Thermal and Fluids Analysis Workshop 2023

Short Course

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

Kan Yang and Stuart Glazer

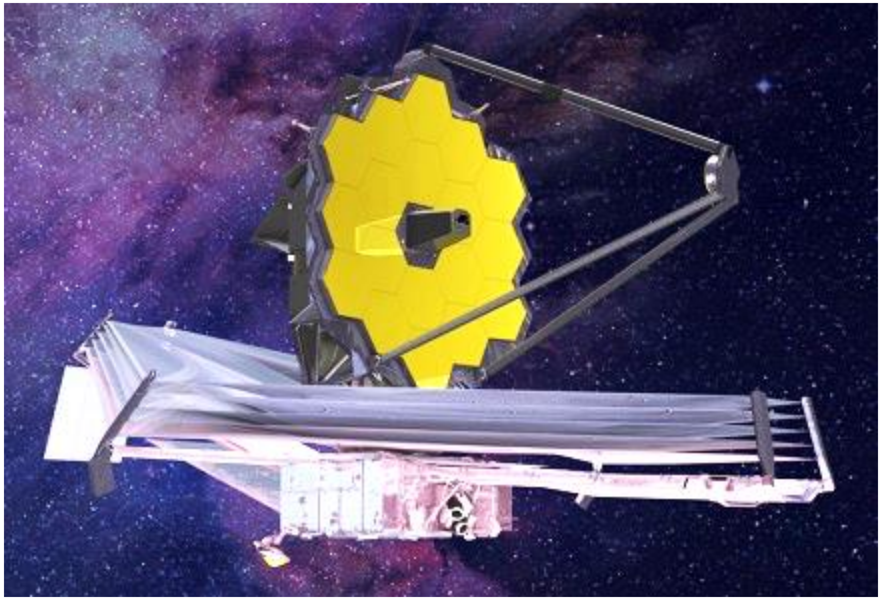
NASA Goddard Space Flight Center

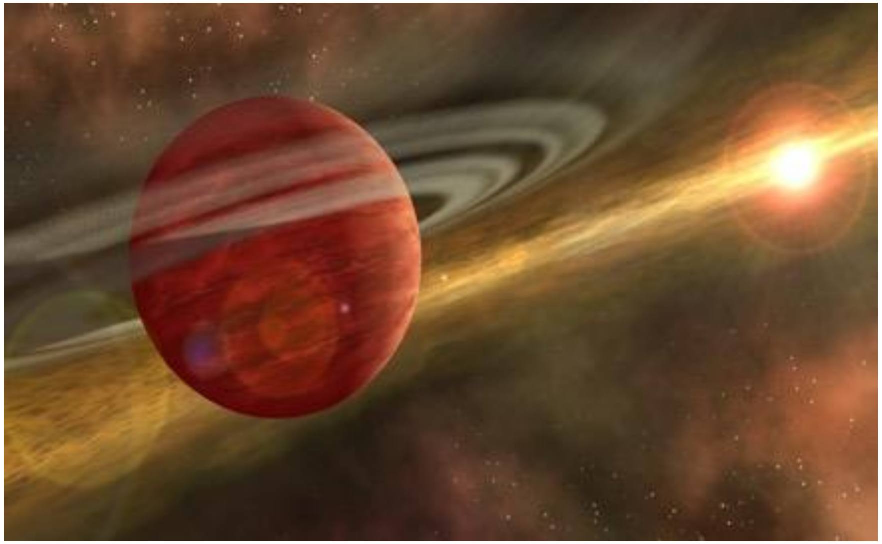
Outline

- **Introduction**
- **Planning for the Passive Cryogenic Test**
  - Test Objectives
  - Test Hardware
  - Establishing Limits and Constraints
    - » Margin Philosophy
    - » Contamination Considerations
  - Thermal Model Development
    - » Thermal Analysis and Timeline Optimization
- **Test Execution**
  - Cooldown
  - Cryogenic Thermal Balance and Model Verification
  - Warmup
- **Off-Nominal Event Planning**
- **Lessons Learned and Applied**
- **Post-Test Milestones**

Introduction

What is the James Webb Space Telescope?





- **A mission to seek light from the first galaxies in the universe and to explore distant worlds**
  - Observe the first luminous objects in the early universe, as well as galaxy and stellar system evolution
  - Explore the Solar System and Exoplanets orbiting other stars
- **Observations are performed by thousands of astronomers worldwide**
  - Optimized to observe in near-to-mid infrared wavelengths (0.6 – 28.5 μm)
- **Led by NASA, in partnership with ESA and CSA**

Who Was James Webb?

James Webb (1906 – 1992)

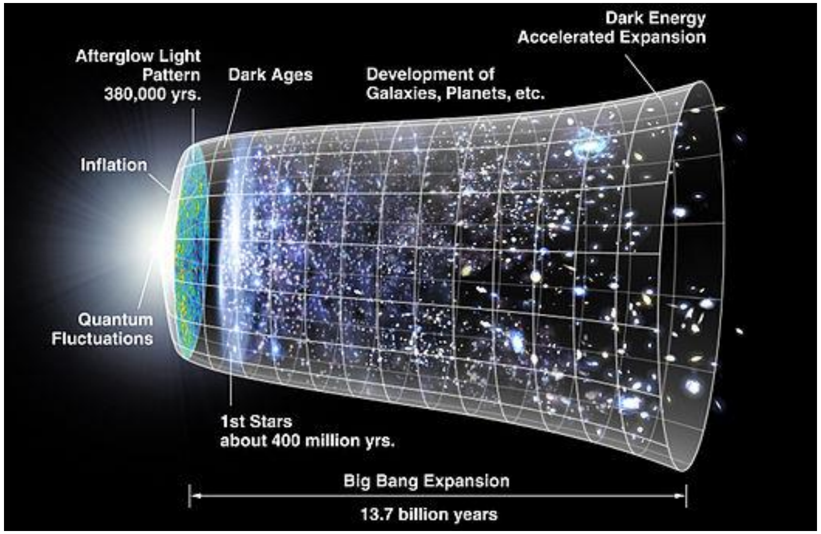
- Second Administrator of NASA (1961 – 1968)
- Oversaw first and second crewed spaceflight programs (Mercury and Gemini)
- Oversaw Mariner and Pioneer planetary exploration programs
- Oversaw Apollo program
- Insisted that NASA have a strong science program

Scientific Successor to the Hubble Space Telescope

Hubble		Webb
7.9 ft (2.4 m)	**MIRROR DIAMETER**	21.3 ft (6.5 m)
44 ft (13.2 m); 24,500 lbs (11,110 kg)	**LENGTH & WEIGHT**	72 ft (22 m); 13,500 lbs (6,124 kg)
Ultraviolet, Visible, Near Infrared (0.1-2.5 micrometers)	**WAVELENGTHS**	Visible, Near Infrared, Mid Infrared (0.6-28.5 micrometers)
Orbiting Earth, 350 miles (570 km) from Earth	**LOCATION**	Orbiting the Sun around L2 940,000 miles (1,500,000 km) from Earth
70°F (21°C)	**TEMPERATURE**	-370°F (-230°C)

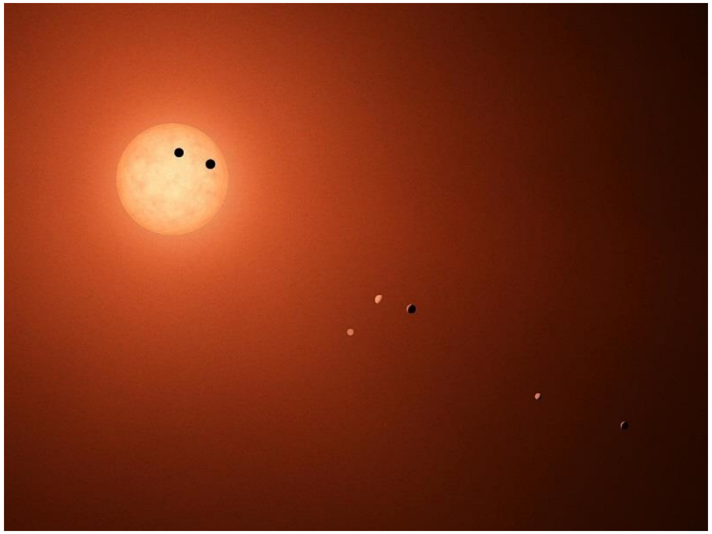
Just How Big is Webb?

JWST Science: What Does Webb Do?



Source: NASA/WMAP

First Light and Reionization

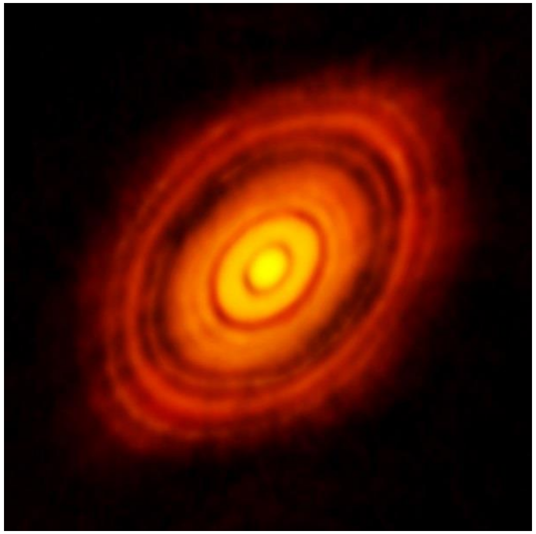


Source: NASA/JPL-Caltech

Planetary Systems and the Origins of Life

Source: NASA/ESA

Assembly of Galaxies



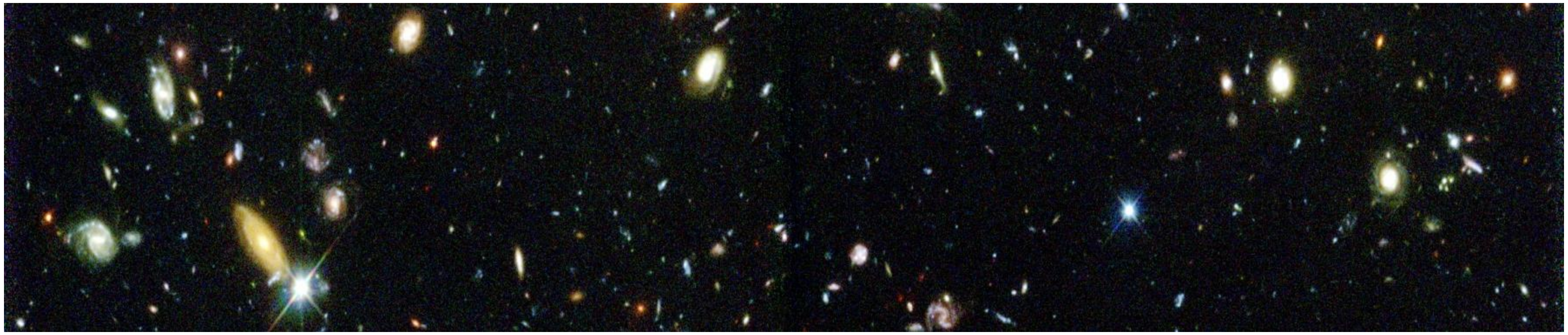
Source: ALMA Observatory

Birth of Stars and
Protoplanetary Systems

Why is this important?

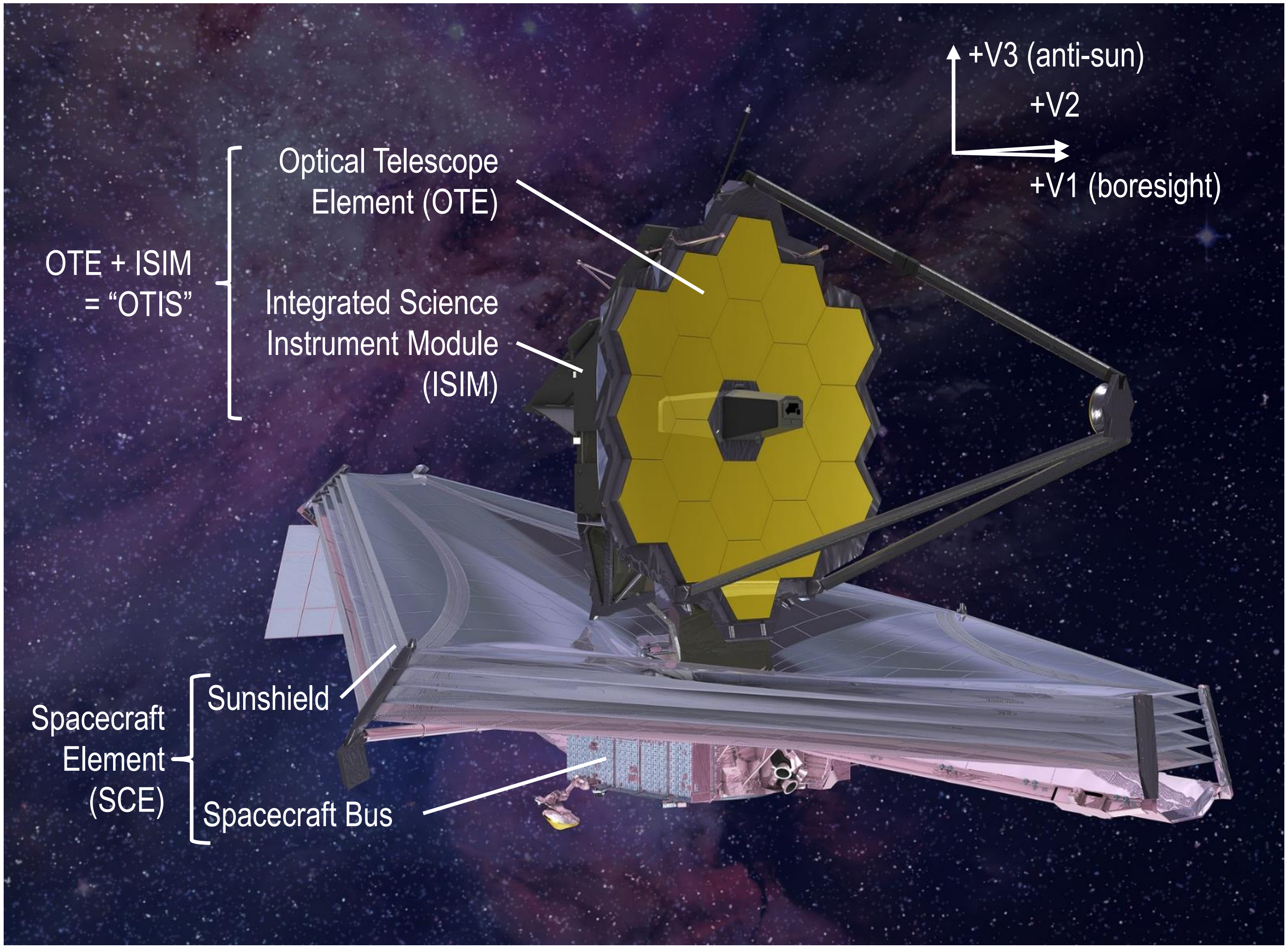
- **The James Webb Space Telescope helps us answer two major questions:**

WHAT HAPPENED AT THE BEGINNING OF THE UNIVERSE?



ARE WE ALONE IN THE UNIVERSE?

Major System-Level Assemblies of the James Webb Space Telescope



Source: NASA/JWST

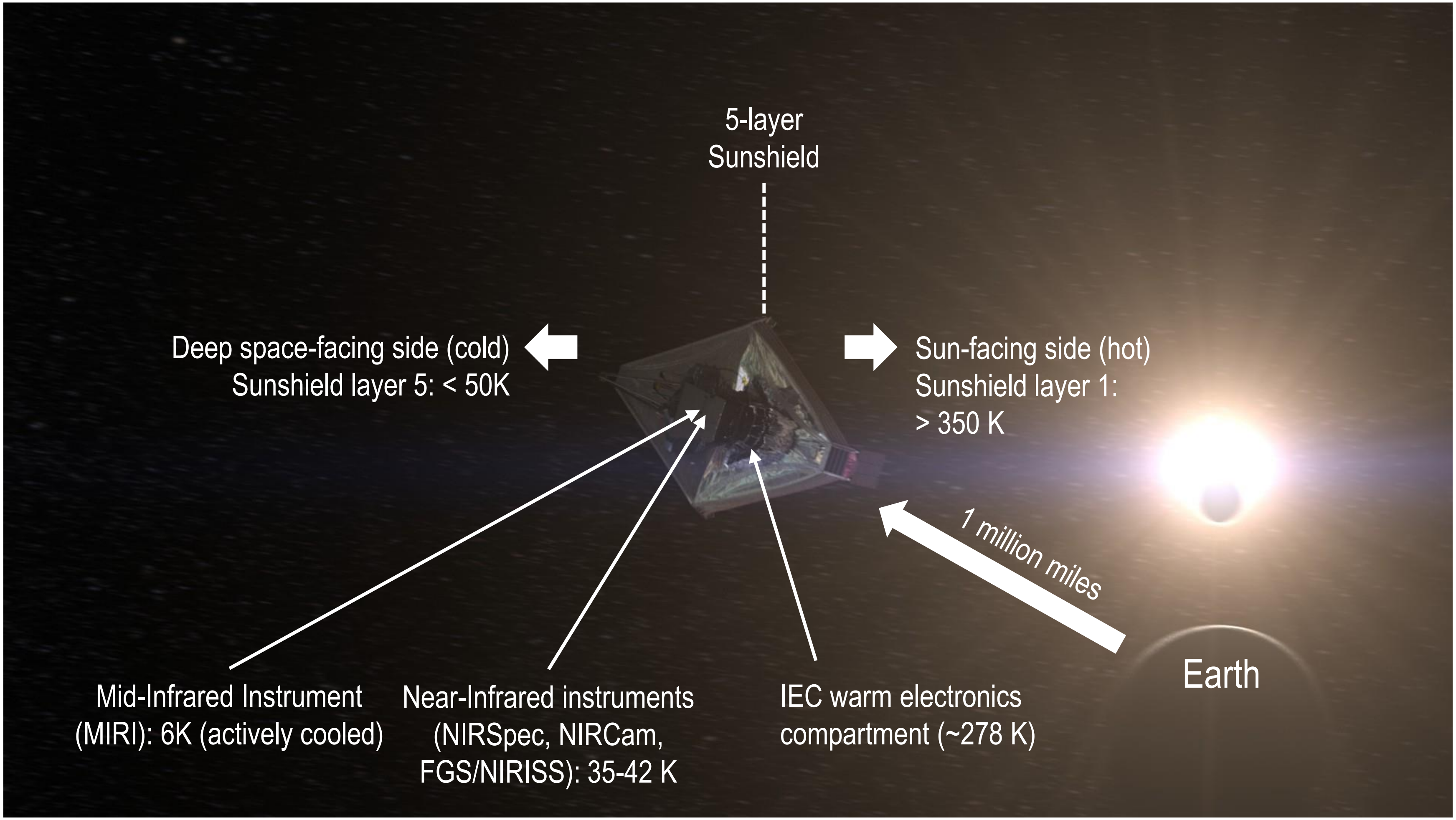
Completed "OTIS" Element at NASA Goddard Space Flight Center SSDIF Clean Room

Source: NASA/JWST

Planning for the Passive Cryogenic Test

Test Objectives

Thermal Environment in Flight



Source: svs.gsfc.nasa.gov

What's the Importance of Thermal Vacuum Testing?

