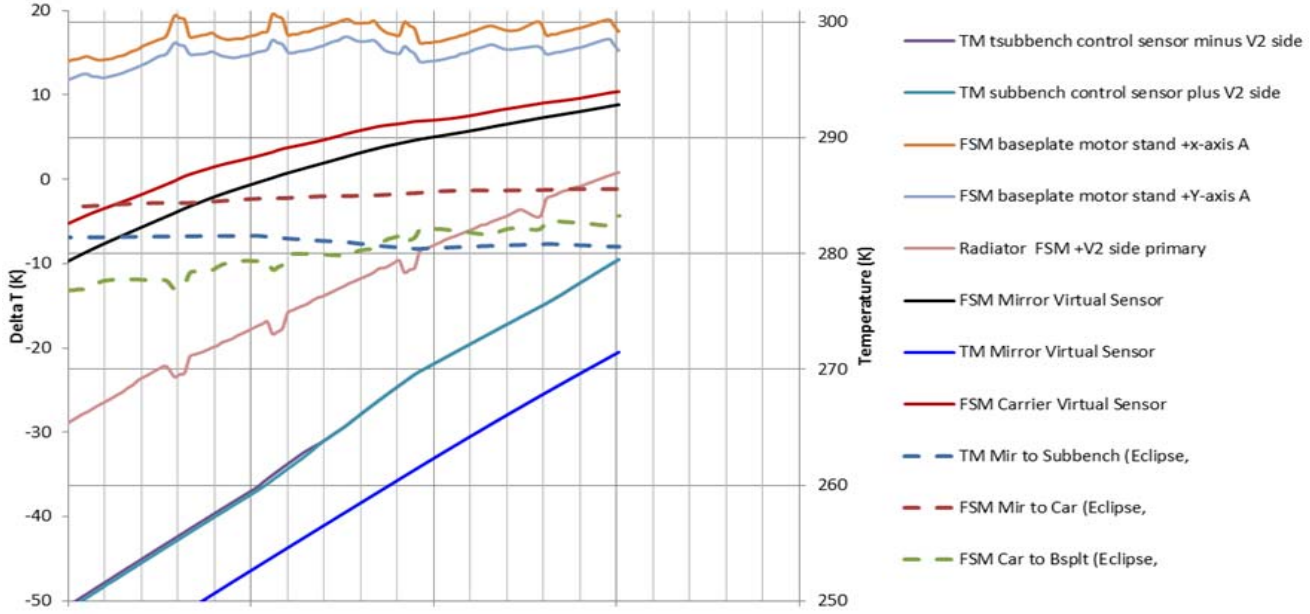


Source: Ball Aerospace

Sample temperature-dependent ΔT requirements for AOS mirror assemblies

Real-Time Model (RTM) for AOS Components[11]

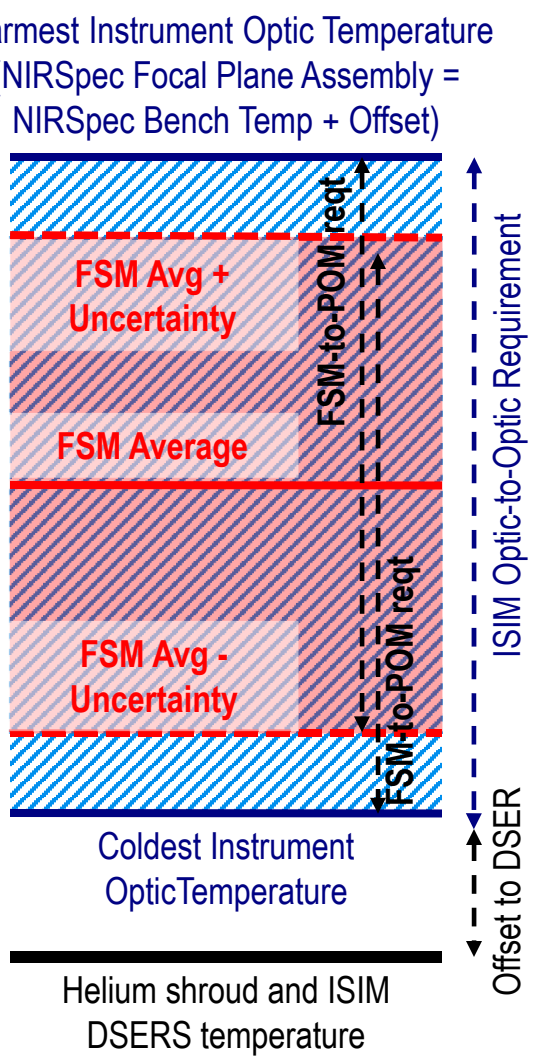
- There were no sensors on the Tertiary Mirror (TM) and Fine Steering Mirror (FSM) had no sensors to track performance against their structural and contamination constraints
- A Real-time Thermal Model (RTM) was developed by Ball Aerospace to produce "virtual sensor" telemetry by calculating energy balances based on nearby sensor data, temperature-dependent conductors and thermal mass
  - Provides tracking of TM and FSM temperatures when no physical sensors are available, but "virtual sensors" have uncertainty to them



AOS Warmup Tracking at OTIS Using Virtual Sensor Data

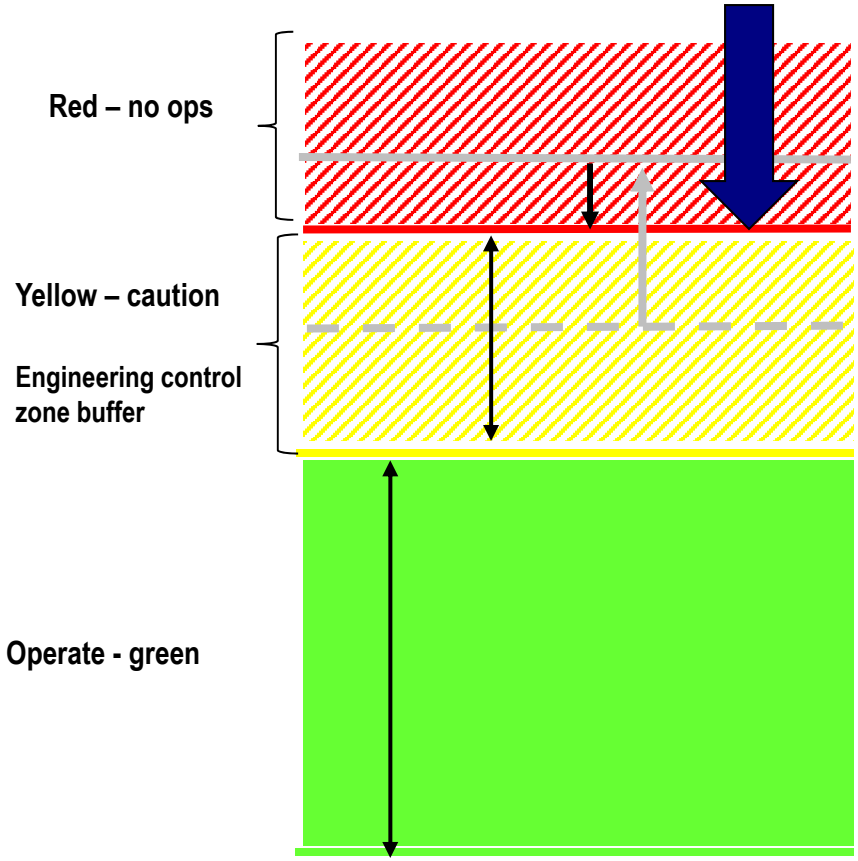
Example: Constraints for the Fine Steering Mirror (FSM)

- **FSM had both structural and contamination constraints**
  - The FSM structural components have temp-dependent ΔTs between mirror substrate, carrier, and baseplate
  - FSM Substrate has no sensor: temp must be calculated by RTM
    - » Uncertainty for calculated FSM temperatures
    - » The FSM mirror also has a view to the ISIM POMs, possible cross-contamination
    - » The FSM must be held within a certain temp constraint of each ISIM during temperatures when composite structure emits water (140 K - 170 K) and molecular (220 K - 285 K) contamination.
    - » ISIM Optics themselves already have L&Cs between each instrument ➔ FSM substrate temperature needs to be maintained almost at median of ISIM temps
    - » The FSM and ISIM POMs must be warmer than Helium shroud and DSERs
- **Heater power tables were generated to provide guideline for required FSM heater power during each test phase**



Thermal Margin Philosophy for Sparse Sensors

Distributed structural thermal 'GRADIENTS'



< Thermal prediction + margin, approved by structural analysis

< *then* ***Sparse sensors derating*** *applied* — Thermal model defined

< Raw thermal prediction using *all* the math model nodes

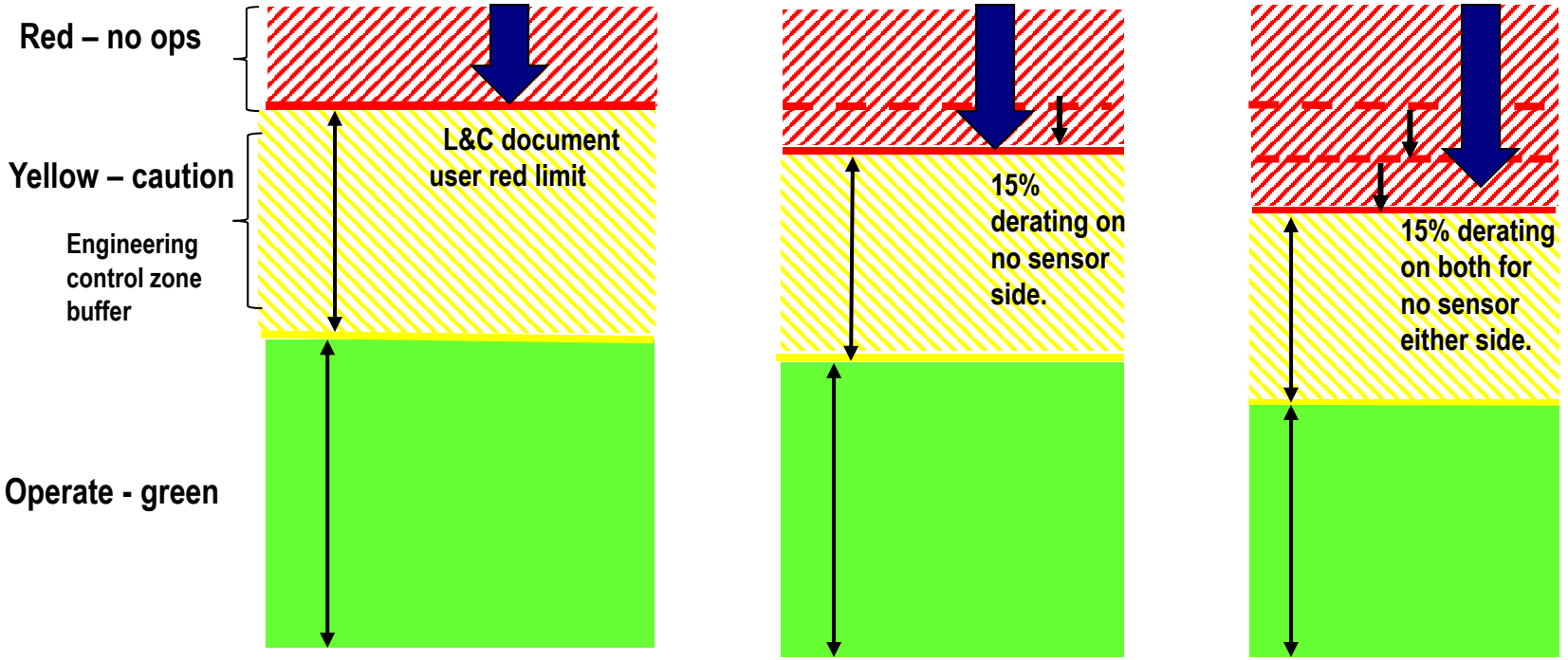
Thermal Margin Philosophy for Interfaces

INTERFACES-type 1: Sensor(s) on both sides – ideal case.

INTERFACES - type 2: Sensor(s) on one side.

INTERFACES - type 3: No sensor(s) on either side.

No added sparse sensor derating needed *if single point sensors are on* isothermal HW)



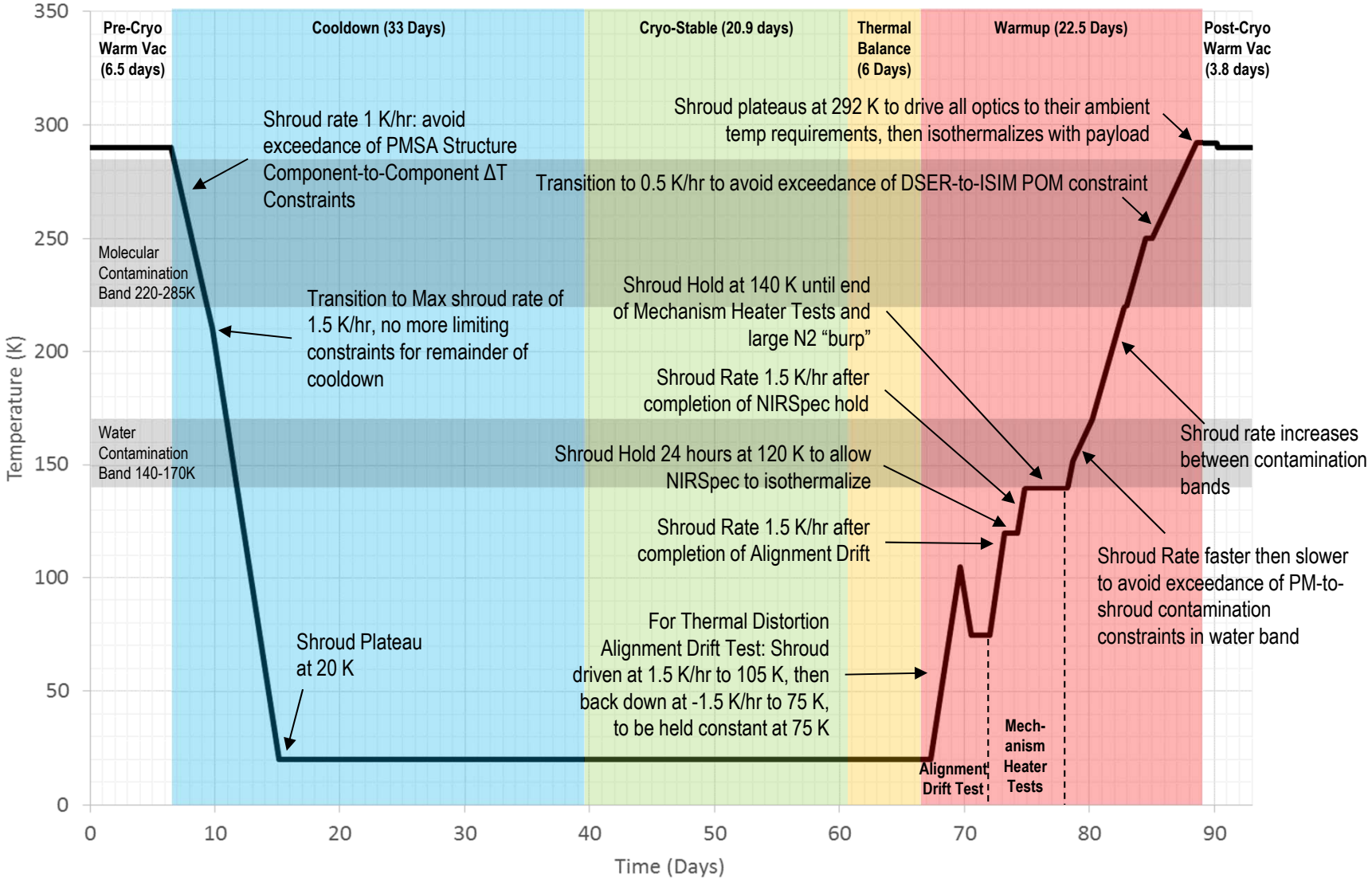
Control Methods and Optimization of Helium Shroud Profile