How do we verify that JWST will work in its intended on-orbit environment? *We perform environmental tests, including thermal vacuum testing.*

Thermal testing is done in a vacuum chamber at *margined* temperature extremes and is designed to verify workmanship, demonstrate performance, and collect data to be used in correlating thermal models

Two types of testing are performed:

Thermal balance plateaus: thermal environment is set, and spacecraft must achieve energy balance with environment. Balance criteria met from achieving temp. rate-of-change requirement on components. Thermal data collected is used to verify predictive accuracy of thermal models

Thermal vacuum cycles: Quality assurance test to take hardware beyond its operational temperatures and ensure it will survive temperature extremes: used to verify workmanship on components

Cryo-vacuum testing of ISIM at NASA Goddard Space Flight Center's Space Environment Simulator Chamber
Source: NASA/Chris Gunn

OTIS CV Thermal Test Objectives [4]

- Preserve hardware integrity upon transition to cryogenic thermal balance (cryo-balance) conditions and transition back to ambient temperatures by respecting all imposed limits and constraints (L&Cs)
- Achieve the simulated on-orbit payload temperature levels and stability for optical, mechanical, and instrument tests
- Predict and measure thermal balance test data for model crosscheck, both on ISIM and OTE components
- Achieve a workmanship thermal conductance assessment of the flight instrument heat straps which for the first time would be connecting all the payload flight instruments and radiators
- Achieve test timeline optimization by executing the OTIS CV cooldown and warmup in a time-efficient manner

What Are Our Temperature Goals on OTIS?

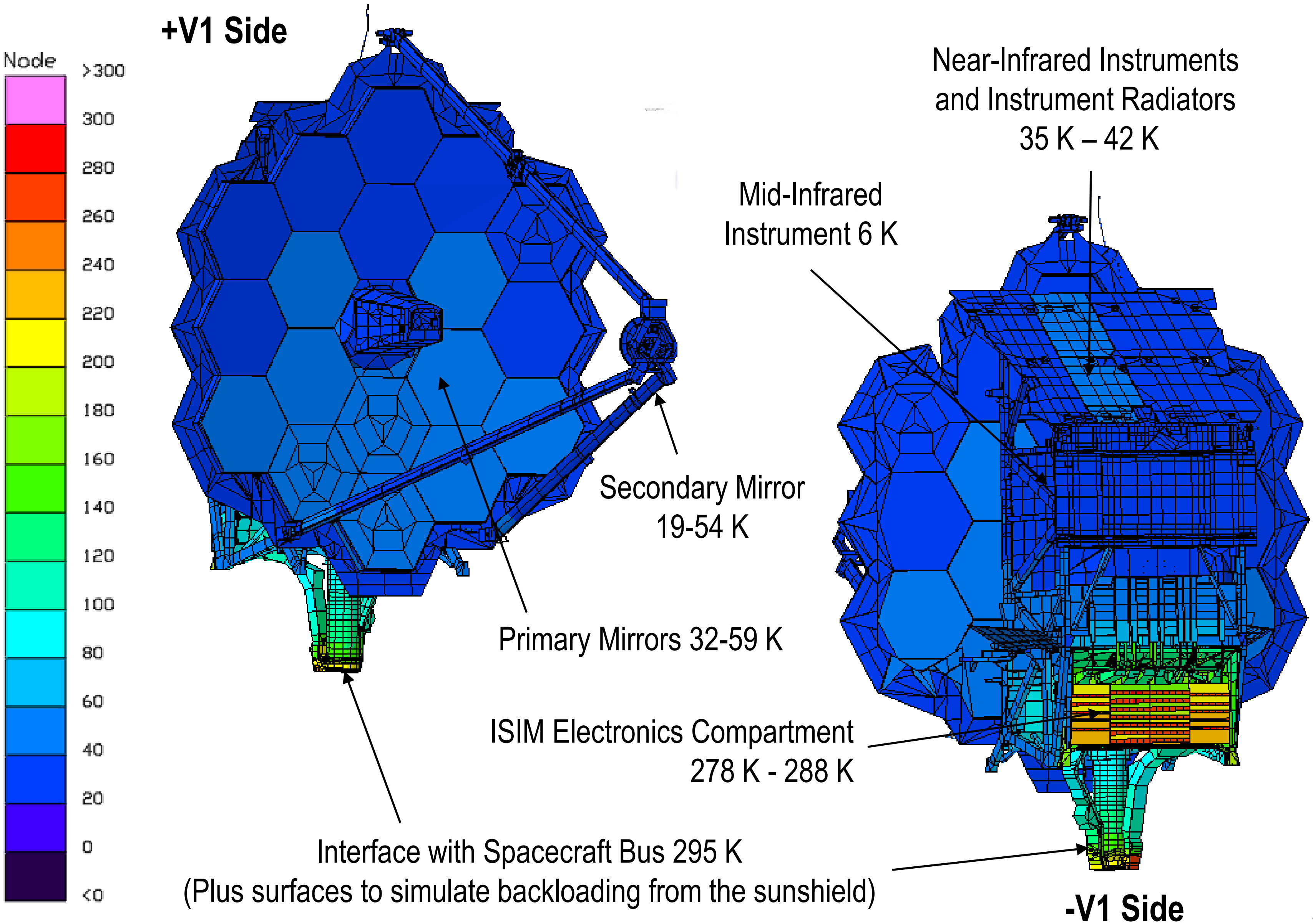
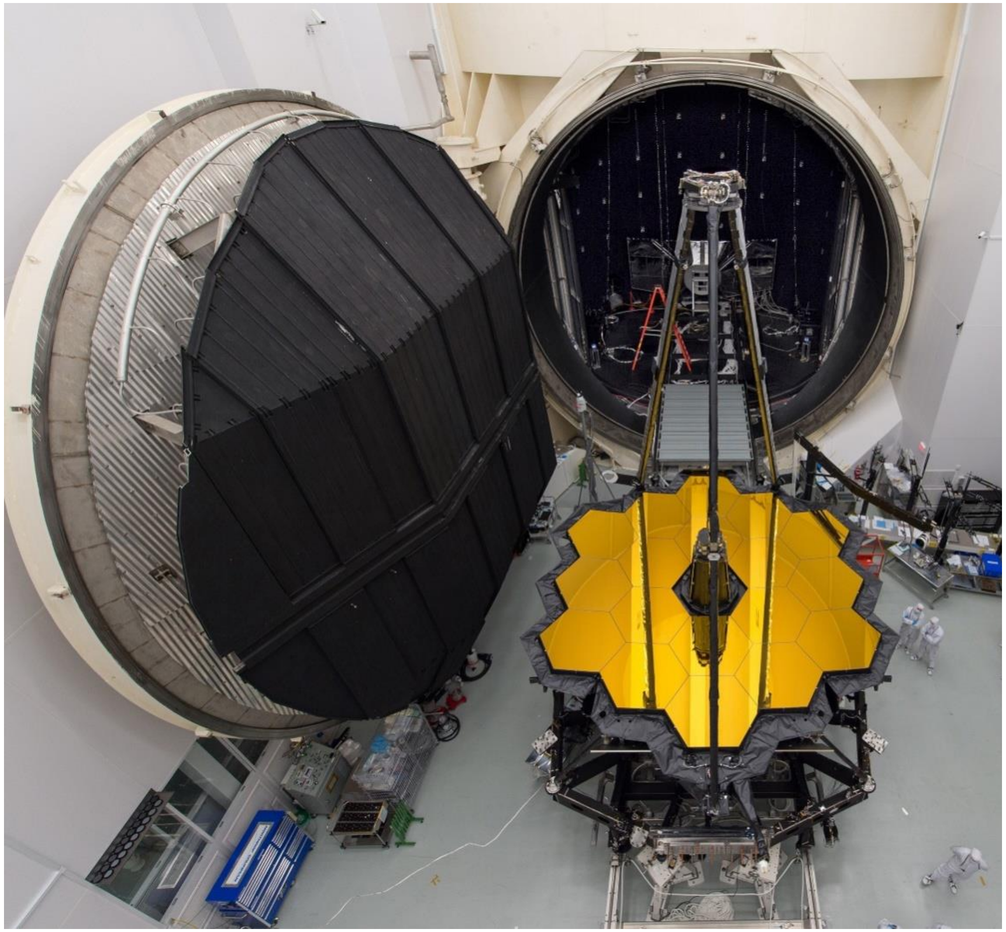


Image sources: NASA/JWST

How Do We Replicate JWST's Flight Thermal Environment in Test ?



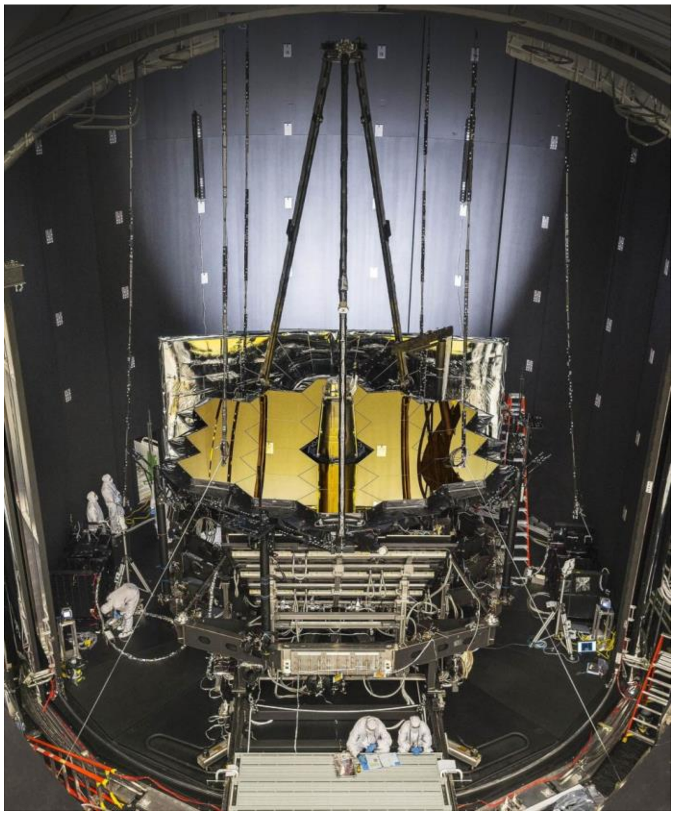
Source: NASA/JWST

- **Use one of the largest thermal vacuum chambers in the world (NASA Johnson Space Center's Chamber A)**
  - Unfortunately, even this chamber is not large enough to fit all of JWST, so we need to test in separate system-level assemblies (OTIS being the major cryogenic test)
- **Install a gaseous helium shroud to lower the payload temperatures to 20K, and an LN2 shroud to lower the overall environmental loads on the helium shroud/refrigerator [5]**
- **Install GSE to simulate heat from the flight spacecraft bus**

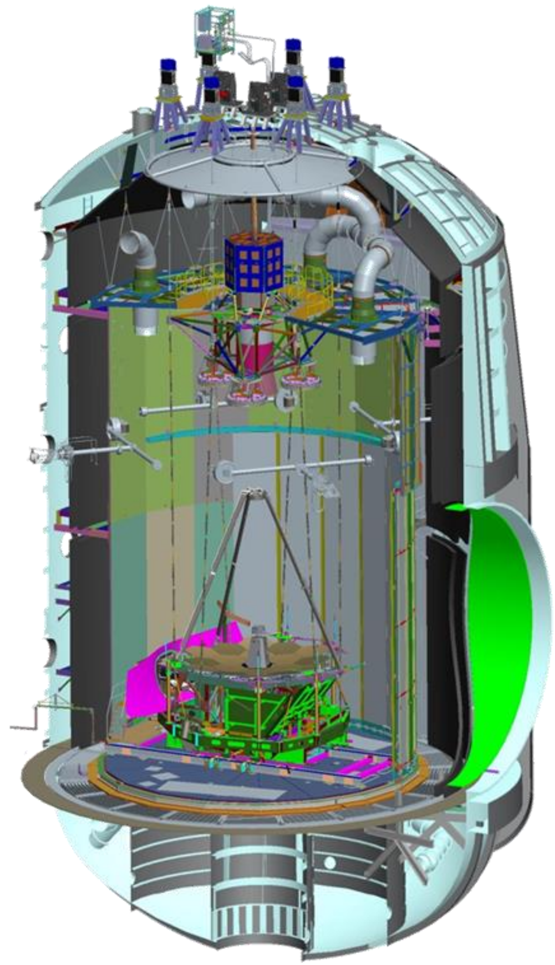
Planning for the Passive Cryogenic Test

Test Hardware

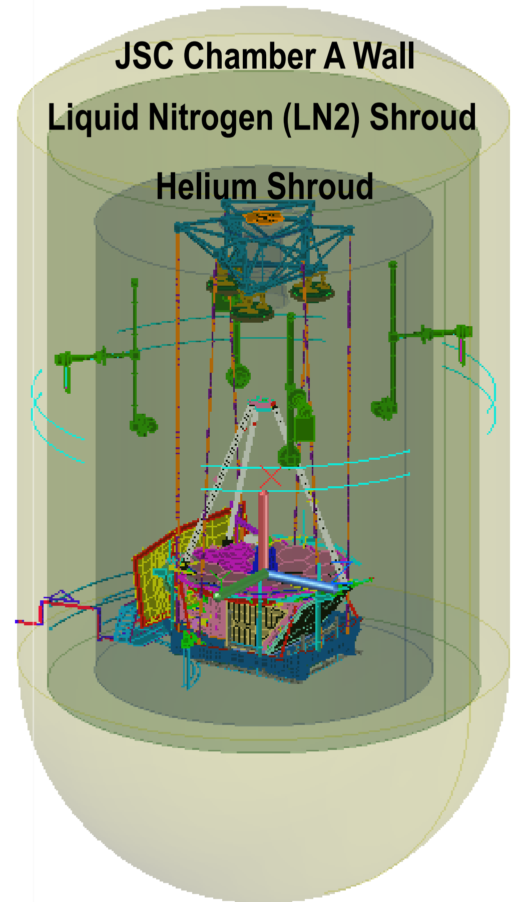
OTIS CV Test Setup Inside Chamber A: Three Different System-Level Representations



Physical Hardware



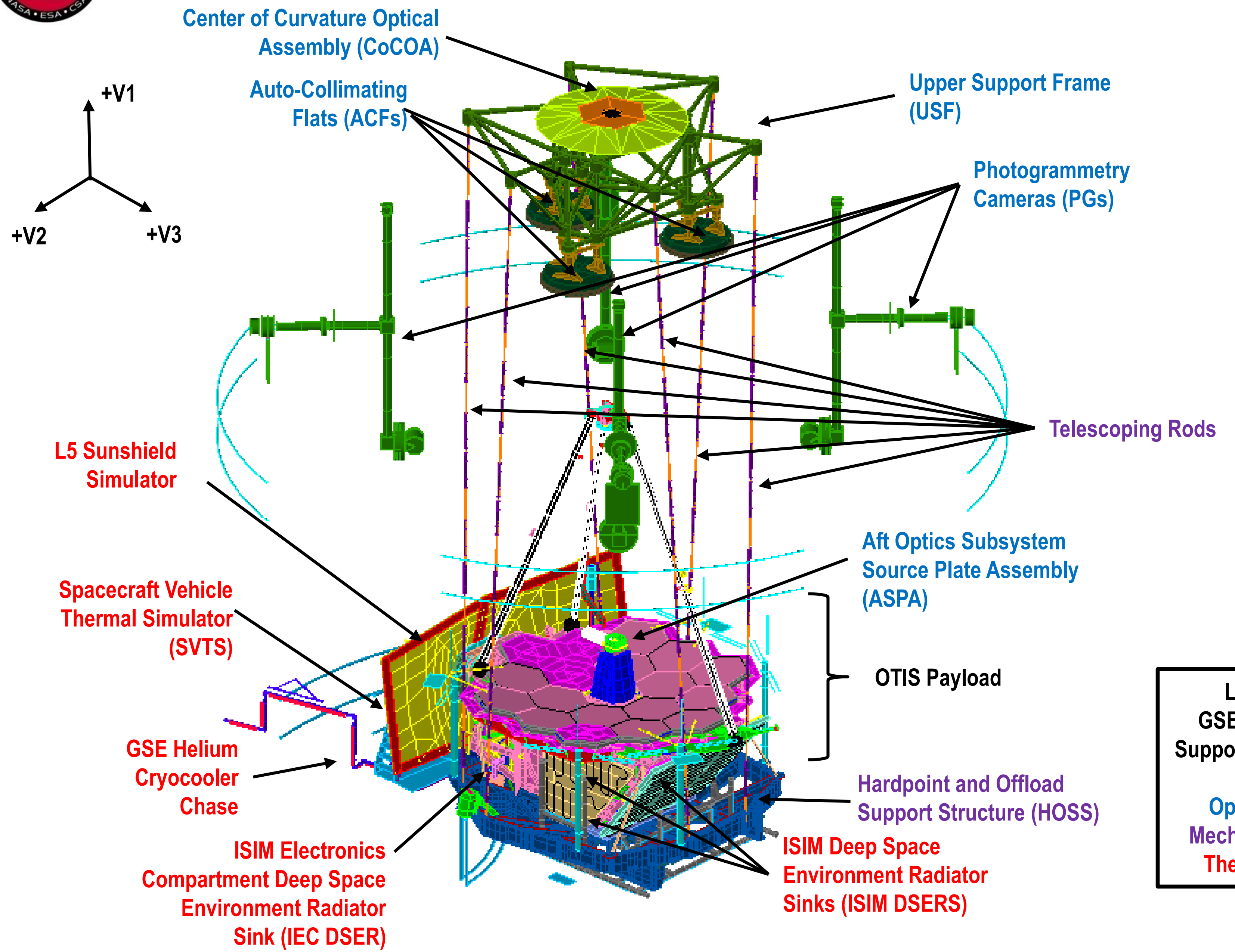
CAD Model



Thermal Model

Image sources: NASA/JWST

JWST OTIS CV Test Setup: Inside the Helium Shroud

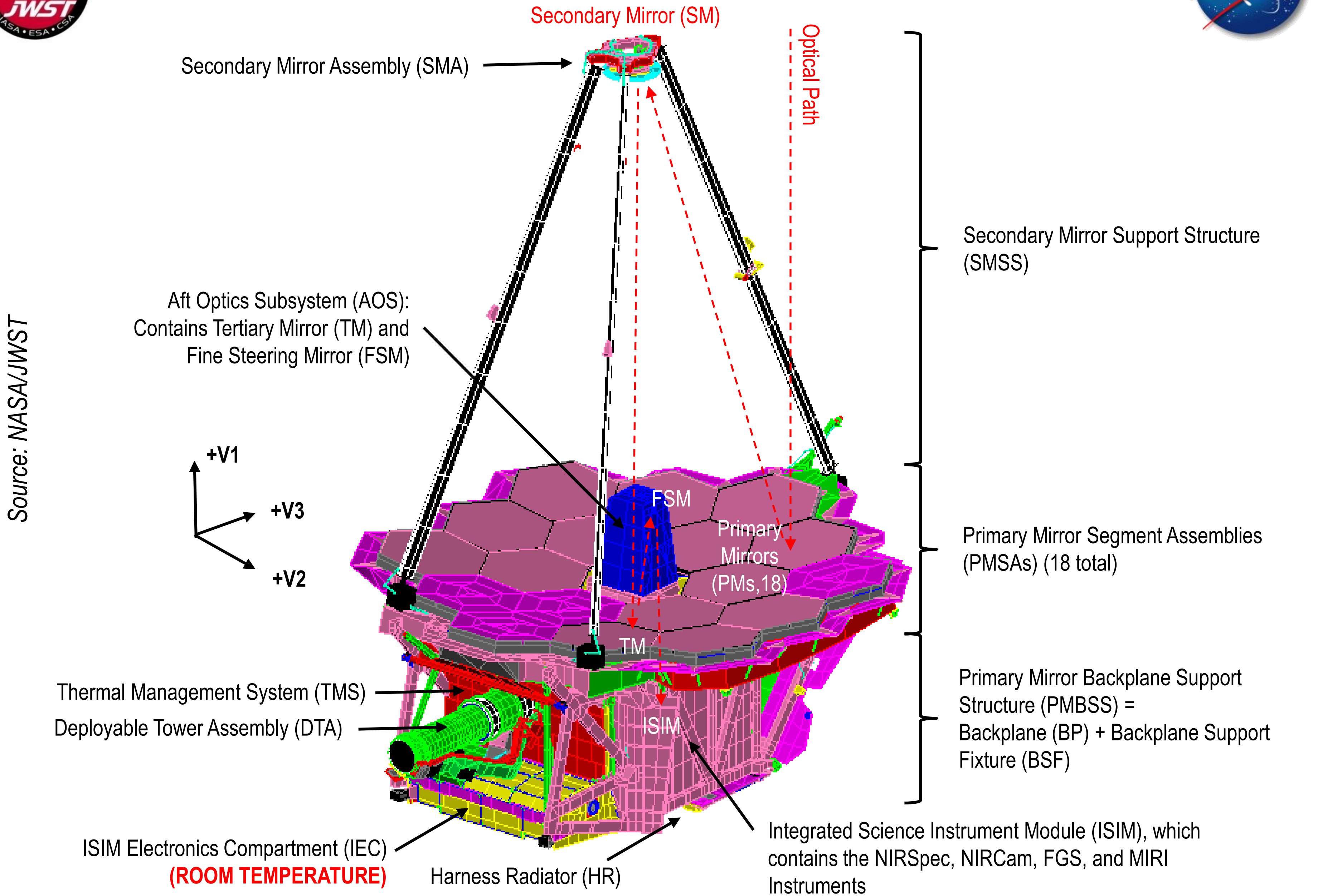


Source: NASA/JWST

LEGEND
GSE = Ground Support Equipment

Optical GSE
Mechanical GSE
Thermal GSE

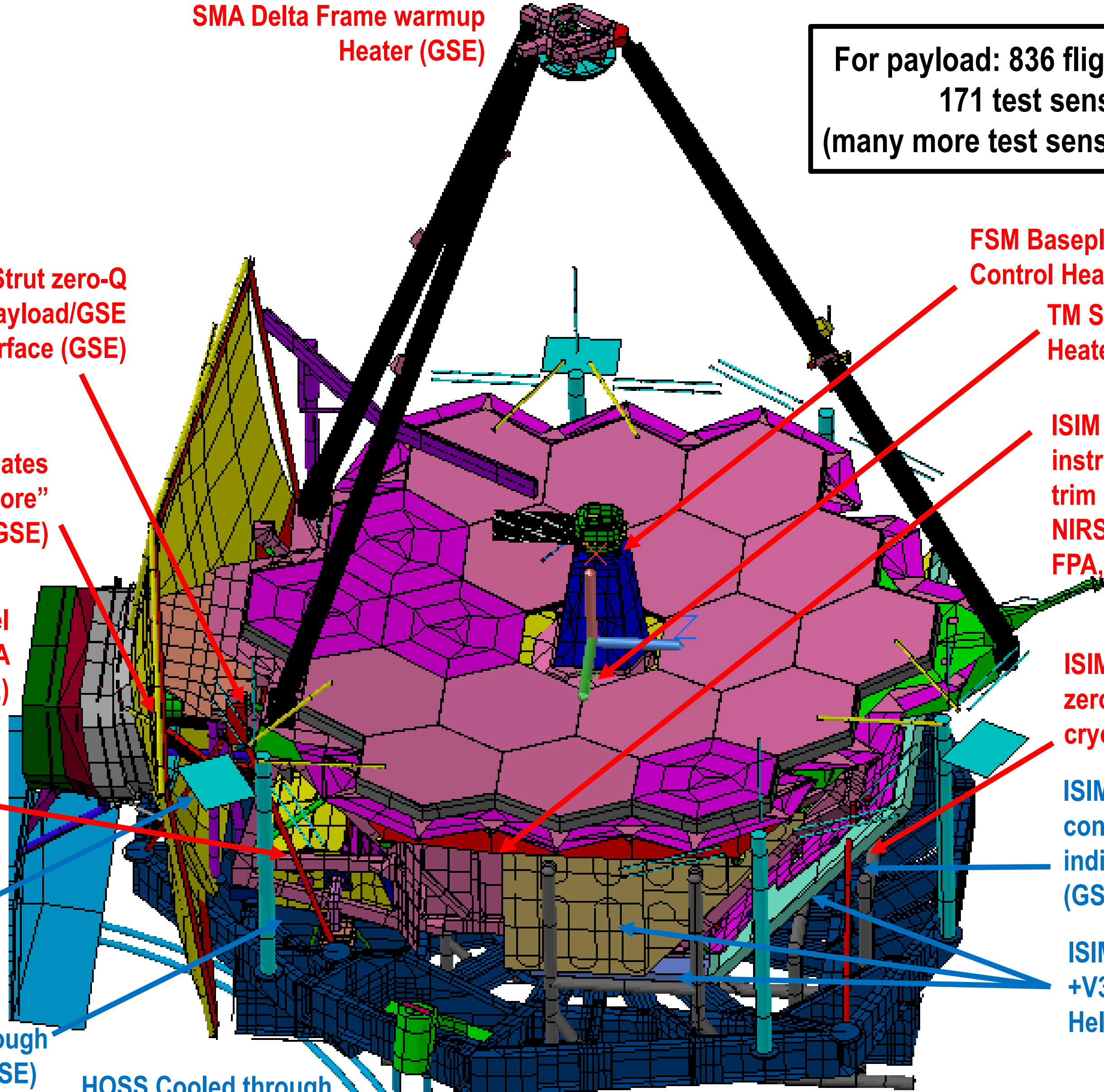
JWST OTIS CV Test Setup: Payload Configuration



OTIS Thermal Control Hardware [6]

Red: Heater Controlled
Blue: Helium Controlled

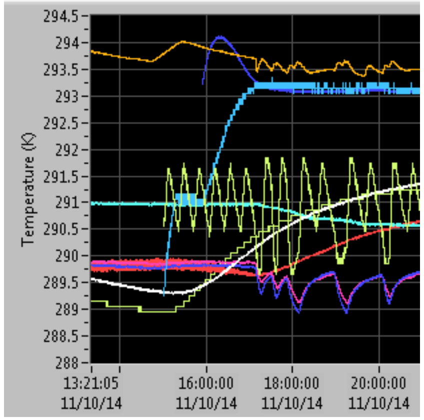
For payload: 836 flight sensors, 171 test sensors (many more test sensors for GSE)



Source: NASA/JWST

GSE Considerations for the Cryogenic Test Environment [7]

- **A robust thermal instrumentation plan was developed with multiple systems to rigorously interpret cryogenic test results**
  - Calibrated diodes, precise data acquisition units for accuracy/resolution through range of test temperatures
  - Radiometers to measure localized heat sources
  - Calorimeters for understanding radiative boundaries and icing
  - Data acquisition software: Fusion, TTS, Eclipse
- **Thermal balance test required precise control of boundary heat leaks on the mW scale, and optical / instrument tests required management of stray light entering optical path**
  - Stationary penetrations on Helium shroud closed out with single layer insulation (SLI) or multi-layer insulation (MLI)
  - Specialized systems of light-tight baffles, shell structures, and MLI used for shroud penetrations which moved due to cryo-shift (e.g. Down / Telescoping Rods) or mechanism operations (e.g. photogrammetry cameras)
  - Harnessing from external environment was anchored to increasingly colder thermal sinks to reduce stray light into chamber



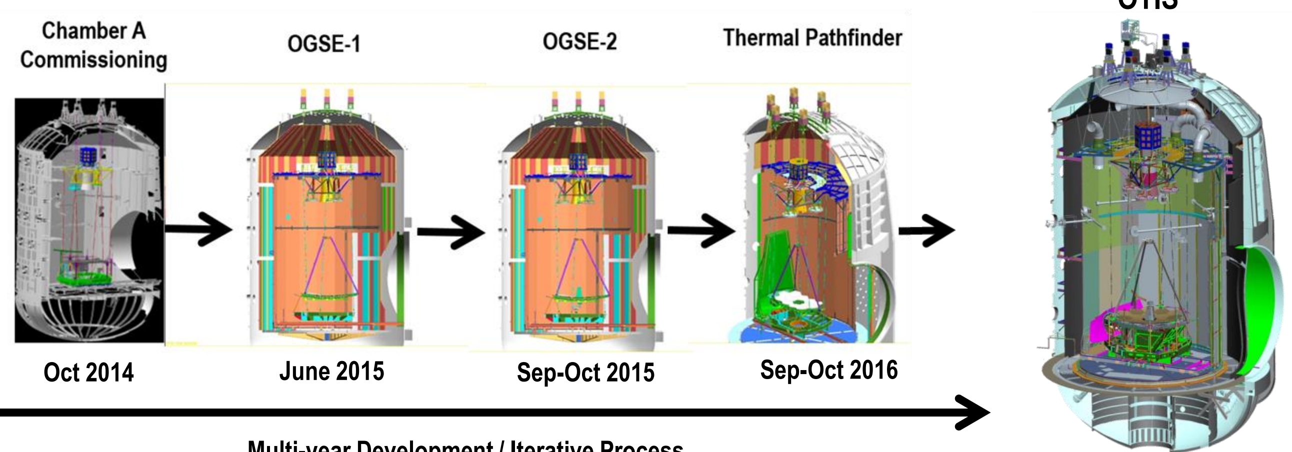
Screenshot of L3Harris TTS Data Acquisition System
Source: L3Harris Corp.

Closeout of Down Rods
Source: L3Harris Corp.

How Did We Prepare for OTIS?

Major ISIM Element Thermal Vacuum/Thermal Balance Tests (SES Chamber, NASA GSFC) [8]

Major OTE Thermal Vacuum/Thermal Balance Tests (Chamber A, NASA JSC) [9-12]



OTIS Analytical Models:

- Contamination
- Cryocooler
- Mechanical / Dynamics
- Optical / Stray Light
- Spacecraft Sim / Software
- Thermal
- Thermal Distortion

Image Sources: NASA/JWST

Planning for the Passive Cryogenic Test

Establishing Limits and Constraints

What Are Our Requirements?

<u>**Constraints**</u> are put in place to avoid actions, conditions, or events, which if realized, will result in <u>damage</u> to flight hardware.

<u>**Limitations**</u> are put in place to avoid actions, conditions, or events, which have the potential for <u>temporarily impacting performance</u> or resulting in <u>loss of test time</u>.

- **For the Thermal Subsystem, there were 84 constraints and 8 limitations out of more than 1,000 total for the OTIS test**
  - Most thermal constraints and limitations were designed to avoid contamination, overstressing of structural elements and instruments. They defined absolute temperature limits; rates of change; gradients within structures or instruments; usage of heaters; and temperature relationships between instruments, optics, and thermal boundaries.
- **The OTIS thermal team installed alarms to monitor and prevent any exceedances of L&Cs**
  - Separate monitoring systems were used for flight and GSE sensors
  - FUSION, an in-house system developed at NASA GSFC, was employed to visualize both flight and GSE sensor data as it pertained to thermal-specific L&Cs
  - An alarm limit philosophy was developed to provide margin and time to respond on components which had L&Cs levied against them, but which did have sensors to directly measure their temperature against L&Cs

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

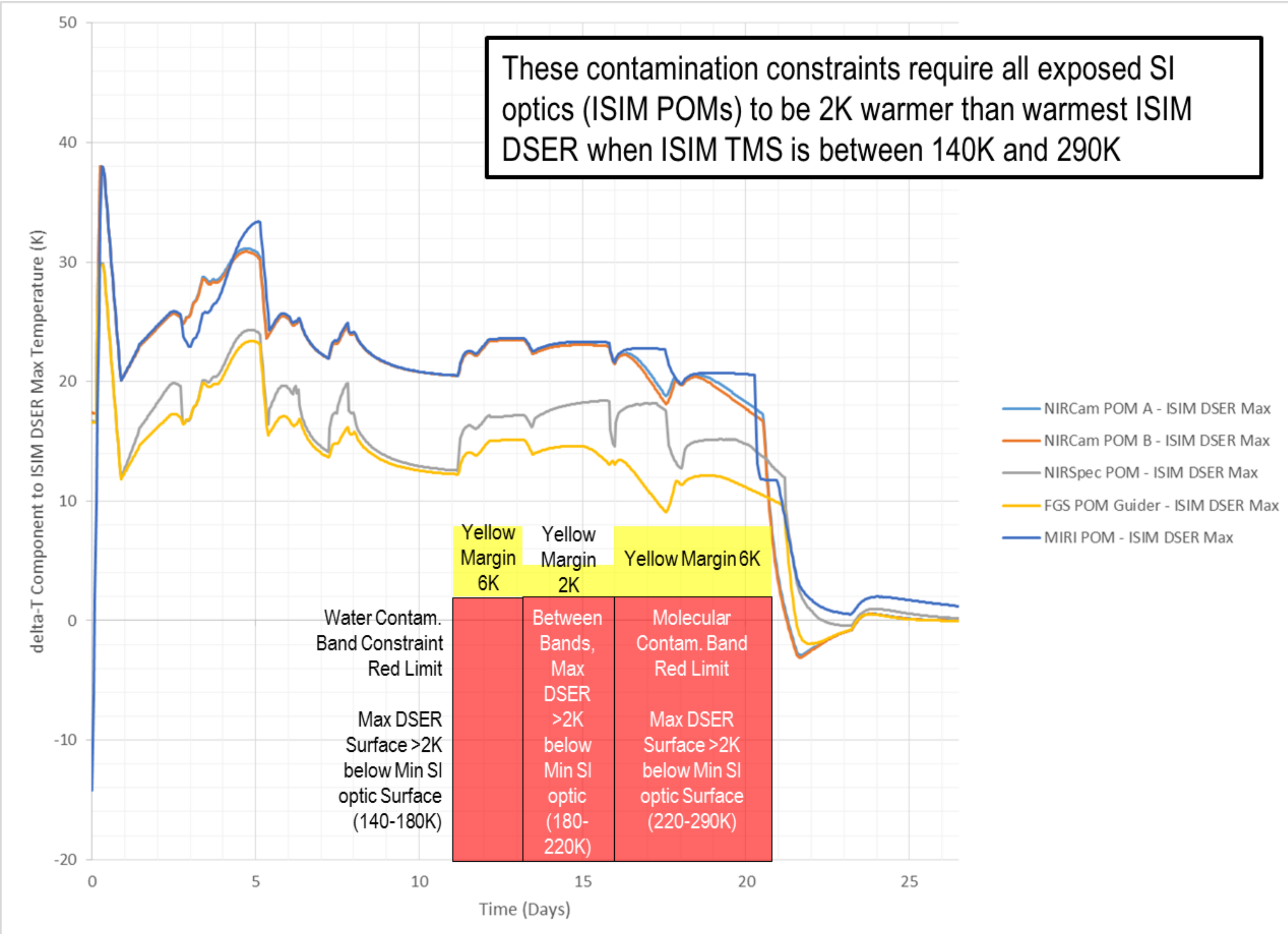
Driving Parameters for OTIS Test Methodology (2 of 2)

- **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

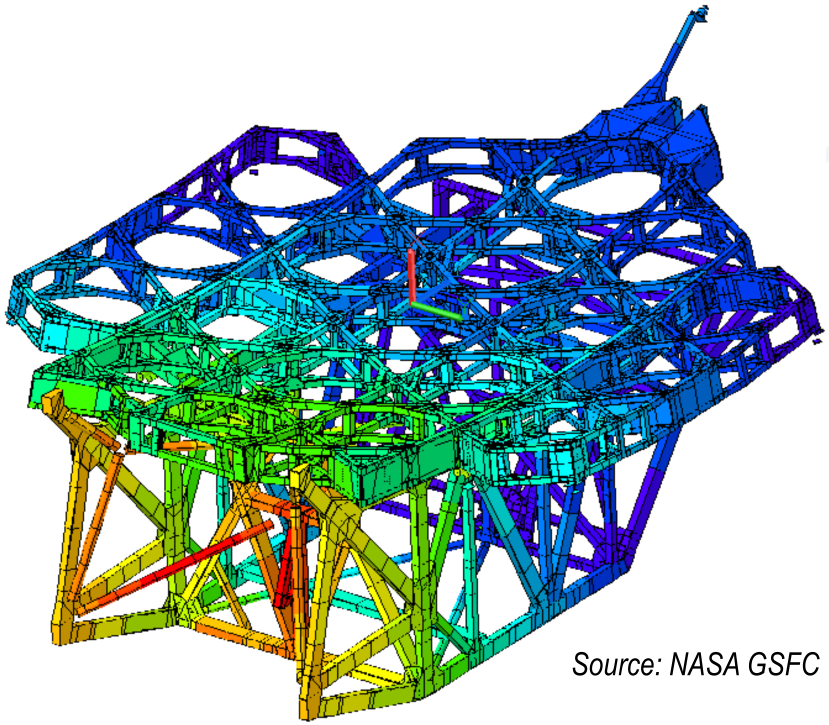
- **Since OTIS has a composite truss frame, at 140-170K water is emitted from the composite structure, and at 220-285K molecular contaminants are released**
  - The sensitive optical components (18 Primary Mirrors, Secondary Mirror, Tertiary Mirror, Fine Steering Mirror, ISIM Pick-Off Mirrors) are at 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, keeping all 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