- **The OTIS CV test employed both passive and active control methods**
  - Helium shroud rate is the biggest driver of payload transition rate and hardware safety
    - » This also directly drives DSER transition rate, all helium uses common refrigerator
    - » The majority of components on the OTIS payload are passively controlled through interaction with the test environment (composite structure, PMSAs, TMS)
  - ISIM instruments, the SM, TM, and FSM, are actively controlled: heaters used when possible to drive transition rate/control L&Cs
- **Many thermal analysis iterations were performed with different control methodologies to determine the most time-optimized means to cool and warm the payload while ensuring hardware safety**
  - Since the helium shroud rate is the biggest driver of payload transition, an optimization code was developed allowing the model to analyze a full cooldown or warmup with the shroud temperature as a variable
  - All thermally-critical L&Cs were programmed into the thermal model to ensure that the payload was not violating any L&Cs with each time step

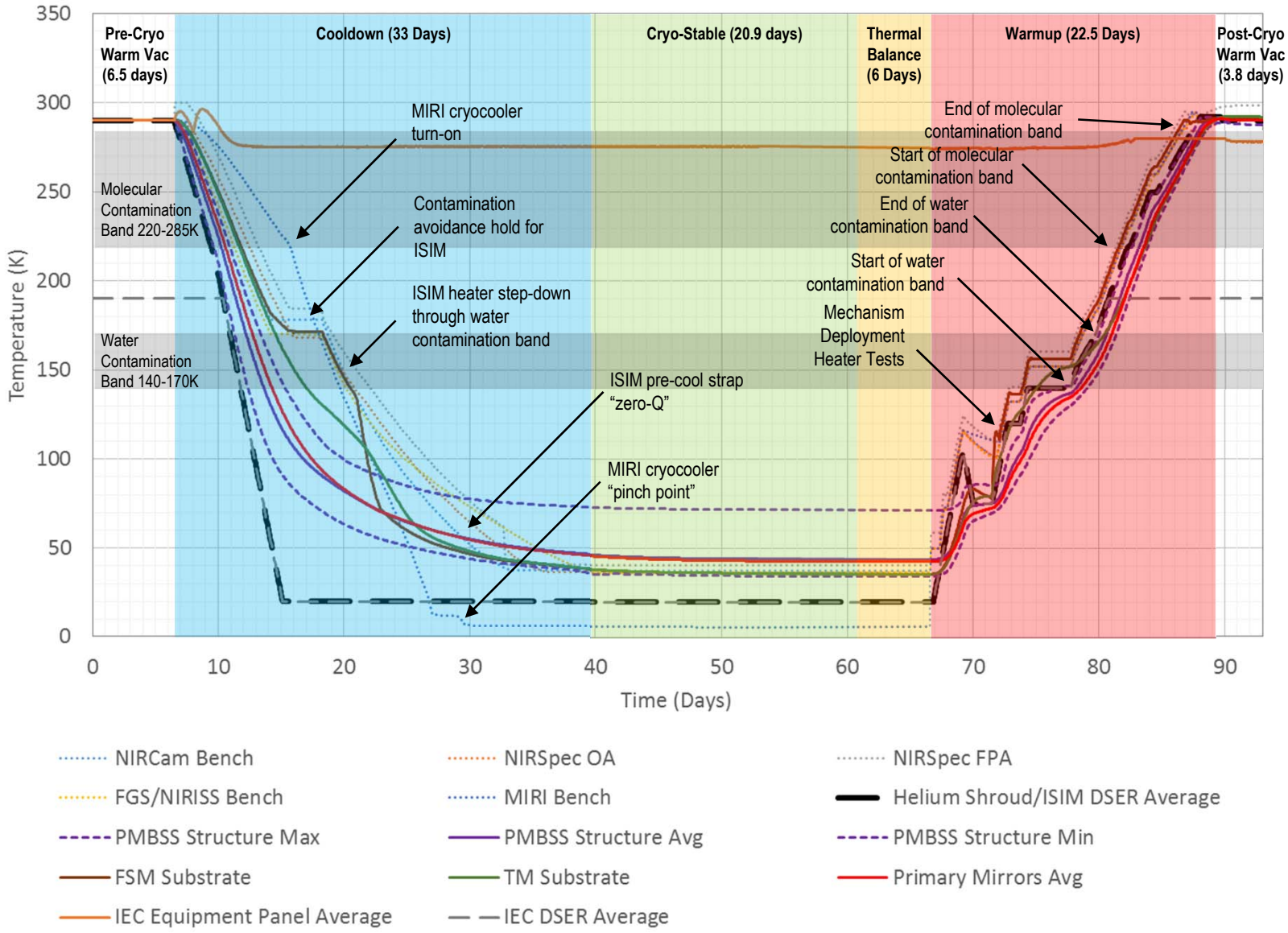
NOTE: With all model predictions, coating emissivities cannot be assumed constant within the 20 K – 300 K temperature range of the OTIS CV Test

- Two radk files: one with room temperature emissivities and one with cryogenic emissivities
- The model transitioned from one set to the other when the PMBSS average reached 90 K

Derived Helium Shroud Profile from Optimization Code[12,13]



Resultant Payload Performance Predictions from Optimized Shroud Profile



How did we do in test vs. predictions?