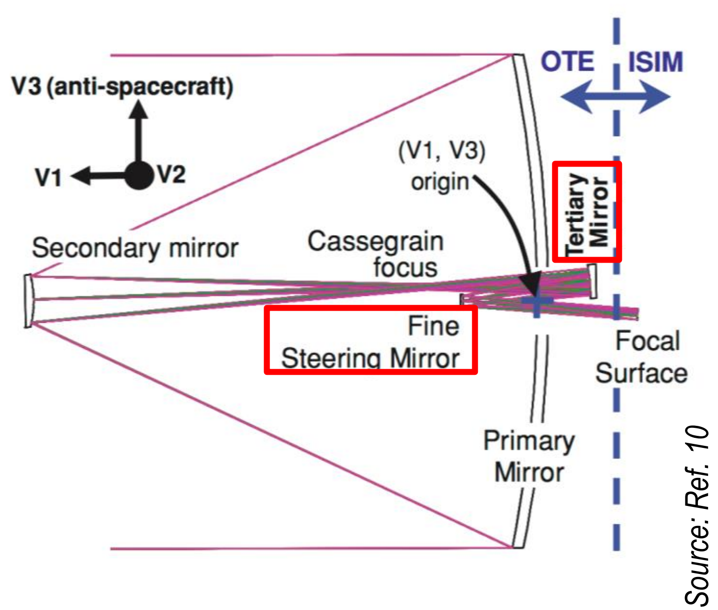


Source: NASA GSFC

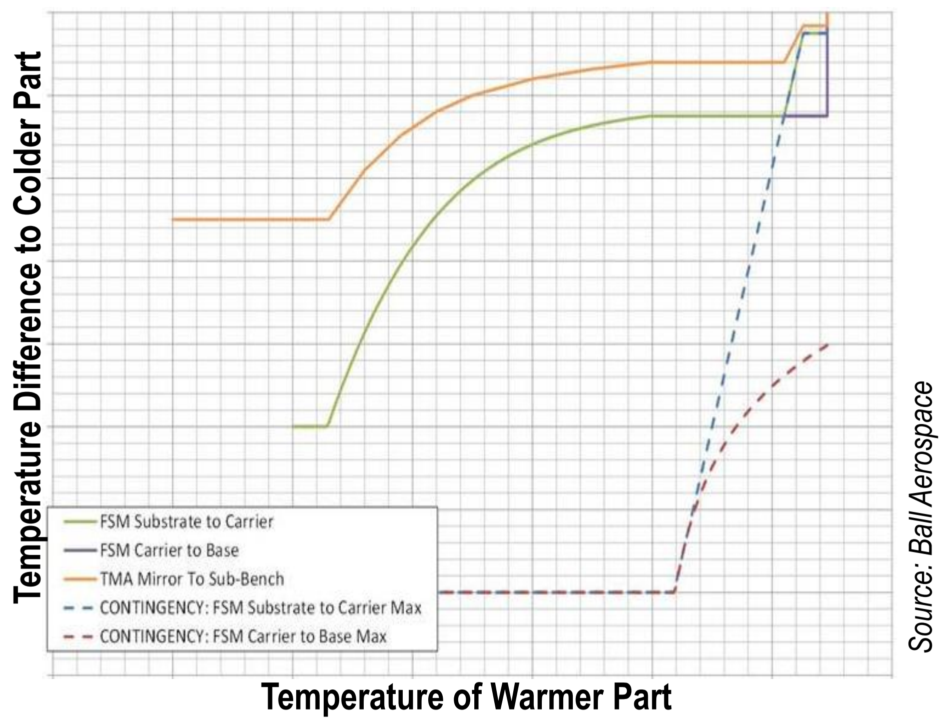
Cryogenic steady-state temperature distribution on PMBSS composite truss structure

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



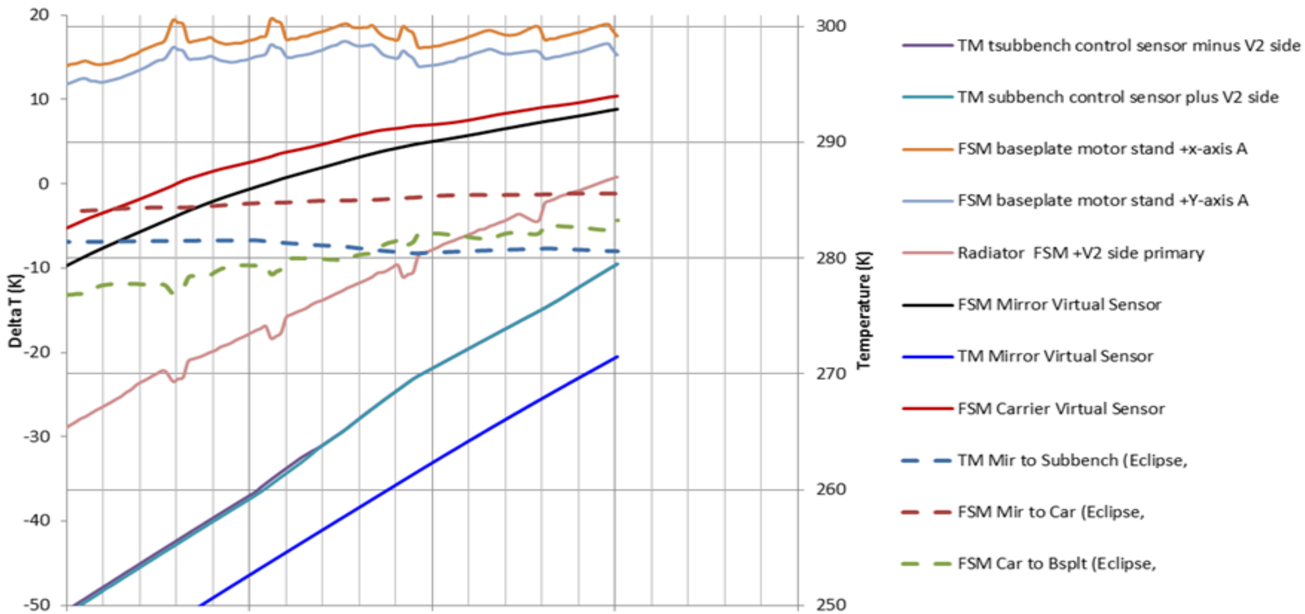
Position of the TM and FSM in the JWST Optical Design



Sample temperature-dependent ΔT requirements for AOS mirror assemblies

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

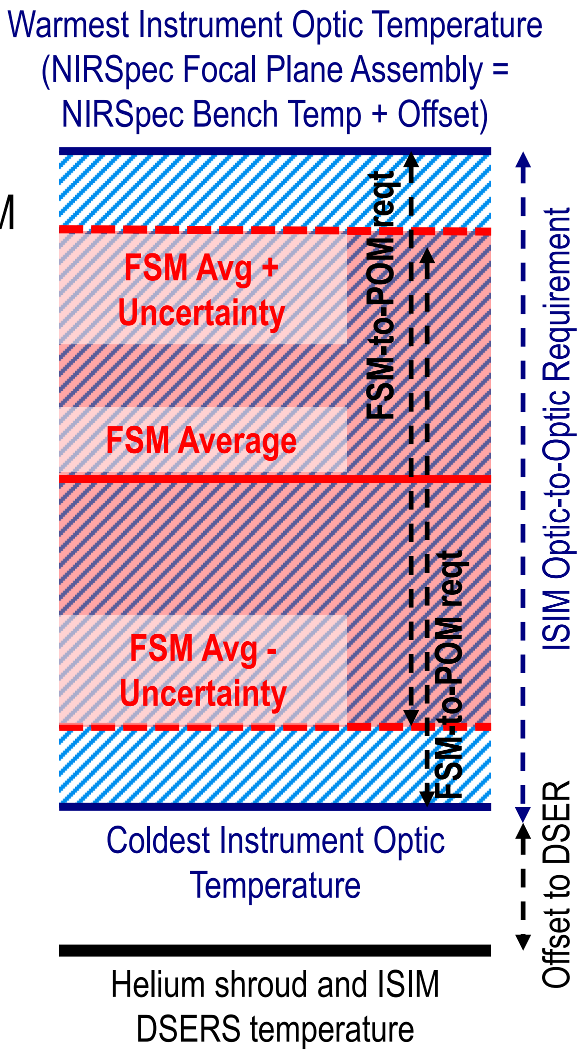
- **There were no sensors on the Tertiary Mirror (TM) and Fine Steering Mirror (FSM) had no sensors to track performance against their structural and contamination constraints**
- **A Real-time Thermal Model (RTM) was developed by Ball Aerospace to produce "virtual sensor" telemetry by calculating energy 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



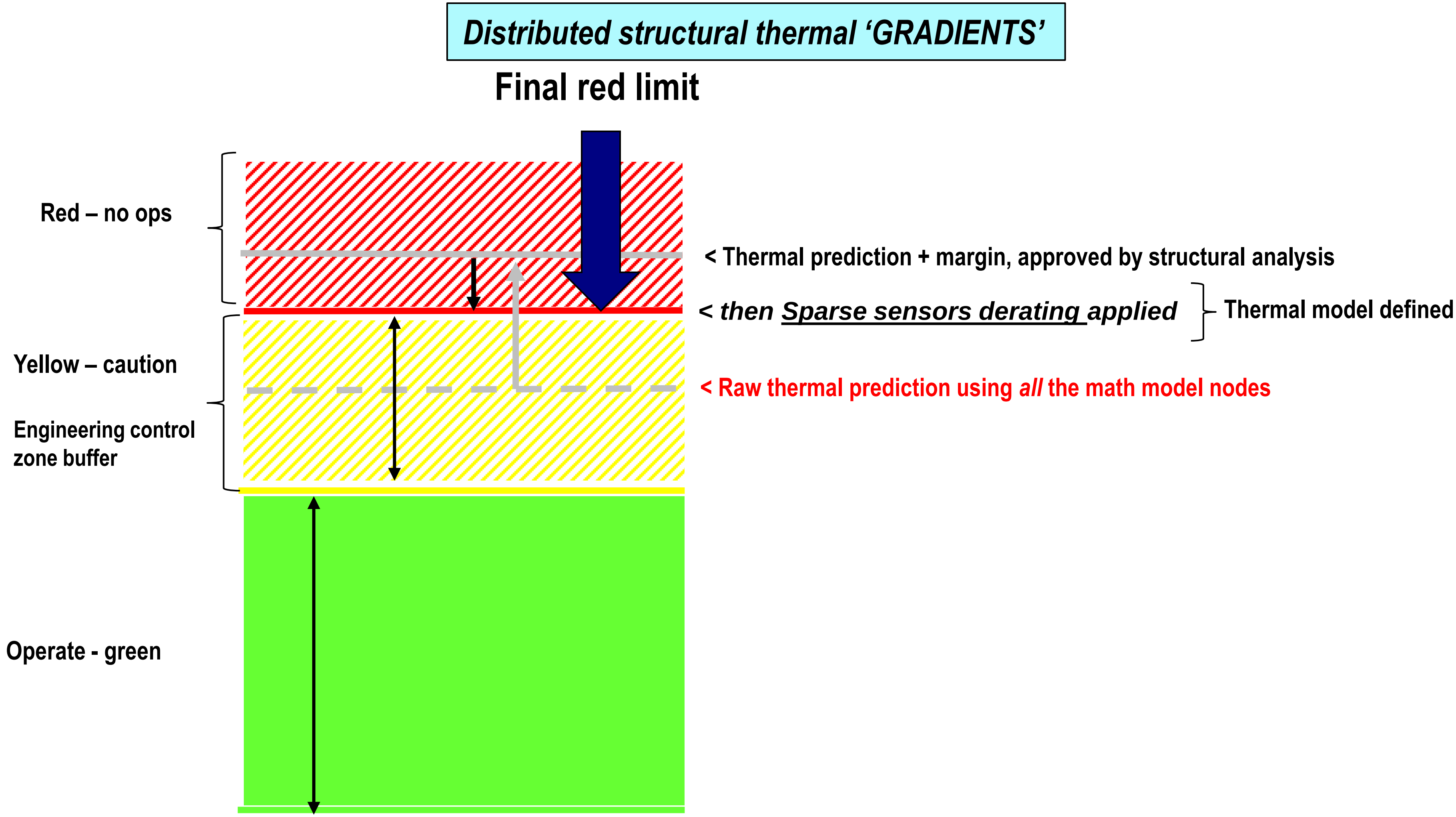
AOS Warmup Tracking at OTIS Using Virtual Sensor Data

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



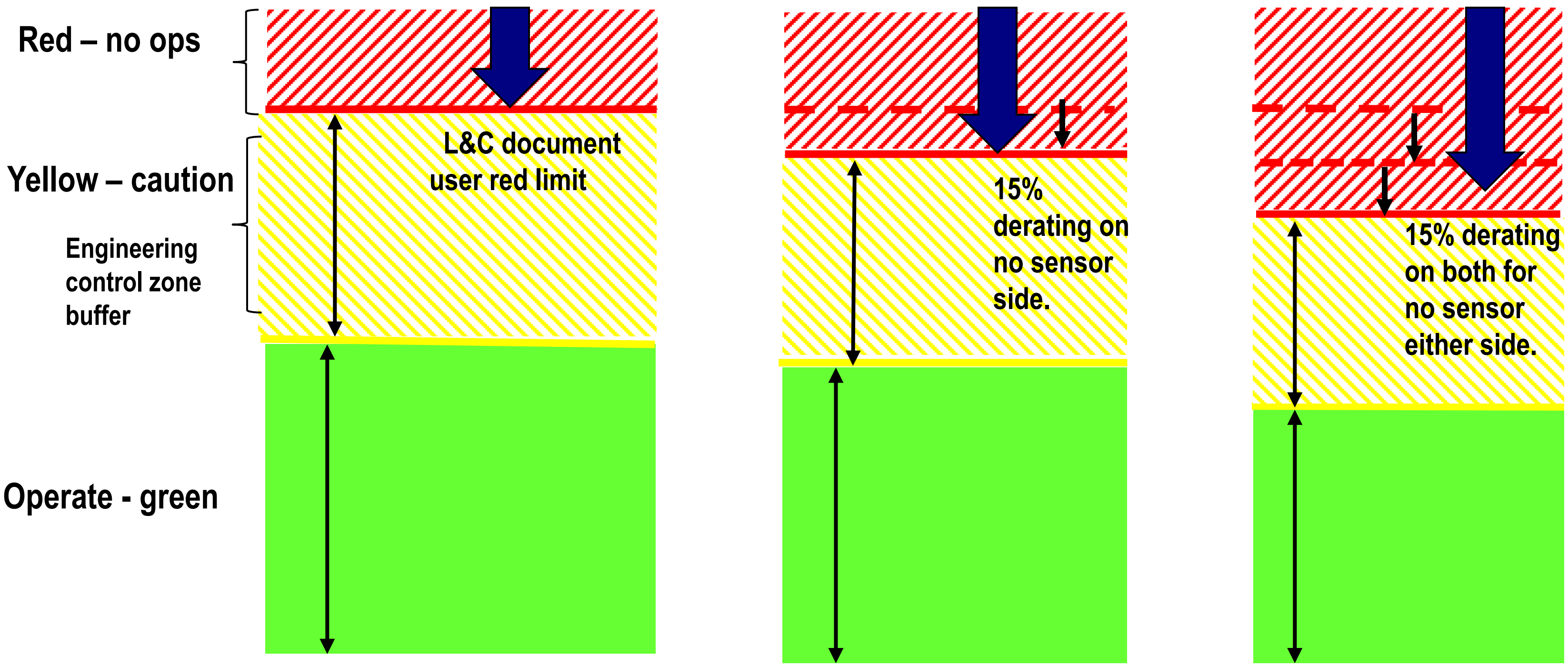
Thermal Margin Philosophy for Interfaces

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)



Planning for the Passive Cryogenic Test

Thermal Model Development

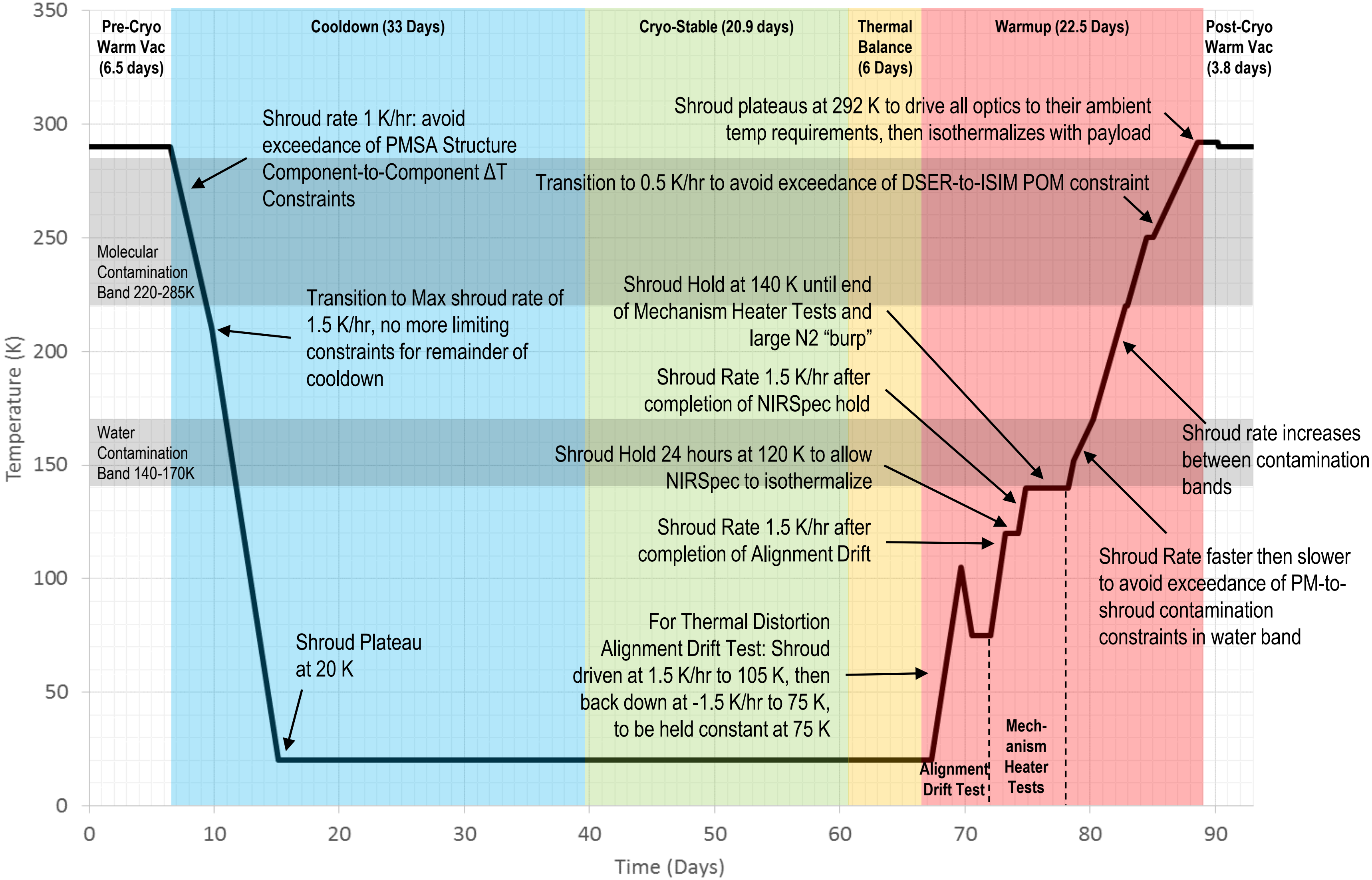
Control Methods and Optimization of Helium Shroud Profile