- **Overall, the OTIS CV payload thermal model predicted the hardware performance well in cooldown**
  - Transient simulation predicted 33 days of cooldown. OTIS payload reached cryo-stable criterion (27 mK/hr on PMBSS average rate, all instruments stable at operating temperatures) at 32 days.
- **Simplifications made for temperature-dependent emissivity regimes caused predictions to be less accurate when hardware was between 60-170K**
- **Thermal balance predictions matched test results very closely**
- **Warmup of the payload occurred faster than model predictions**
  - Transient simulation predicted 22.5 days of warmup. OTIS payload reached end of warmup by 20 days.
  - Some primary schedule drivers from pre-test warmup simulation were observed to be secondary schedule drivers in test

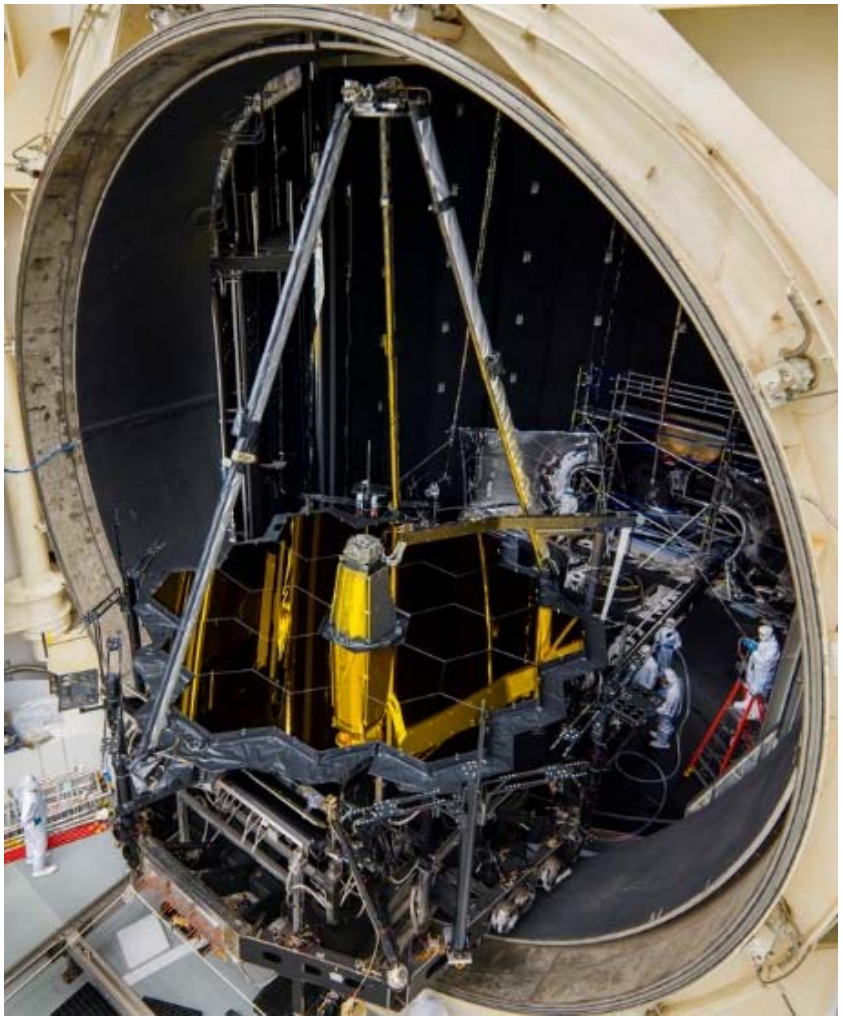
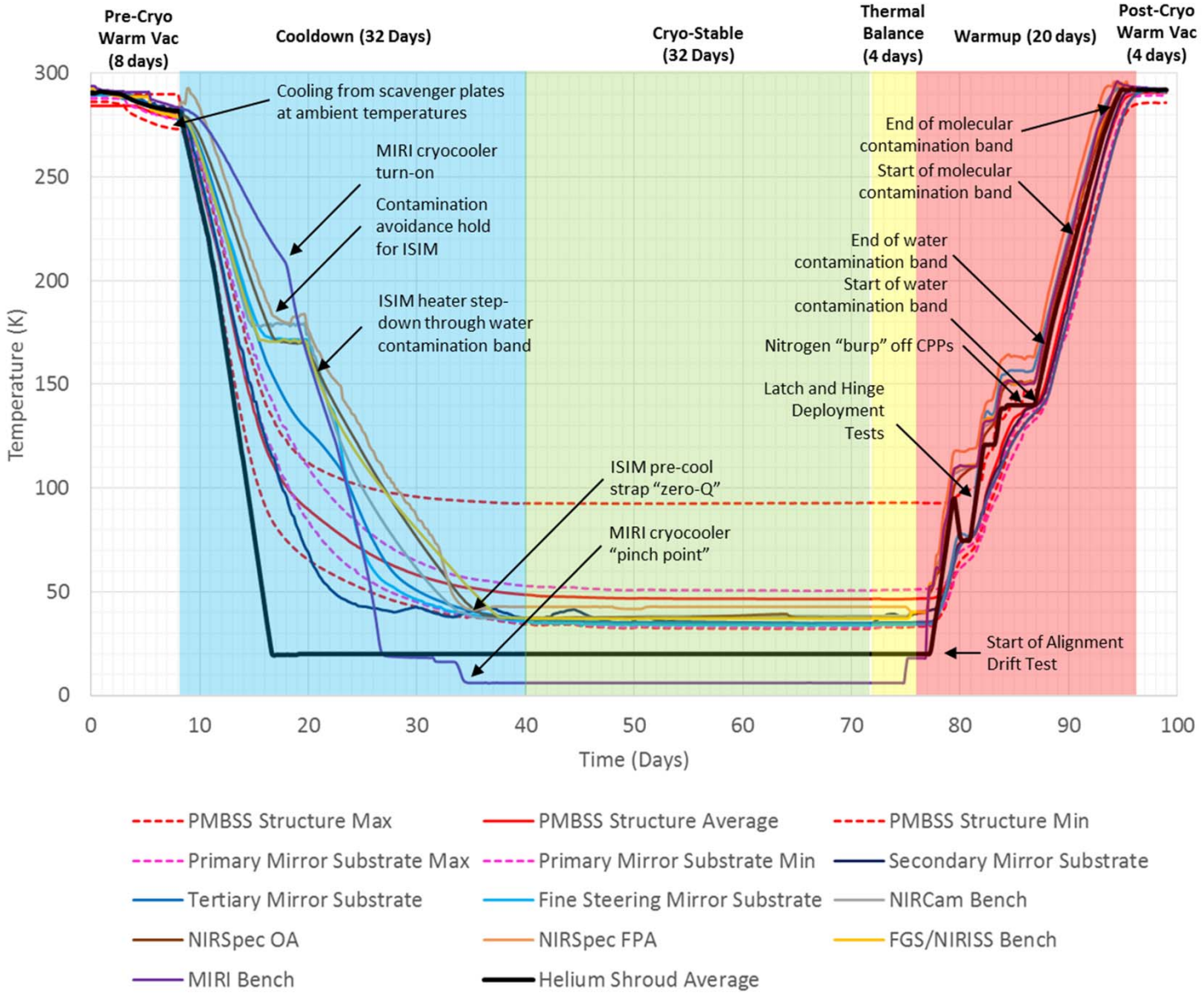
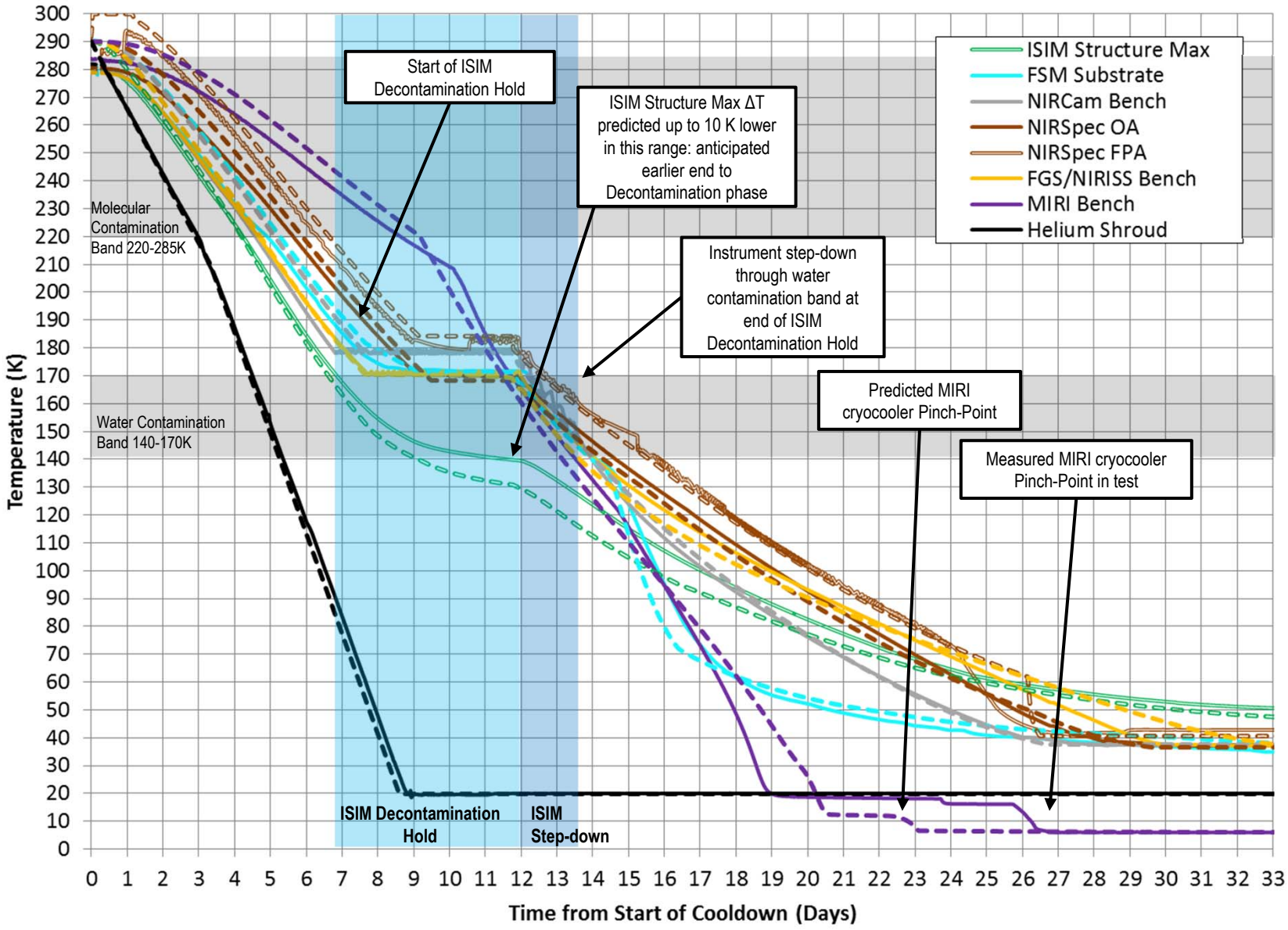


Image Source: NASA/Chris Gunn

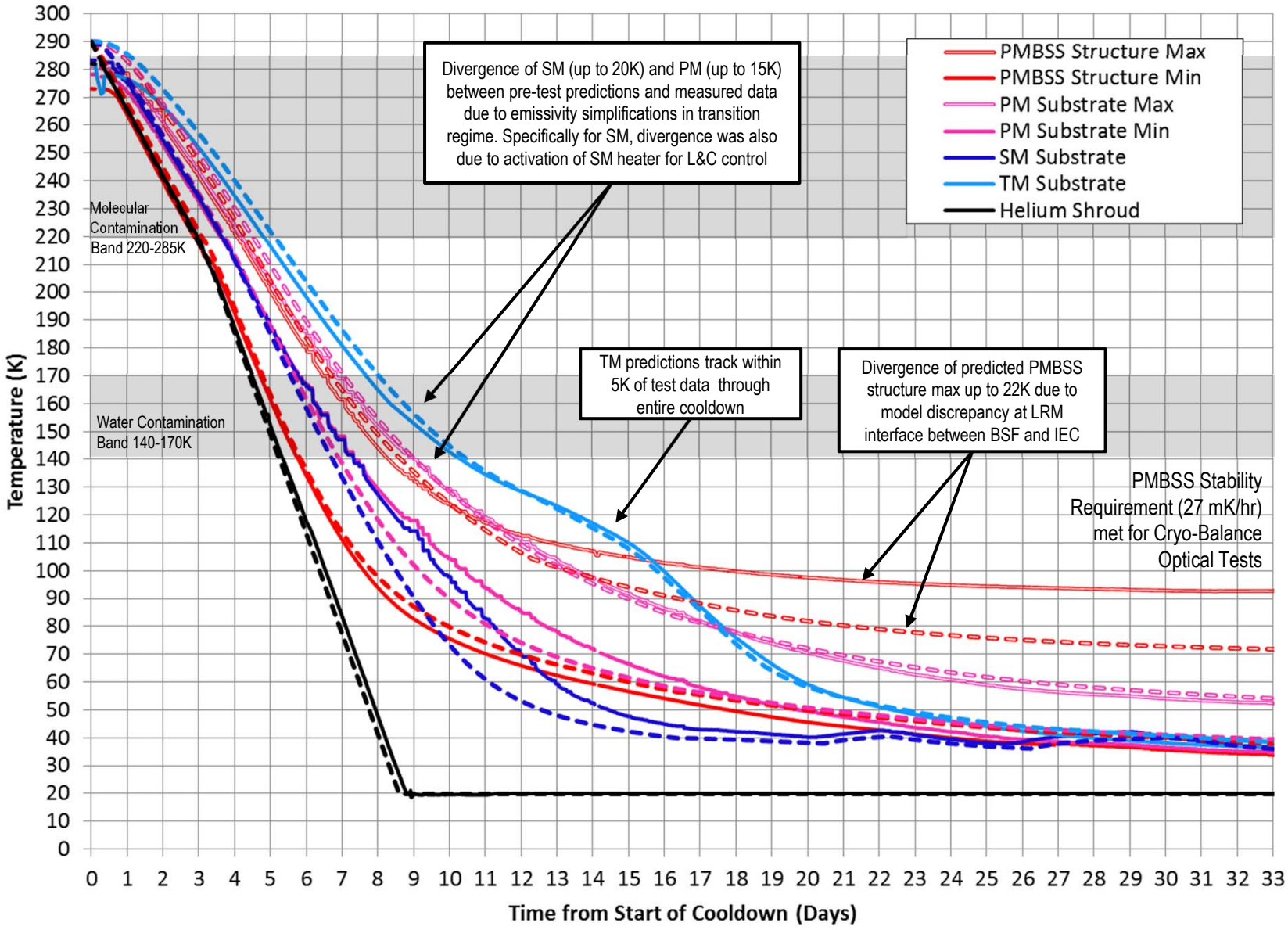
As-Tested Shroud Profile from the OTIS CV Test