- **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

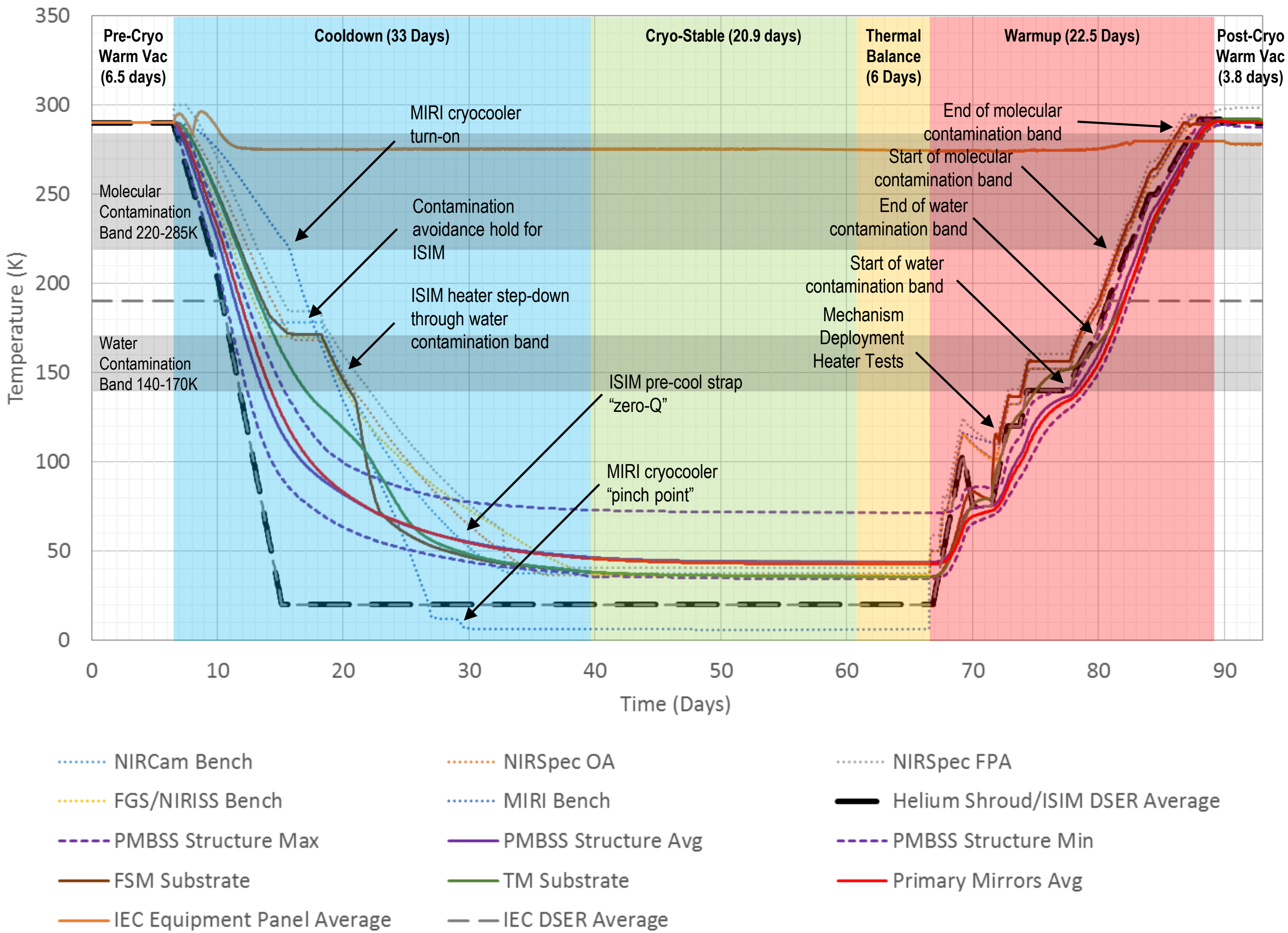
NOTE: With all model predictions, coating emissivities cannot be assumed constant within the 20 K – 300 K temperature range of the OTIS CV Test

- 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

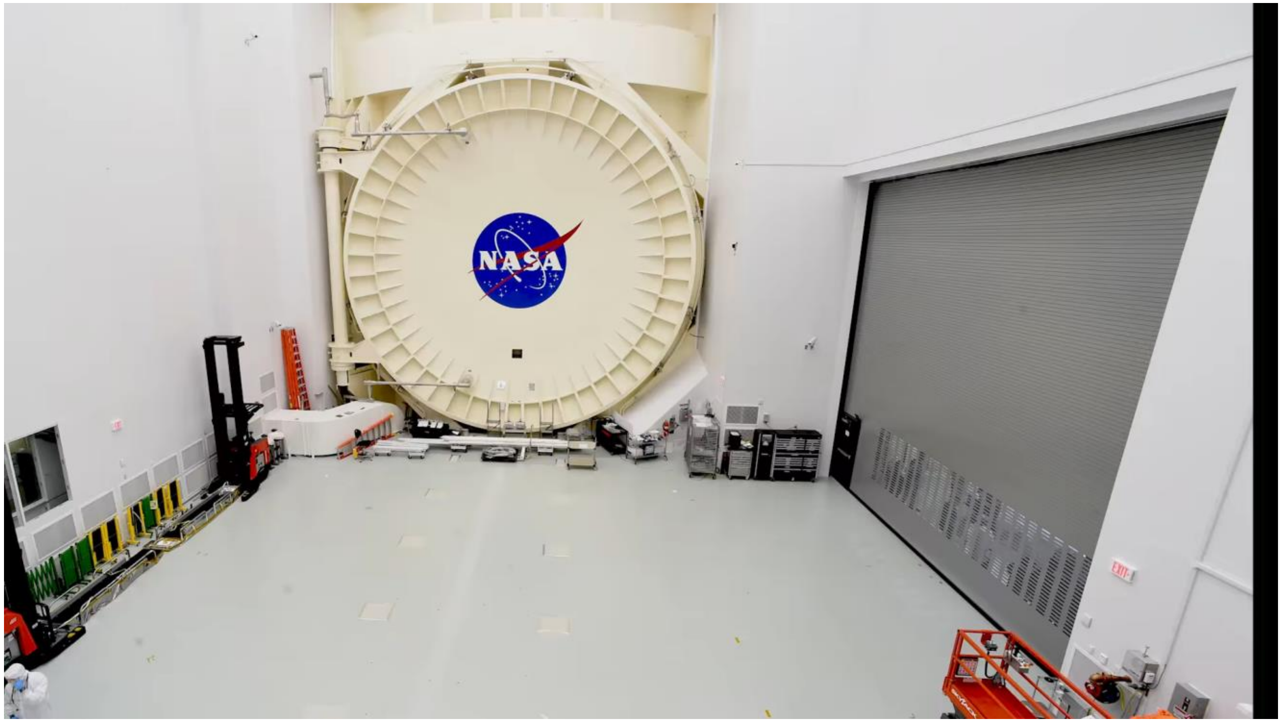


Test Execution

How did we do in test vs. predictions?

OTIS CV Test: The Moment of Truth!

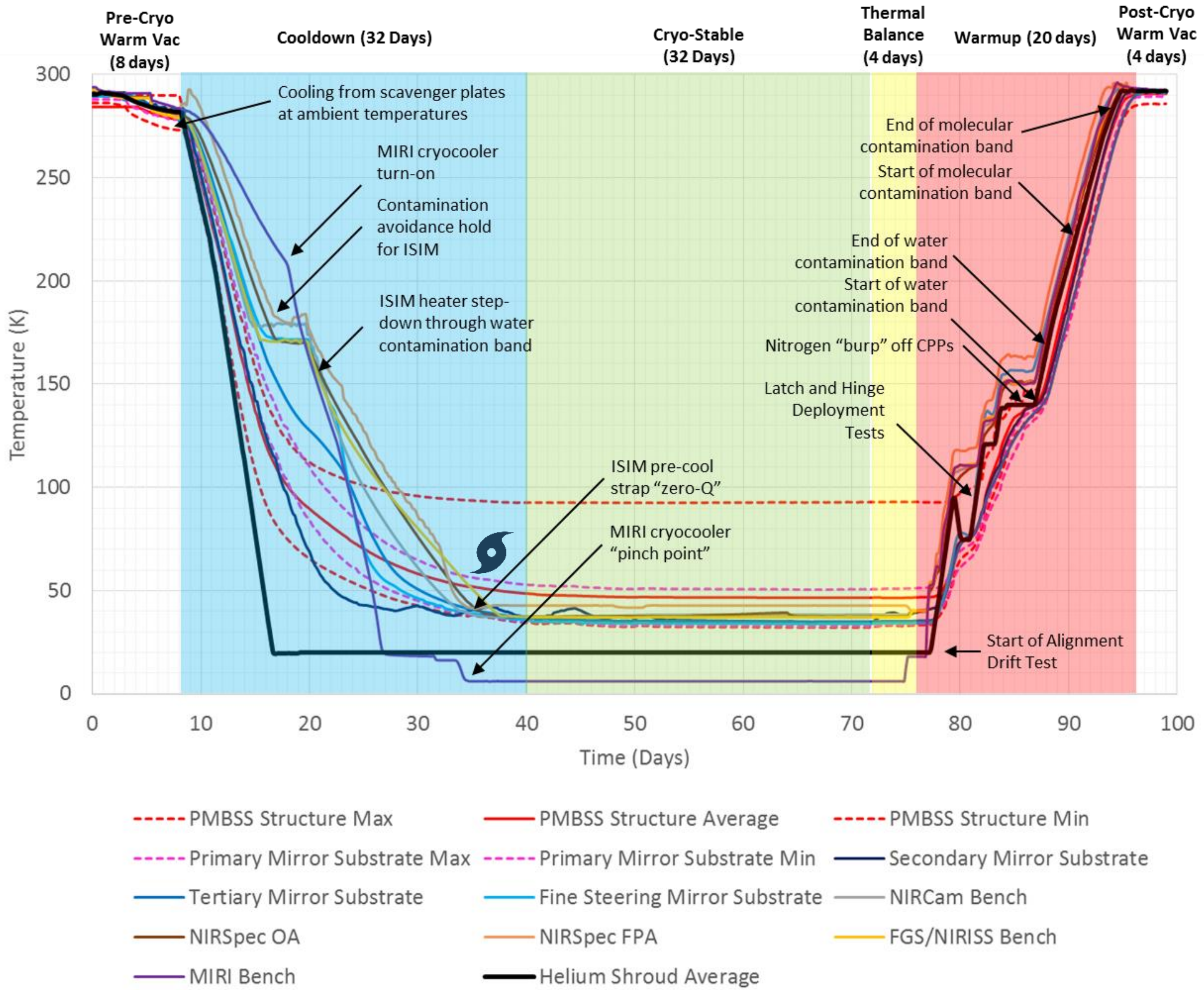
- **After many years of planning (as early as from 2008!), and many consecutive summers of precursor tests at JSC, we finally executed the OTIS CV Test from July through October of 2017!**
- **The test required monitoring by a team of >100 engineers and technicians 24/7 throughout the entire 3+ months**



Source: NASA SVS/ Mike Clare

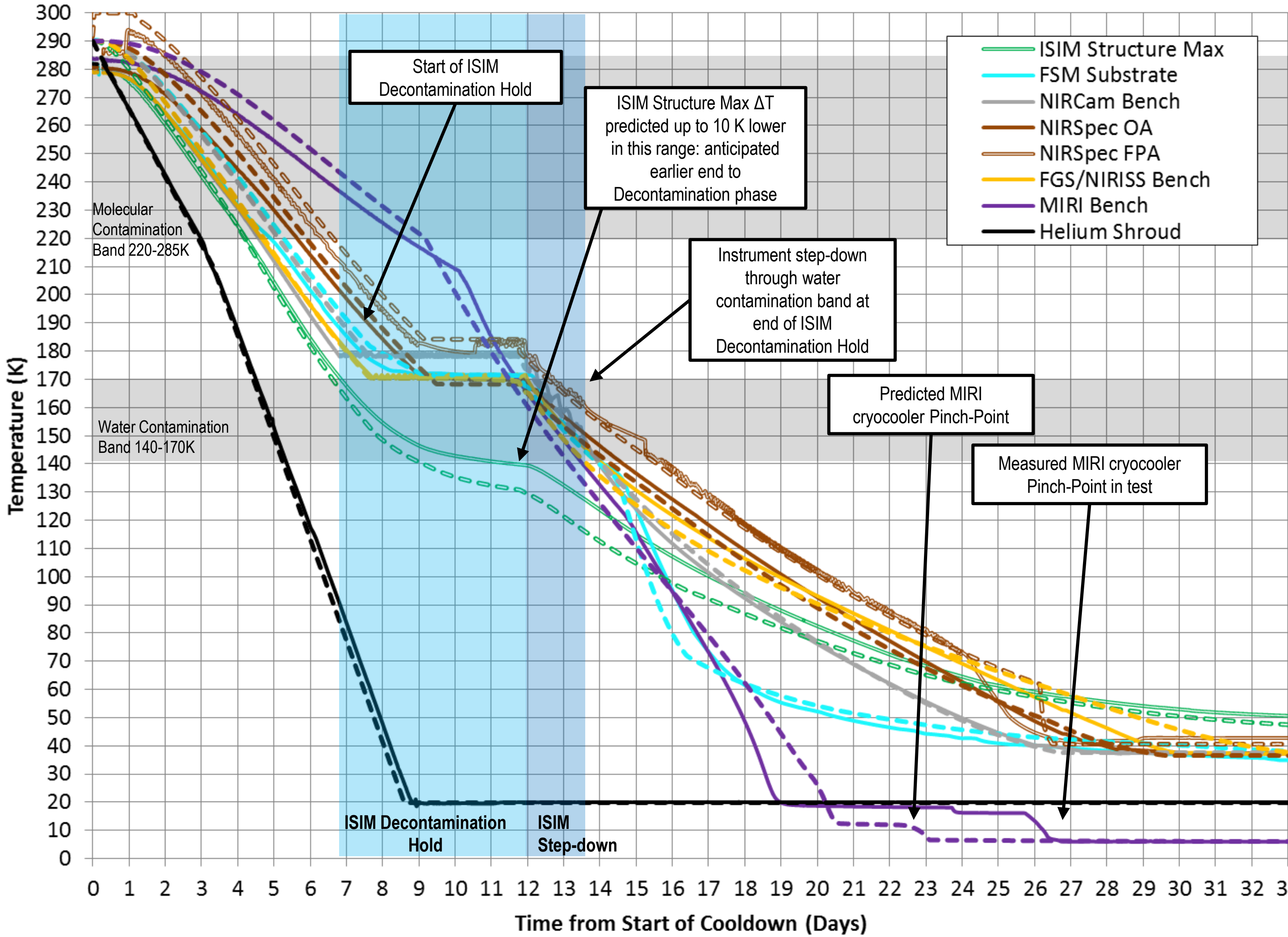
Preparing the OTIS CV Payload to enter Chamber A at JSC