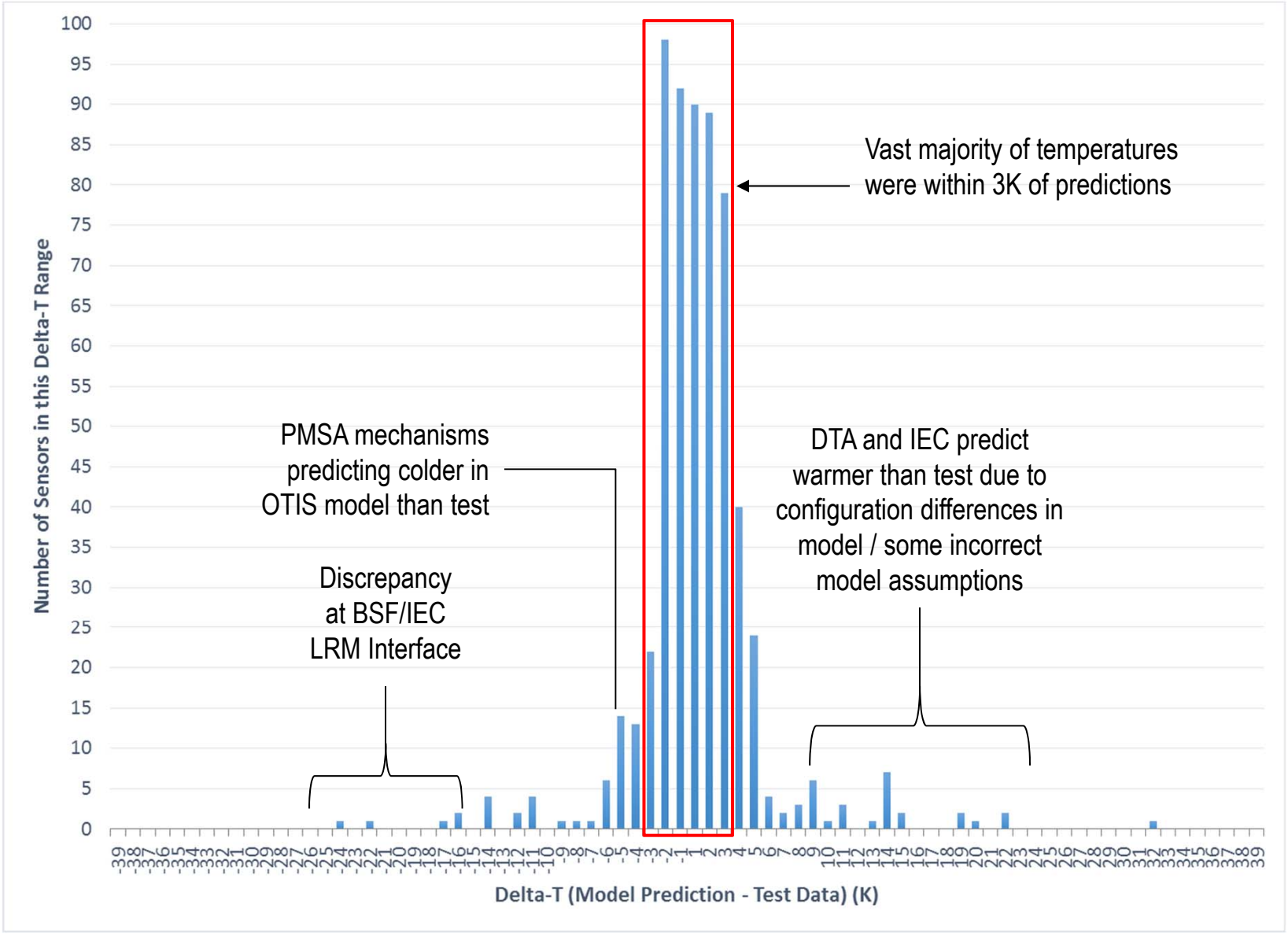
Comparison Between Model Predictions and Measured Test Data in Cooldown: ISIM



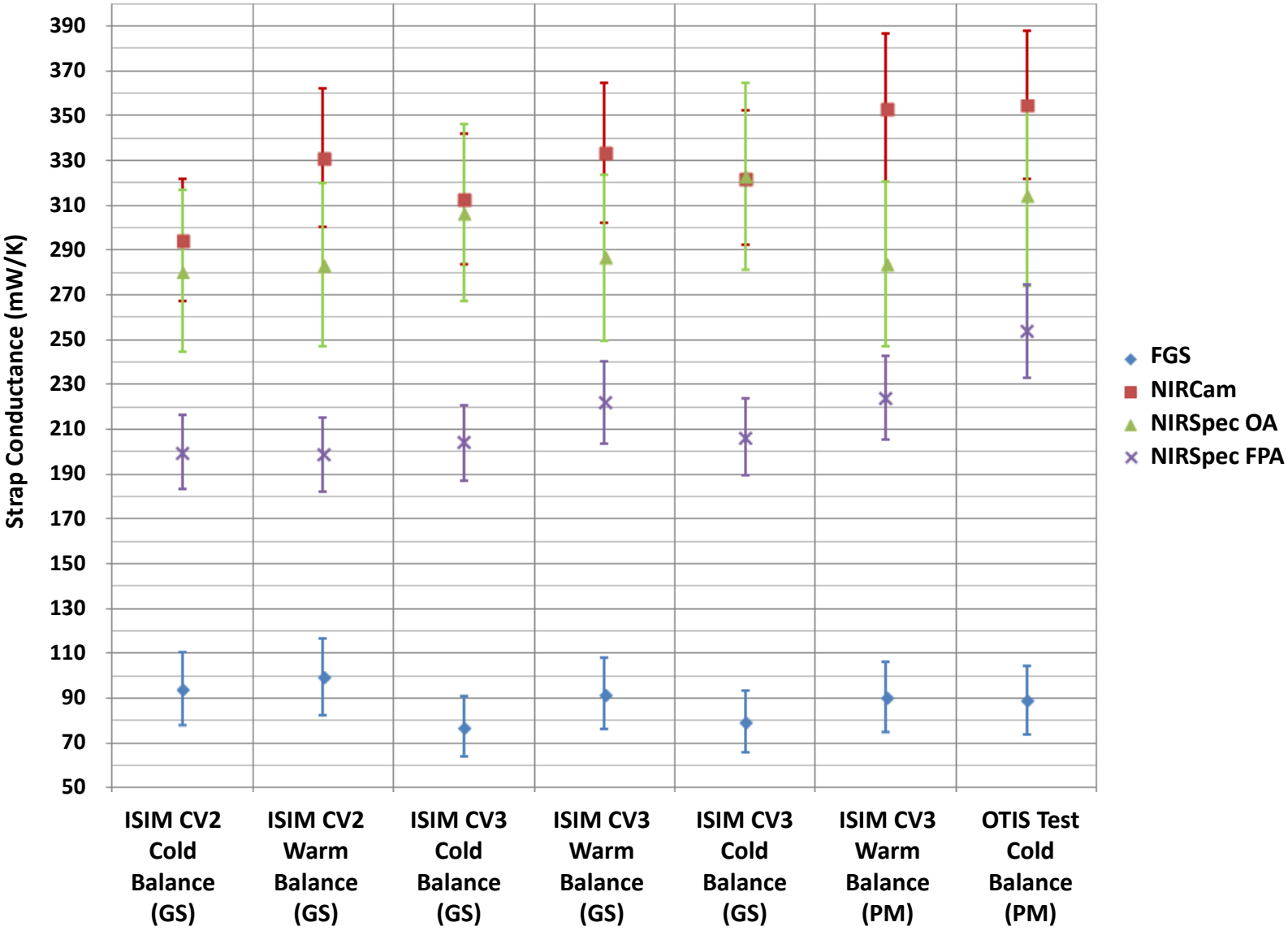
Comparison Between Model Predictions and Measured Test Data in Cooldown: OTE