As-Tested Shroud Profile from the OTIS CV Test

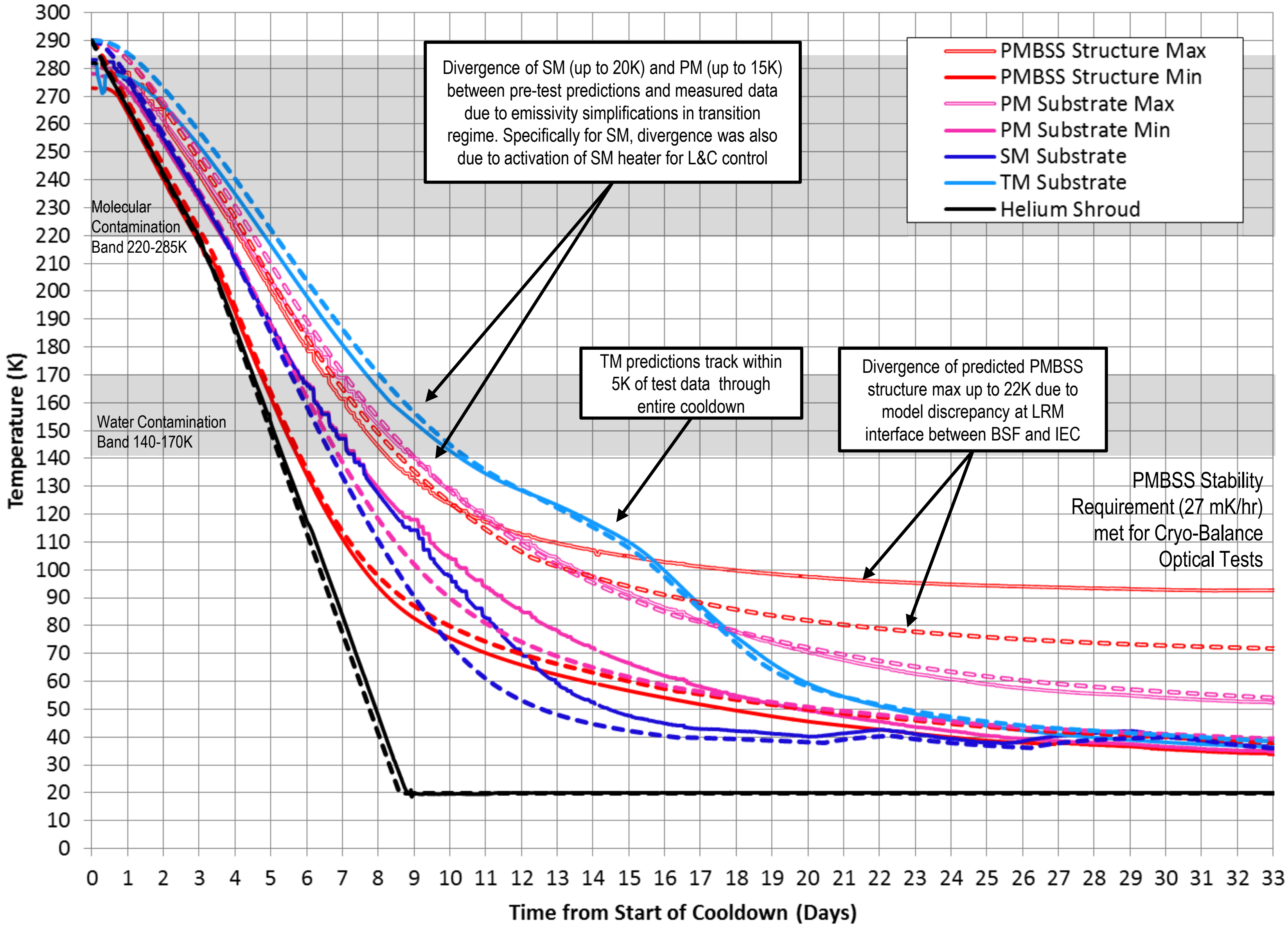


Test Execution
Cooldown

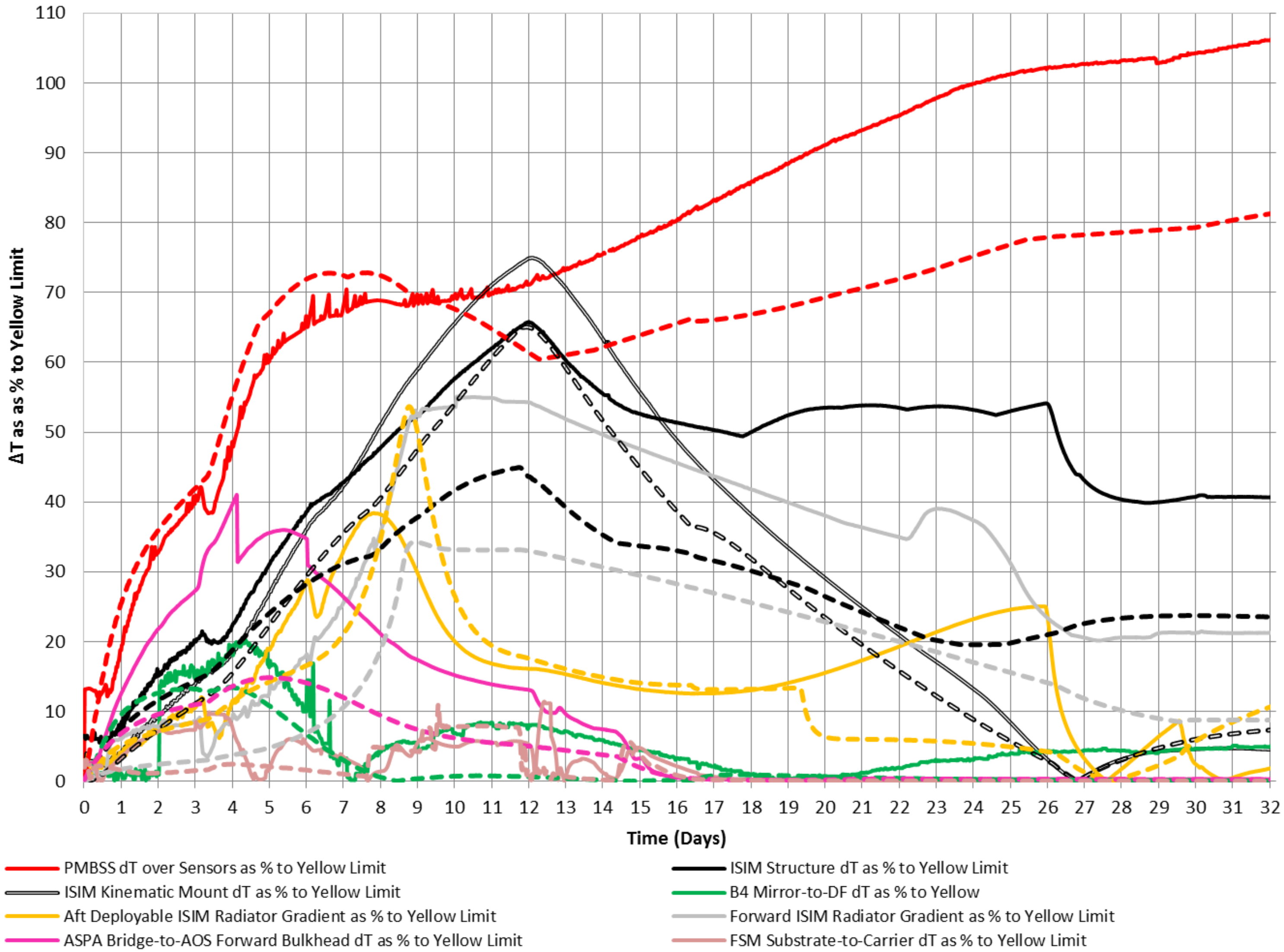
Comparison Between Model Predictions and Measured Test Data in Cooldown: ISIM



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



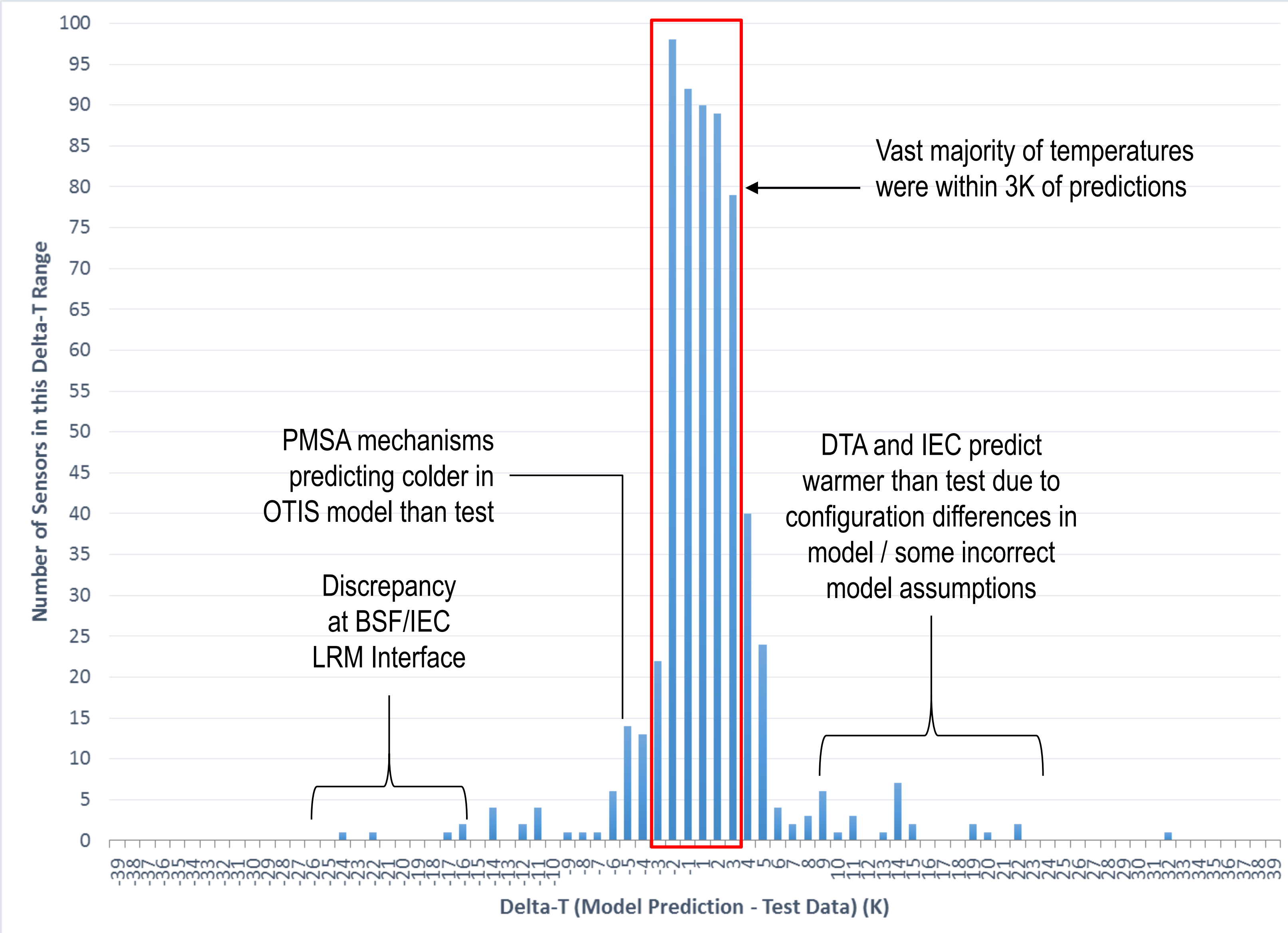
Sample ΔT as % to Yellow Limit Plot for L&C Tracking



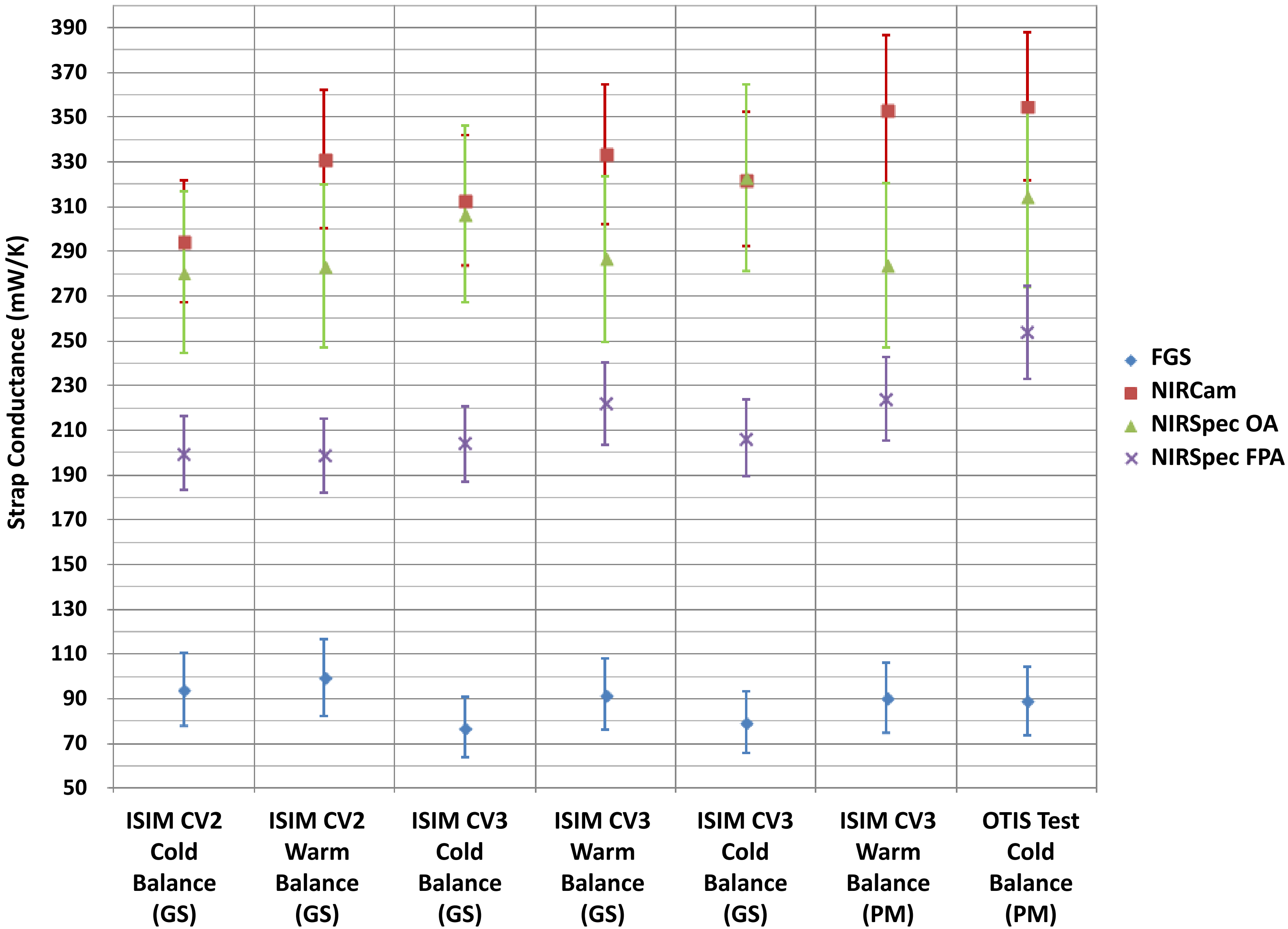
Test Execution

Cryogenic Thermal Balance and Model Verification

Thermal Balance: Temperature Difference Between Model and Test Sensors

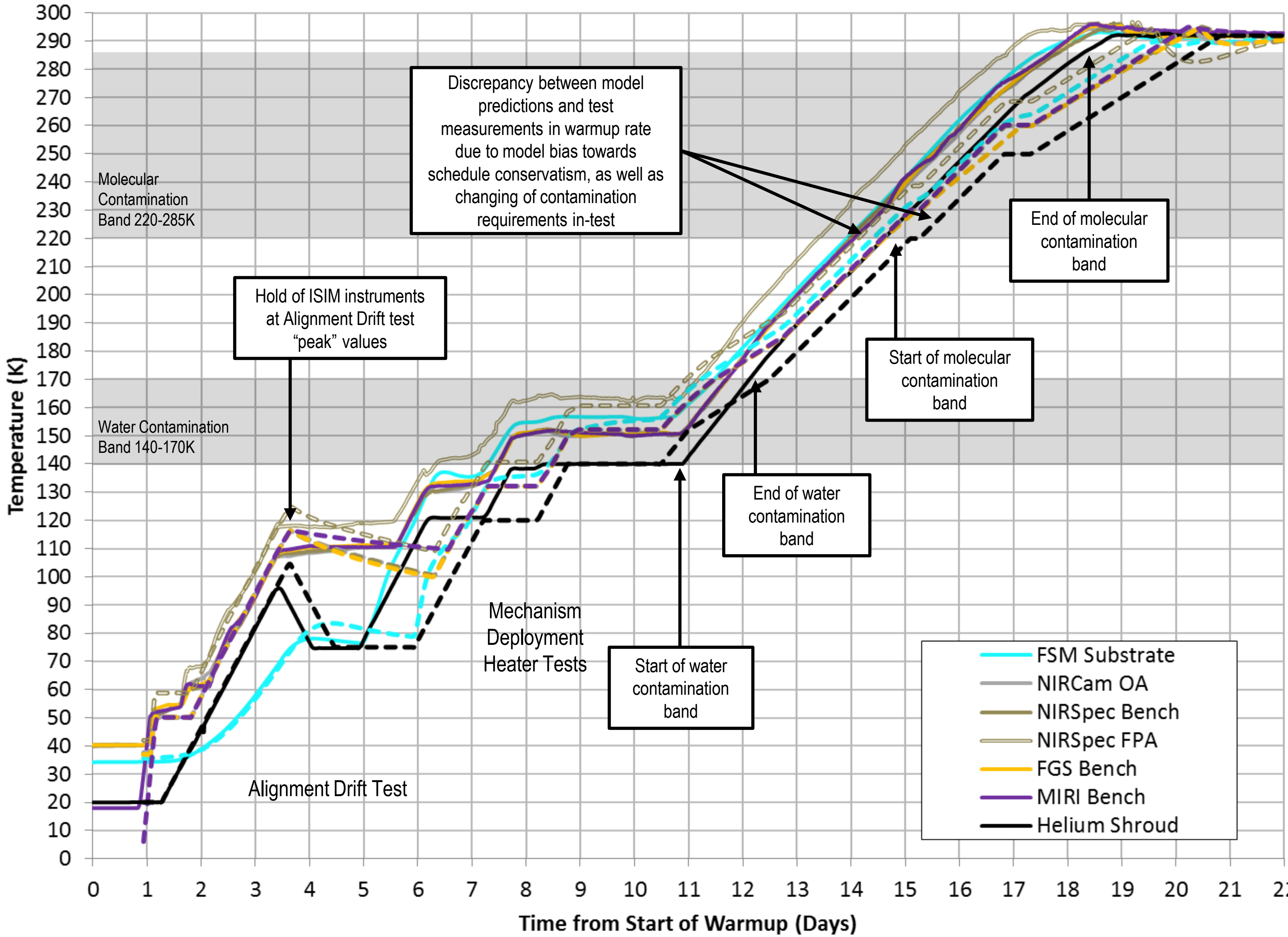


ISIM Heat Strap Conductance Measurements[14]