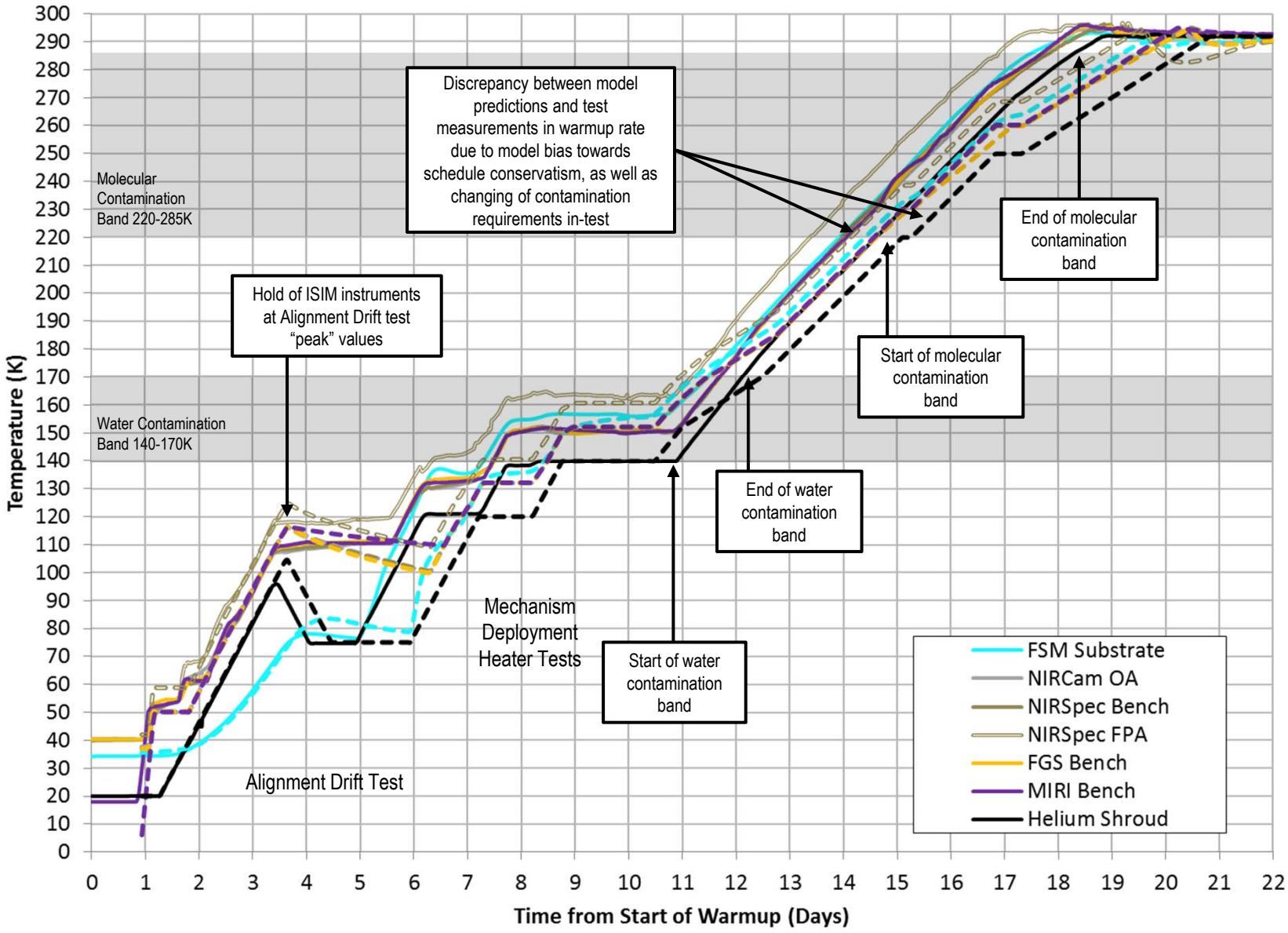
Thermal Balance: Temperature Difference Between Model and Test Sensors



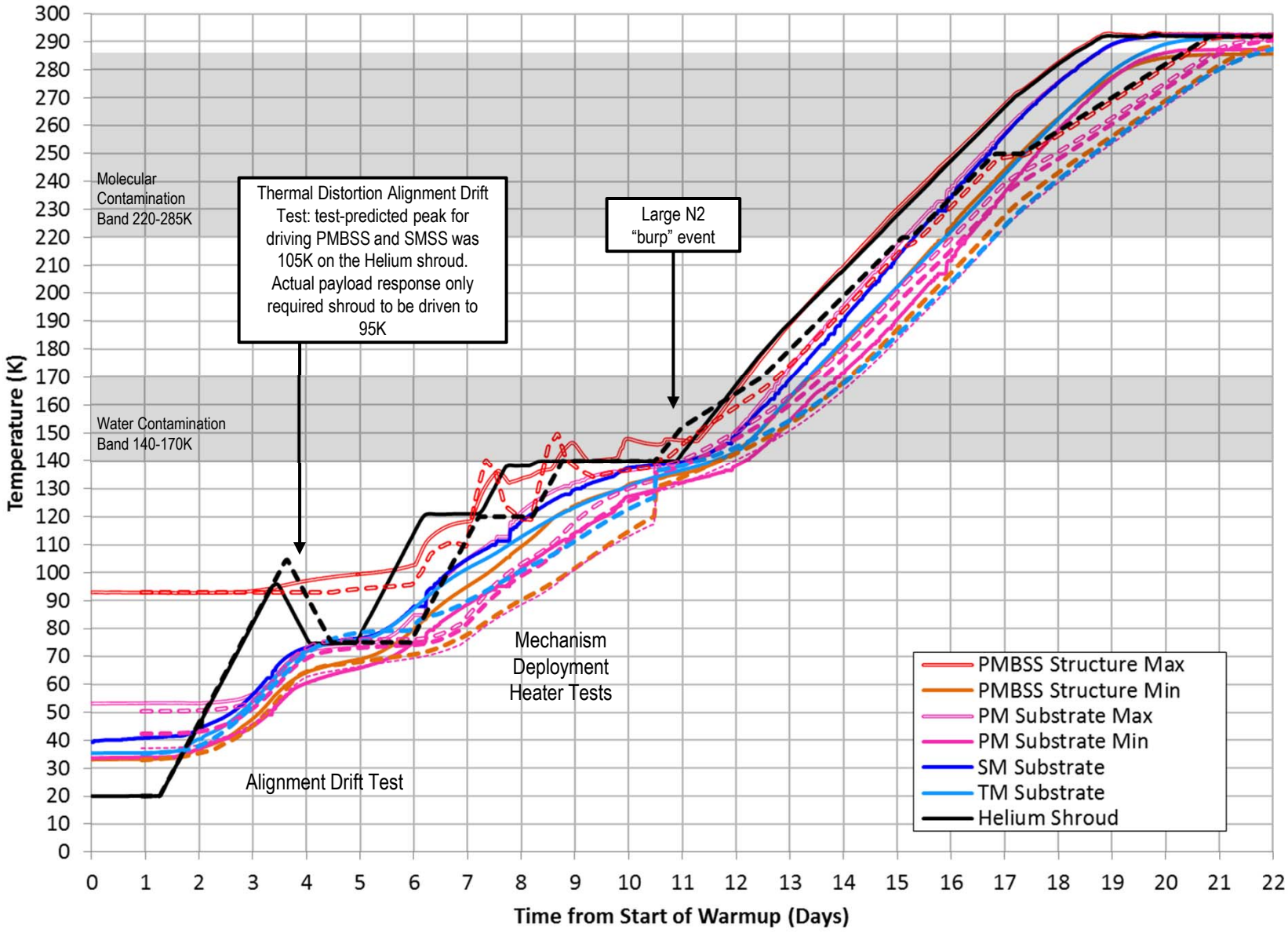
ISIM Heat Strap Conductance Measurements[14]