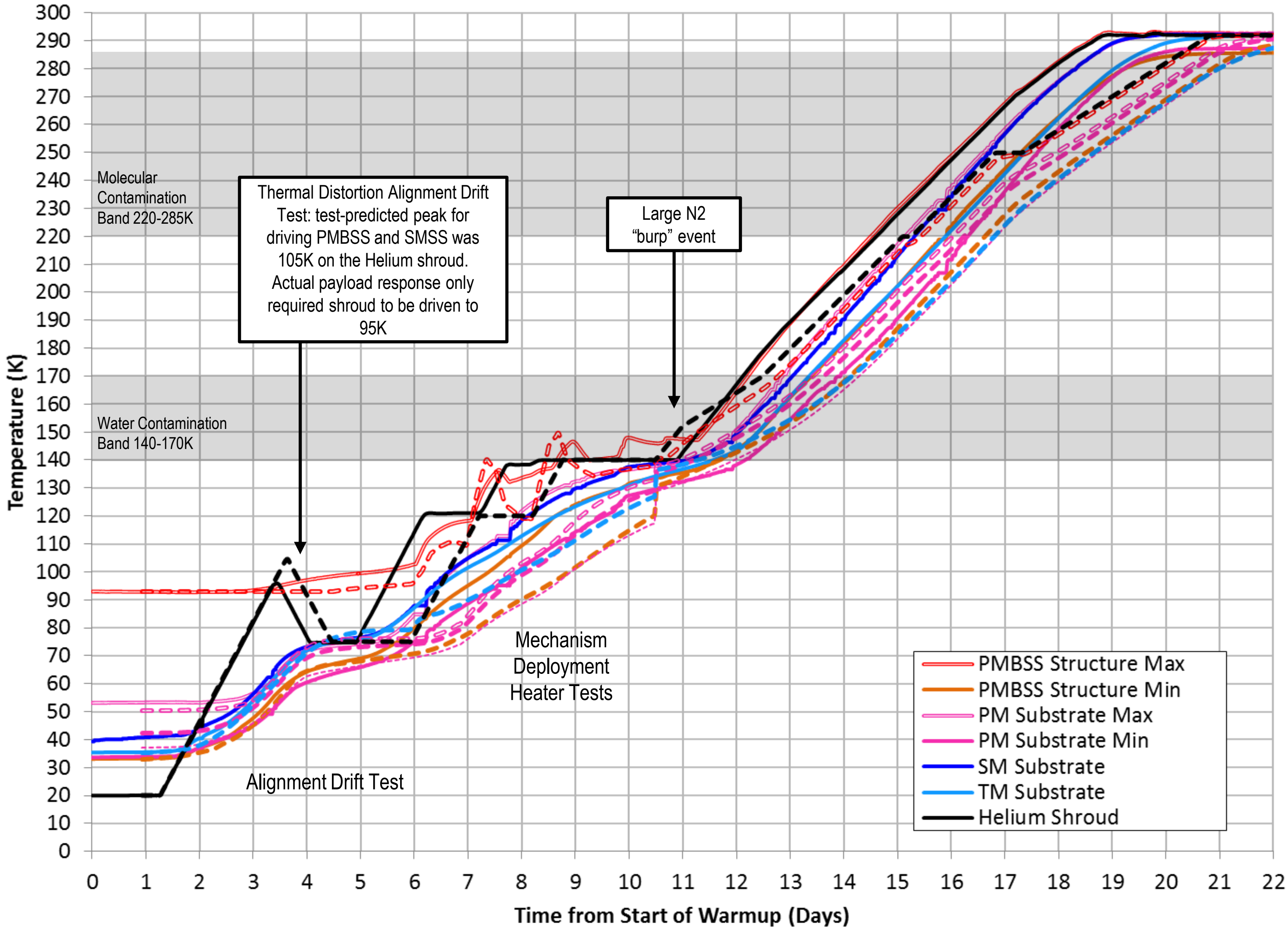


Test Execution
Warmup

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



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



Summary: 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

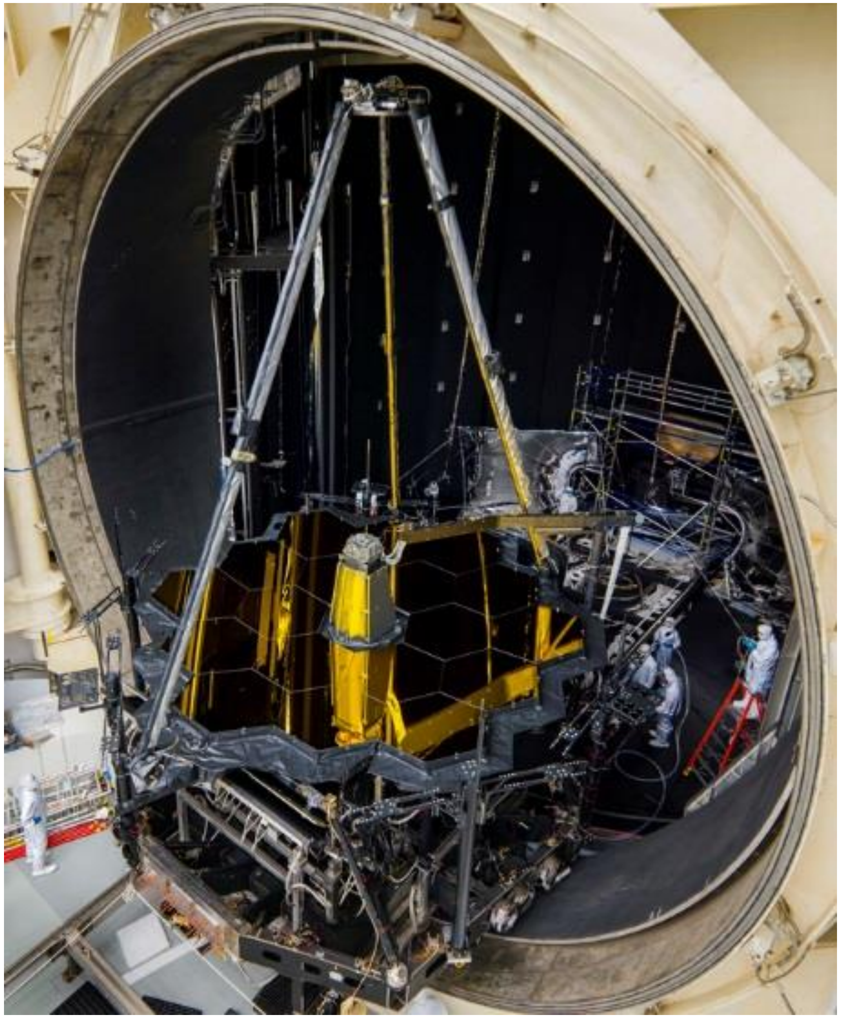


Image Source: NASA/Chris Gunn

Planning for the Passive Cryogenic Test

Off-Nominal Event Planning

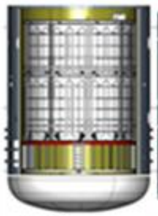
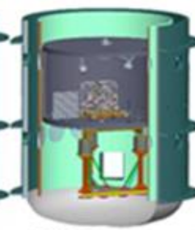
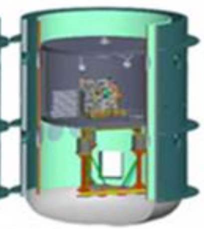
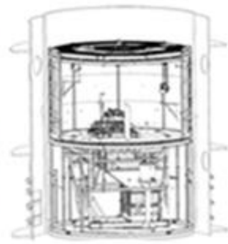
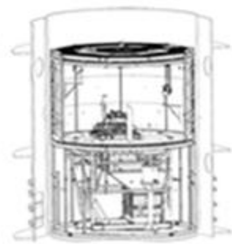
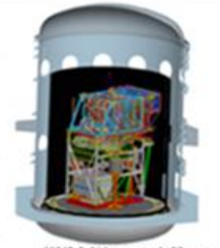
Presented by: Stuart Glazer

Murphy's Law

"Anything that can go wrong will go wrong."

-Edward A. Murphy, Aerospace Engineer at Edwards AFB, 1949

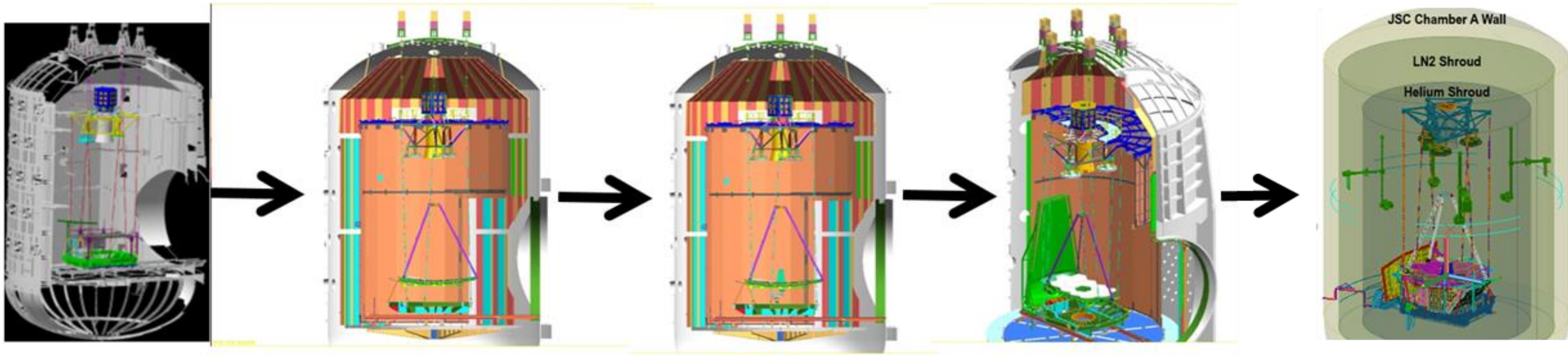
Major ISIM Element TV/TB Tests in SES Facility at GSFC

<table>
<tr><td colspan="8">Test Items – Test Exposure of Items in <u>SES Testing</u></td></tr>
<tr><td>Tests</td>
<td>
He Shroud Acceptance Test (-03)
COMPLETE 2008</td>
<td>
Chamber Certification Test (-01)
COMPLETE March 2010</td>
<td>
ISIM Structure Cryoset Test
COMPLETE May 2010</td>
<td>
ISIM Structure Cryo-Proof Test
COMPLETE Nov 2010</td>
<td>
OSIM Cryo-Cal Test 1
COMPLETE Aug 2012</td>
<td>
OSIM Cryo-Cal Test 2
COMPLETE May 2013</td>
<td>
ISIM Element Cryo-Vacuum Tests (3 tests completed)
CV1: Nov 2013, CV2 Nov 2014 CV3 Feb 2016</td></tr>
<tr><td>Items in Test</td>
<td>He Shroud (-03)</td>
<td>He Shroud (-01)
Lower GESHA
Upper GESHA
GIS
ITP
Photogrammetry
Fabreeka VIS*
MIRI MLI Expmnt
Bolometers</td>
<td>He Shroud (-01)
Lower GESHA
Upper GESHA
GIS
ITP / MATF
Photogrammetry
Fabreeka VIS*
MIRI MLI Expmnt
Bolometers
Flight Structure
IATF</td>
<td>He Shroud (-01)
Lower GESHA
Upper GESHA
GIS
ITP
Photogrammetry
Fabreeka VIS*
Radiometer
Flight Structure
IATF</td>
<td colspan="2">He Shroud (-01)
Lower GESHA
Upper GESHA
GIS
ITP / MATF
Photogrammetry
Fabreeka VIS
OSIM Baffle
OSIM
OSIM Shroud
BIA
SIF/Shroud Support Frame</td>
<td>He Shroud (-01)
Lower/Upper GESHA, GIS
ITP/ MATF
Fabreeka VIS*
Flight Structure
IATF
OSIM
OSIM Shroud
SIF/Shroud Support Frame
Science Instruments (SI)
Flight Harness
Flight Heat Straps
MIRI Cryo-Cooler
MCA
SIF & Interfaces to Frame
Surrogate TMS
IEC w/ Shroud /LN2 Panel
Harness Radiator
HR Shroud</td></tr>
<tr><td>Cycles</td>
<td>1 cycle to 15K
B/O to 70C</td>
<td>1 cycle to 15K
1 cycle to 30K
B/O to 50C</td>
<td>1 cycle to 39K
1 cycle to 28K
B/O to 40C</td>
<td>1 cycle to 28K</td>
<td colspan="2">1 cycle to 30K (BIA)
1 cycle of OSIM to 100K</td>
<td>CV1: 1 cycle to 43K
CV2: 1 cycle to 37K + 43K
CV3: 1 cycle to 37K + 43K</td></tr>
<tr><td></td><td colspan="7">* - caveat; Fabreeka's were not energized in these tests
- caveat; NIRSpec, NIRCam are not in CV1, and Cryo Cooler CHA ETU used in CV 1 & 2 tests.</td></tr>
</table>

Major Off-Nominal Events during ISIM TVAC Tests at GSFC

Test	Date	Event	Consequences
OSIM Cryo-Cal 1	6/12/2013	Derecho (high wind storm) – extended power loss in area	Impacts to personnel availability
ISIM CV1	10/1/2013-10/17/2013	17-day US Government shutdown	Test placed on "hold" – no progress
ISIM CV2	7/3/2014	Emergency light in test control room caught fire	Control room evacuated, test on hold until smoke cleared
ISIM CV2	7/8/2014	Thunderstorm – Power outage at facility	Emergency generator did not start automatically. He compressor off for ~ 30 minutes. Shroud warmed, test time lost.
ISIM CV2	7/9/2014	Thunderstorm – Lightning strike at GSFC	Lost cooling water for He compressor. Facility electrician was not on shift to restore power to cooling water. Shroud warmed, test time lost.
ISIM CV2	7/10/2014	Continue from above event	He compressor turned off without cooling water.
ISIM CV2	10/3/2014	Fire alarm in B10 basement (part of GSFC thermal test complex)	Thermal engineers, control personnel briefly evacuated (<30 minutes), test resumed without incident
ISIM CV3	1/22/2016 through 1/25/2016	Extreme blizzard ~2 to 3 feet snow in area	Extremely hazardous travel conditions. Test personnel either sheltered at GSFC or if staying within 1 mile of GSFC, were transported to/from GSFC by persons with heavy trucks. Test continued without loss of any facilities.

Major OTE/OTIS TV/TB Tests in Chamber A at JSC



Chamber A Commissioning

- Cryo load and stress test of suspension system with payload mass simulator
- Chamber verification
- OGSE vacuum integrity
- OGSE functional testing and thermal characterization
- Cryo shift measurements

OGSE-1

- Pathfinder cryo-vac exposure
- Cryo proof AOS interfaces
- Operated OGSE (CoCOA, PG, DMI) in OTIS-like config
- Checked out BIA in Chamber A
- Thermal Distortion and Dynamics testing
- Vacuum portion of cooldown to check SM model characteristics

OGSE-2

- Added flight AOS and GSE AOS Source Plate.
- Checked out Half-pass and Pass-and-a-half tests
- Used BIA camera as SI simulator
- Thermal Distortion and Dynamics testing

Thermal Pathfinder

- Thermal GSE Checkout (including SVTS, DSERS)
- Dry run cooldown, practiced warmup tests
- Backplane Thermal Balance (design validation off critical path)
- Thermal Distortion and Dynamics testing

OTIS

- **Complete Flight ISIM plus OTE (OTIS)**
- **Previously Checked GSE**
- **Independently controlled IEC DSERS**

Major Off-Nominal Events during OTE, OTIS Tests

Test	Date	Event	Consequences
OTE Pathfinder		Water pipe break in basement of test complex at JSC	Primary He compressor Train 3 unavailable during event, had to switch to alternate Train 3 use.
OTIS	8/26/2017 through 8/30/2017	Hurricane Harvey hits Houston area. Weather conditions during the hurricane JSC included thunderstorms, tornado watches, flood warnings, and periods of severe rainfall (Houston received ~1270 mm (50 inches) of rain in 4 days).	Extreme care had to be used in transit between hotels and JSC for test personnel. Shifts were extended to 12 hours to minimize travel, some people slept at JSC for a few nights, and active optical testing was curtailed for a time. JSC center was closed for ~9 days to regular JSC employees from the start of the hurricane until facilities could be verified as safe for return. Meanwhile, roof of Building 32 (test building) leaked, resulting in substantial use of plastic sheeting to keep critical electronic equipment in the building and the control center dry and safe. Principal concerns included potential loss of electrical power, and inability to refill LN2 tanks. Loss of power would have resulted in loss of He Train 3, and would have required warming to LN2 temperature. Loss of LN2 would have eventually resulted in full warmup We were fortunate that neither occurred during the Hurricane, as they would have had week(s) of impact to test time. Since we had just entered Cryo-stable phase of test, most test objectives had not yet been met.

Principal OTIS Thermal Test Objectives

Primary Objective of OTIS TV/TB test was considered verification of optical requirements, but included many other tests. Only one thermal balance point was planned. The five principal thermal objectives defined were:

- **OTIS Temperature Limits and Constraints -** The OTIS temperature limits and constraints shall conform to the requirements found in OTIS Limitations and Constraints Implementation Plan.
- **Boundary and Influence temperatures -** The test shall verify at thermal balance the element-to-element and key subsystem boundary temperatures and interface temperatures and/or rates as specified in OTIS Thermal Operation Document
- **Thermal Model Validation -** The test shall verify OTIS system thermal workmanship, and provide thermal balance test data to validate the OTIS thermal model.
- **Model Validation Tolerances - ** The data collected shall be sufficient to validate the models consistent with the numerical requirements found in JWST Systems Analysis and Model Validation Plan
- **OTIS Heat Strap Workmanship Test -** The test shall perform a workmanship thermal conductance assessment of the flight SI heat straps in the OTIS test configuration at operating temperatures.

Thermal-Applicable Limitations and Constraints

<u>Source Document: </u>"OTIS JSC Constraints & Limitations Implementation Plan"

- **<u>Constraints</u>** are put in place to avoid actions, conditions, or events, which if realized, will result in <u>damage</u> to flight hardware.
- **<u>Limitations</u>** are put in place to avoid actions, conditions, or events, which have the potential for <u>temporarily impacting performance</u> or resulting in <u>loss of test time</u>.
- Several Hundred L&C's divided into two groups
  - Thermal Applicable – Monitored and alarmed by OTIS Thermal Team (**<u>92 total</u>**)
    - **<u>84 Constraints</u>**
    - **<u>8 Limitations</u>**
  - Non Applicable - Not monitored by OTIS Thermal Team
- Most thermal constraints and limitations were designed to avoid contamination, overstressing of structural elements and instruments. They defined absolute temperature limits, rates of change, gradients within structures, instruments, and temperature relationships between instruments, optics, thermal boundaries, usage of heaters

OTIS Susceptibility to Off-Nominal Events (1 of 2)

- **Large temperature range of components**
  - Electrical boxes in IEC: 278K
  - Near IR instruments, instrument detectors: 36.5K - 42.8K, Mid Infrared Instr.: 6.2K
  - Flight radiators: 30K-40K;
  - Telescope optics generally in the 40K-60K range.
  - GHe shroud, other thermal boundaries: 20K, LN2 shroud: 80K
- **Complexity of GSE**
  - 16 individually controlled GHe flow valves: 7 for shroud, 9 for individual DSER's & thermal boundaries plus supplemental heater circuits for precise temp. control
- **Nominal cooldown from ambient to steady state cold planned over 3 weeks**
  - To control stress in mechanical components (rate limitations, gradient restrictions).
- **Nominal warmup planned over 3 weeks**
  - Nominal warmup carefully choreographed, reliant on precise thermal control of shroud, multiple thermal boundaries, instruments. N2 frozen on He shrouds

    released at ~27K - 34K, caused pressure increase which changed heat transfer mechanism to FMHT, causing rapid temperature and gradient changes, with possible effect on structural component integrity. Large number of rate, gradient C&L's identified.

OTIS Susceptibility to Off-Nominal Events (2 of 2)

- **Contamination from water moisture, particulates, molecular contaminants** a major concern
  - Sensitive optics in telescope and instruments must be warmer than surroundings during warmup, cooldown to avoid water and molecular contaminants collecting on critical surfaces. Key instrument, optical temperatures kept close to each other during critical parts of transitions to avoid cross-contamination.
- **Extremely high value flight payload**
- **Long test duration 93 days, very high test cost**

Pre-Test Preparations for Off-Nominal Events (1 of 3)

- **Extensive preparations made during test planning and development:**
  - Critical power supplies, test data, control systems on UPS, diesel generator circuits;
  - spare power supplies/temperature measurement equipment available;
  - redundant flight/test sensors identified, added to control heater circuits;
  - Pre-test checkout of JSC facilities (N2 system, He compressors, control software).
  - Test GSE checked to assure proper operation and safety of payload during off-nominal conditions.
  - Roof repairs made to Building 32 (Chamber A, cleanroom, control room)
  - Alternate control room in Building 30 prepared and checked.
  - MIRI heater procedures updated
  - IEC DSER helium lines modified to be controlled individually – could provide both cooling, and could also be shut off and warmed with heaters within 3.5 hours to protect IEC electronics boxes if flight heaters on IEC failed. Was also used to protect IEC in warmup.
  - Backup SC simulator moved next to primary unit, in case primary unit failed. Backup simulator could be activated within 1 hour.