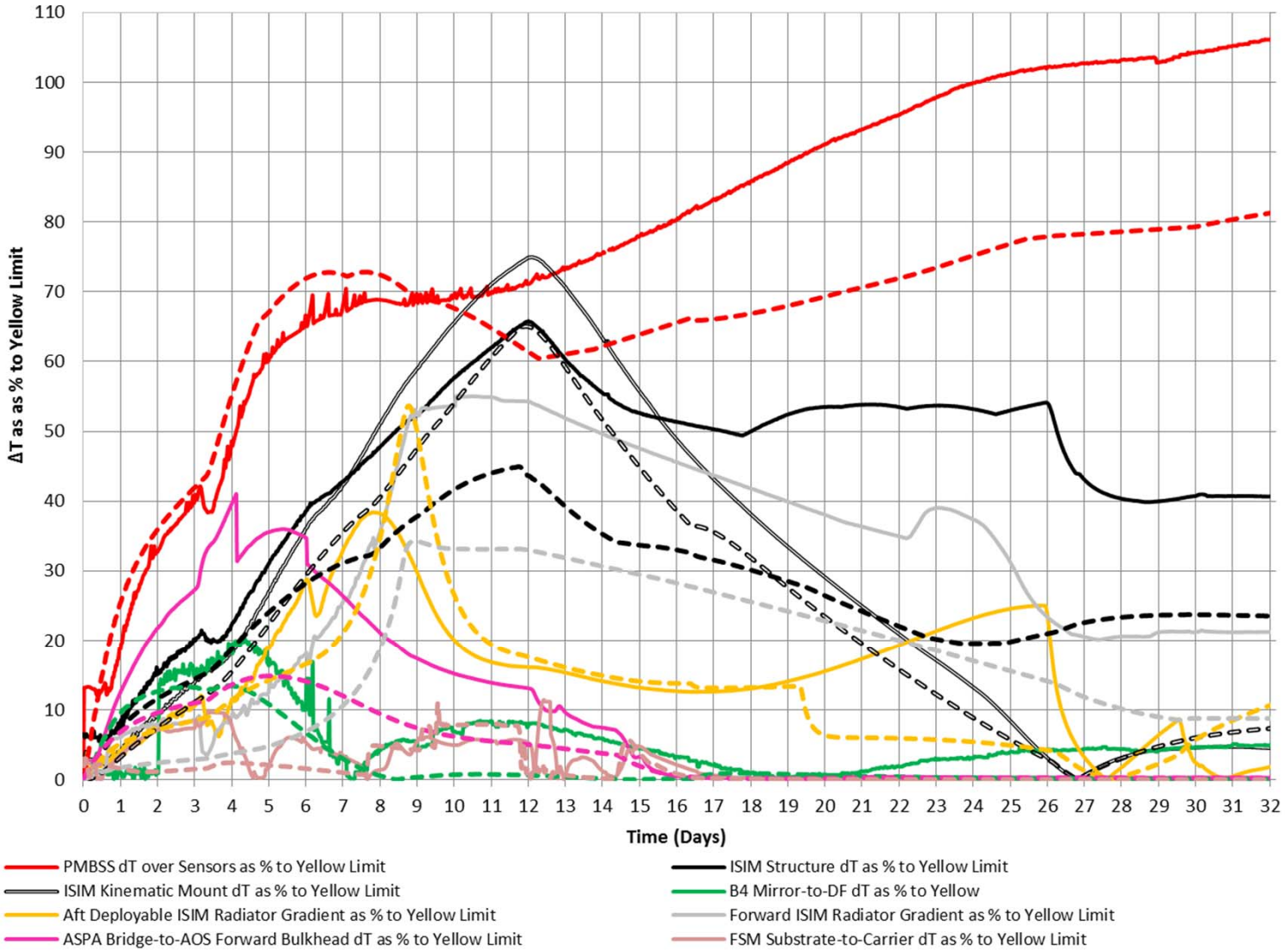
Comparison Between Model Predictions and Measured Test Data in Warmup: ISIM



Comparison Between Model Predictions and Measured Test Data in Warmup: OTE



Sample ΔT as % to Yellow Limit Plot for L&C Tracking



Part II Summary

- **In this lecture, we completed a detailed discussion of the OTIS CV test thermal model, covering the following topics:**
  - Driving constraints for model development
  - Process for developing the OTIS CV test methodology
  - Comparison of pre-test predictions with test measurements

- **In the next lecture, we will discuss the pre-test planning for off-nominal events**
  - Off-nominal “matrix” for emergency actions to take at each phase of the test
  - How pre-test planning prepared us for actual off-nominal events in our test

Reference: Acronyms

Acronym	Definition	Acronym	Definition
AOS	Aft Optical System	*ESA*	European Space Agency
ACF	Auto-Collimating Flat	*FGS*	Fine Guidance Sensor
ADIR	Aft Deployable ISIM Radiator	*FIR*	Fixed ISIM Radiator
ASPA	Aft Optical System Source Plate Assembly	*FPA*	Focal Plane Arrays
BP	Back Plane	*FSM*	Fine Steering Mirror
BSF	Backplane Support Fixture	*GSE*	Ground Support Equipment
CoCOA	Center of Curvature Optical Assembly	*GSFC*	NASA Goddard Space Flight Center
CPP	Cryo-Pumping Panels, cold panels between the Helium and LN2 shrouds at NASA JSC	*HOSS*	Hardpoint and Offload Support Structure
CSA	Canadian Space Agency	*IEC*	ISIM Electronics Compartment
CTE	Coefficient of thermal expansion	*IR*	Infrared
CV	Cryogenic Vacuum	*ISIM*	Integrated Science Instrument Module, which contains the Science Instruments (SIs)
ΔT, Δt	Change in temperature; change in time	*JSC*	NASA Johnson Space Center
DTA	Deployable Tower Assembly	*JWST*	James Webb Space Telescope
DSERS	Deep Space Environment Radiative Sink	*K*	Kelvin
EC	European Consortium	*L&Cs*	Limits and Constraints

Reference: Acronyms

Acronym	Definition	Acronym	Definition
L5	Layer 5 Sunshield simulator	*PM*	Primary Mirror(s)
LN2, N2	Liquid Nitrogen; Gaseous Nitrogen	*PMSA*	Primary Mirror Segment Assembly
LRM	Launch Release Mechanism	*PMBSS*	Primary Mirror Backplane Support Structure (BSF + BP)
MIRI	Mid-Infrared Instrument	*Q*	Heat
MLI	Multi-Layer Insulation	*SI*	Science Instrument
NASA	National Aeronautics and Space Administration	*SINDA*	Systems Improved Numerical Differential Analyzer modeling tool
NGAS	Northrop Grumman Aerospace Systems	*SM*	Secondary Mirror
NIRCam	Near-Infrared Camera Instrument	*SMA*	Secondary Mirror Assembly
NIRSpec	Near-Infrared Spectrograph Instrument	*SMSS*	Secondary Mirror Support Structure
OA	Optical Assembly	*SVTS*	Space Vehicle thermal Simulator
OGSE	Optical Ground Support Equipment, a series of pre-OTIS Optical pathfinder tests	*TM*	Tertiary Mirror
OTE	Optical Telescope Element	*TMS*	Thermal Management System
OTIS	Optical Telescope Element plus Integrated Science Instrument Module (OTE + ISIM)	*TPF*	Thermal Pathfinder test
PG	PhotoGrammetry cameras	*W*	Watt(s)
POM	Instrument Pick-Off Mirror		

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