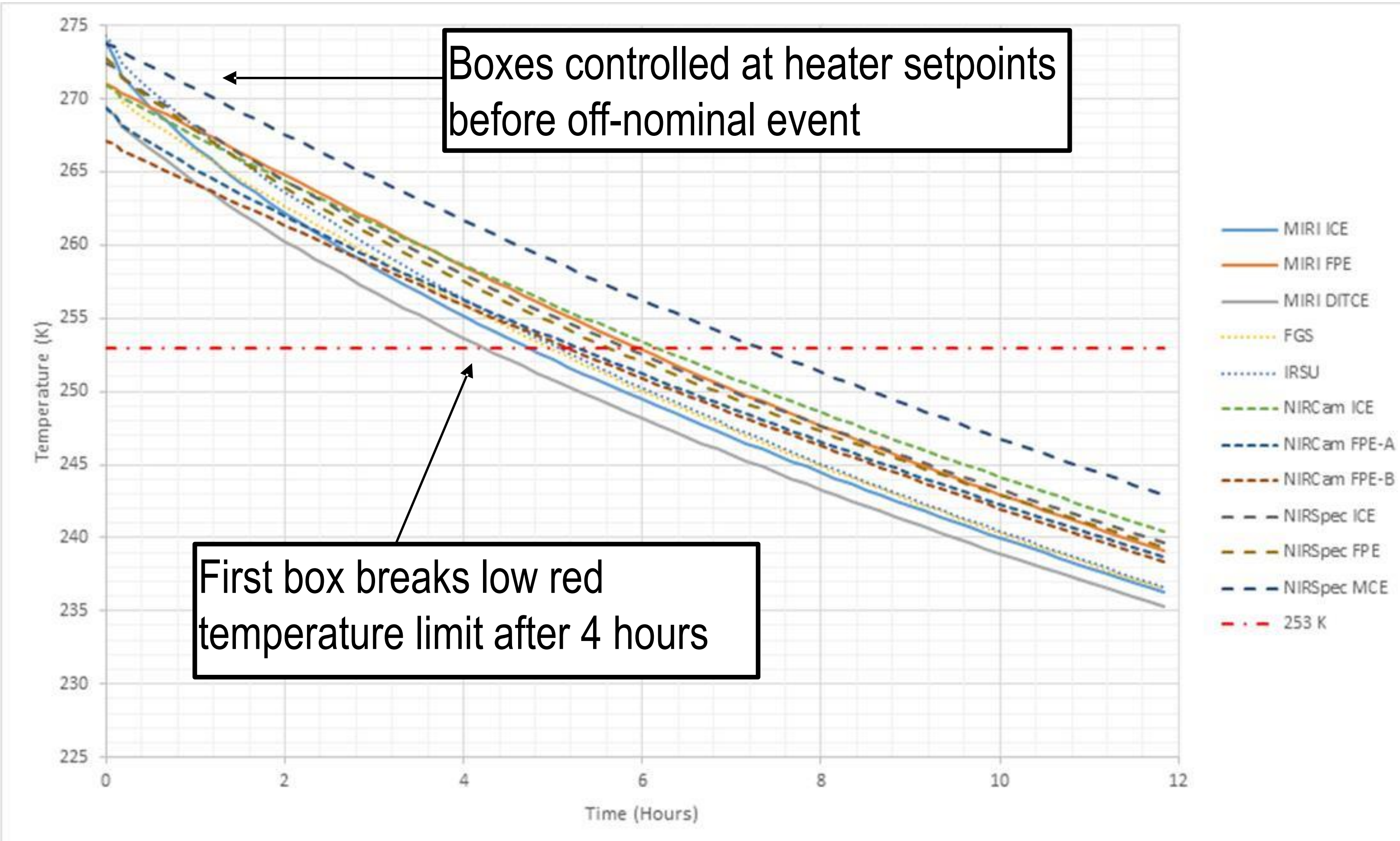
Pre-Test Preparations for Off-Nominal Events (2 of 3)

- **Critical test control equipment covered with plastic sheeting** prior to test start to protect from potential water damage if water leaked into building.
- **Potential for hurricanes was identified early on**
  - Volunteer Hurricane Rideout Team and Recovery Team members identified and took required FEMA training. Rideout team members took physical exams.

Pre-Test Preparations for Off-Nominal Events (3 of 3)

- **Thermal staffing shift schedule**
  - Established for entire anticipated test period prior to test start.
  - Multiple thermal engineers on shift 24/7 throughout test, with “floaters” (experienced senior thermal engineers with background in JWST) always present in Houston area, ready to assist and replace scheduled shift support if necessary.
  - Thermal support personnel undertook test support and safety training.

Example: IEC Electronic Box Temperatures after Failure of Flight Heaters with DSER at 20K (SC simulator failure)



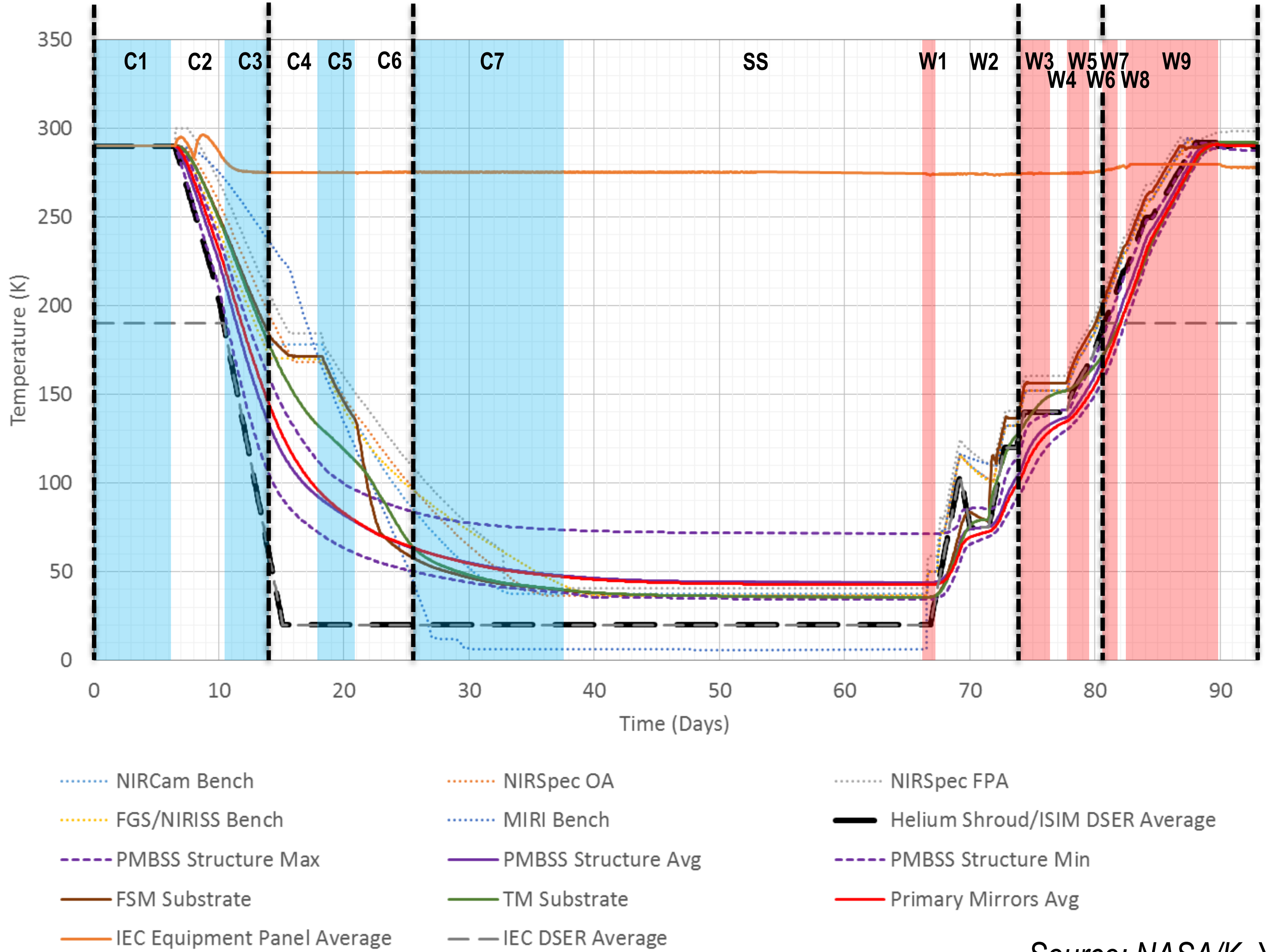
Source: NASA/K. Yang

Additional OTIS Off-Nominal Planning

- **Subsystems directed to perform extensive planning for off-nominal events, to assure safety of personnel and flight hardware.**
- **Payload thermal developed OTIS Off-Nominal Thermal Consequences and Mitigations Workbook.**
  - Excel spreadsheet, reviewed/approved by GSE thermal, facilities, Flight systems teams, identified the following 10 major events, and developed mitigation actions to be taken by Payload thermal, GSE thermal, facilities, test director, depending on test thermal state (see next page):
    - Partial Loss of Vacuum pumps;
    - Loss of LN2 System;
    - Loss of He system-Train 1 – CPP;
    - Loss of He system – Train 3-Shroud, DSERs;
    - Loss of SC Simulator;
    - Loss of IRSU;
    - Loss of Eclipse;
    - Loss of the Thermal Test Set (TTS) data system;
    - Loss of the Fusion data system;
    - Loss of Facility Electrical Power (Loss of both Helium refrigerators. partial loss of vacuum pumps);
    - Emergency safing procedure (minutes to prepare for safing);
    - Safing procedure if 48 hours notice available (i.e., hurricane)

Entire workbook is too detailed to show, but 48 hour safing procedure shown as example

Off-Nominal Phase Correspondence to OTIS CV Test Thermal Model Predictions



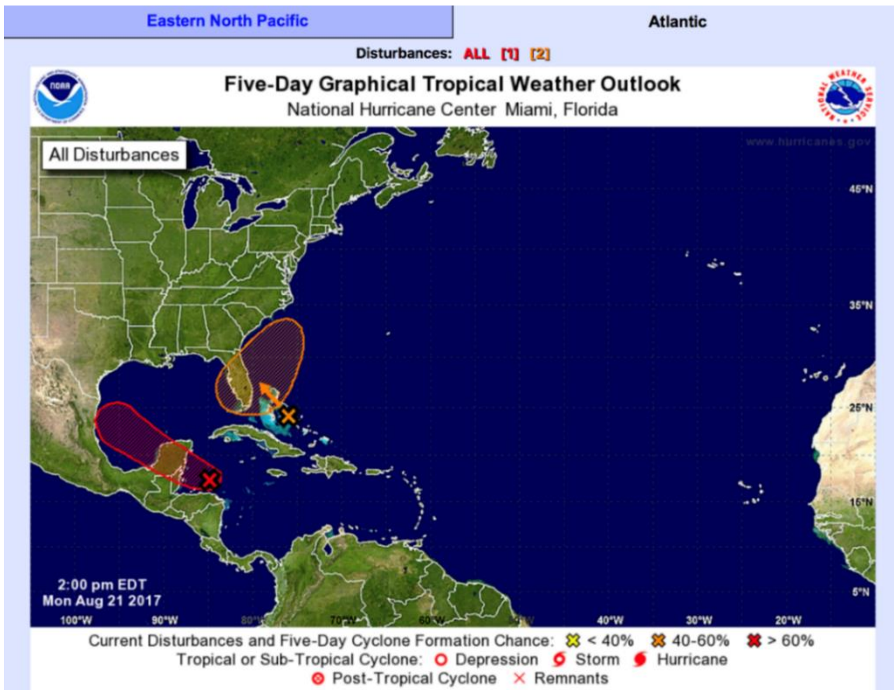
Source: NASA/K. Yang

Example of Actions Taken During Weather Event: 48-Hour Safing

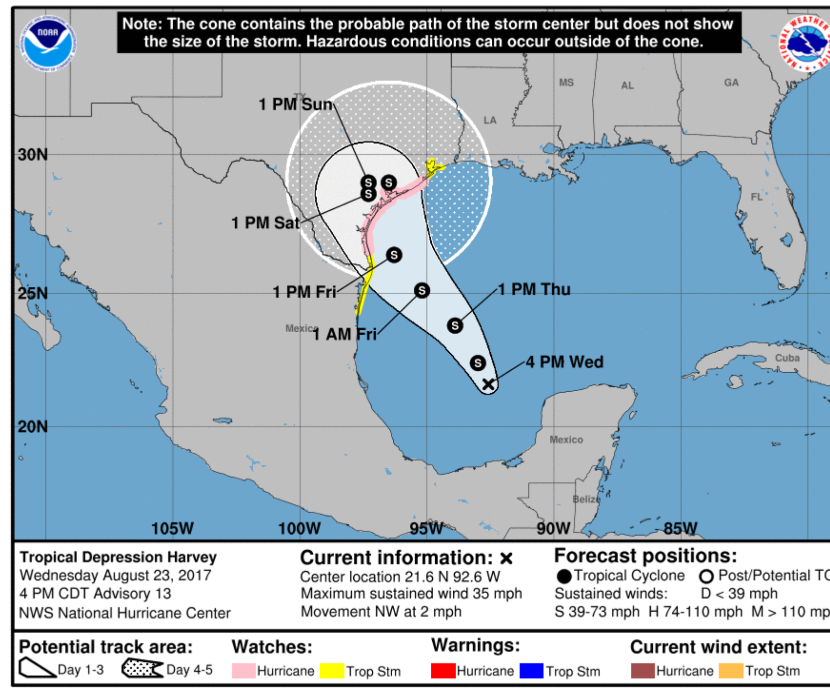
Test Phase	Description	Safing Goal Temp	Facility	Flight Payload / Spacecraft Simulator	GSE
C1	Pre-Test or Post-Test Ambient Temperature Vacuum Testing	Return to Ambient	Follow warmup plan for 2 days (if not at ambient). Start by Isothermalizing LN2 and Helium shroud, then warm both as much as possible towards ambient. Bring IEC DSER line ambient.	Follow warmup plan for 2 days (if not at ambient). Leave IRSU and SC Sim on to read temps, but turn off all payload heaters and SIs after 2 days. If evacuation is necessary, turn off IRSU and SC Sim.	Follow warmup plan for 2 days (if not at ambient). Maintain IEC DSER temp until ISIM heaters and SIs turned off, after which raise IEC DSER temp to ambient. If evacuation necessary, turn off all GSE heaters.
C2	Cooldown: Before shroud reaches 175K				
C3	Cooldown: Before SIs cool to ~ 175K				
C4	Cooldown: Near-IR SIs in process of being held within 5K, waiting for MIRI	Cool all Payload and He Shroud to LN2 Shroud Temp (90K)	Burp N2 off He shroud and CPPs if applicable; bring He shroud to LN2 shroud temp (~90K), keep LN2 shroud flooded. Coordinate with GSE thermal for IEC DSER control.	Keep IEC survival heater setpoint at 278K. Turn off ISIM heaters if ISIM Tube max < 140K. Leave IRSU and SC Sim on to read temps, but turn off all payload heaters and SIs before 48 hrs reached. If evacuation is necessary, turn off IRSU and SC Sim.	Control FSM, TM, SM gradients with heaters. Maintain IEC DSER temp until ISIM heaters and SIs turned off, after which raise IEC DSER temp to 273-293K. L3Harris to decide which GSE heaters to leave on to safeguard GSE/payload.
C5	Cooldown: SIs being stepped down through water contamination band (140K-170K)				
C6	Cooldown: After Near-IR SI heaters turned off, SIs allowed to cool, MIRI > 40K				
C7	Cooldown: After Near-IR SI heaters turned off, SIs allowed to cool, MIRI < 40K	Achieve LN2 Shroud Temp (90K) on all Payload and He Shroud	When SIs are all >45K, burp N2 off He shroud and CPPs. Then, bring He shroud to LN2 shroud temp (~90K), keep LN2 shroud flooded. Coordinate with GSE thermal for IEC DSER control.	Keep IEC survival temp setpoint at 278K. Warm MIRI using GSE heater >45K if necessary, then use heaters if needed to bring SIs to 80-90K keeping within constraints. Leave IRSU and SC Sim on to read temps, but turn off all payload heaters and SIs before 48 hrs reached. If evacuation is necessary, turn off IRSU and SC Sim.	Use TM, FSM, SM heaters to aid warmup. Maintain IEC DSER temp until ISIM heaters and SIs turned off, after which raise IEC DSER temp to 273-293K. L3Harris to decide which GSE heaters to leave on to safeguard GSE/payload.
SS	Steady-state Cryo-stable conditions				
W1	Warmup: SIs to 45K and Shroud to 40K (N_2 migrates to CPPs)				
W2	Warmup: MIRI > 45K and He shroud warming to 140K (SIs being warmed by their heaters)				
W3	Warmup: Shroud plateau at 140K before second (major) N_2 burp when CPP warmed > 30K	Cool all Payload and He Shroud to LN2 Shroud Temp (90K)	Follow cooldown plan for 2 days to bring He shroud to LN2 shroud temp. Keep LN2 shroud flooded (~90K). Coordinate with GSE thermal for IEC DSER control.	Bring SIs to 80-90K. Keep IEC survival temp setpoint at 278K. Leave IRSU and SC Sim on to read temps, but turn off all payload heaters and SIs before 48 hrs reached. If evacuation is necessary, turn off IRSU and SC Sim.	Control FSM, TM, SM gradients with heaters. Maintain IEC DSER temp until ISIM heaters and SIs turned off, after which raise IEC DSER temp to 273-293K. L3Harris to decide which GSE heaters to leave on to safeguard GSE/payload.
W4	Warmup: During N_2 burp at 140K (SIs > 140K, Payload ~140K)				
W5	Warmup: Payload in water contamination band (140K-170K)				
W6	Warmup: During H_2O burp off shroud (Payload ~170K, SIs > 170K)				
W7	Warmup: After H_2O burp, He shroud warming to 220K	Warm to ambient	Follow warmup plan for 2 days, then bring LN2 shroud to He shroud temp and turn off temp control. Leave scav plates flooded. Coordinate with GSE thermal for IEC DSER control.	Follow warmup plan for 2 days, then turn off SIs and heaters. Keep IEC survival temp setpoint at 278K. Leave IRSU and SC Sim on to read temps, but turn off all payload heaters and SIs before 48 hrs reached. If evacuation is necessary, turn off IRSU and SC Sim.	Follow warmup plan for 2 days. Maintain IEC DSER temp until ISIM heaters and SIs turned off, after which raise IEC DSER temp to 273-293K. Use TM, FSM, SM heaters to aid warmup. L3Harris to decide which GSE heaters to leave on to safeguard GSE/payload.
W8	Warmup: Shroud plateau at 220K before molecular contamination band				
W9	Warmup: 220K to ambient through molecular contamination band				

Early Warnings for Hurricane Harvey

Hurricane forecasts were monitored daily throughout OTIS CV test. Initial warnings of possible Hurricane Harvey impacting Houston area were seen ~5 days before landfall



Source: NOAA/National Hurricane Center, Ref. 6



Source: NOAA/National Hurricane Center, Ref. 6

Monday, August 21st, 2017

Wednesday, August 23rd, 2017

Initial Preparations for Hurricane Harvey

(Photo Credit: L. Feinberg)

- By Friday, August 25, Project had purchased 40 air mattresses, set up in conference rooms
- Project had stockpiled food rations for several days

- Potential effect on personnel more severe than blizzard during ISIM CV3 test, since most test participants were non-resident in Houston area and had to fly in from around the US and world to staff test.
- Plans made to extend shifts to 12 hours to minimize travel to/from hotels
- Hurricane Ride-out team members were identified, prepared to stay at JSC
- Hurricane safing procedures reviewed, plans to deal with individual system failures printed (on laminated paper)

Dealing with Harvey: Initial impacts - Saturday night into Sunday morning, August 26/27

Weather conditions

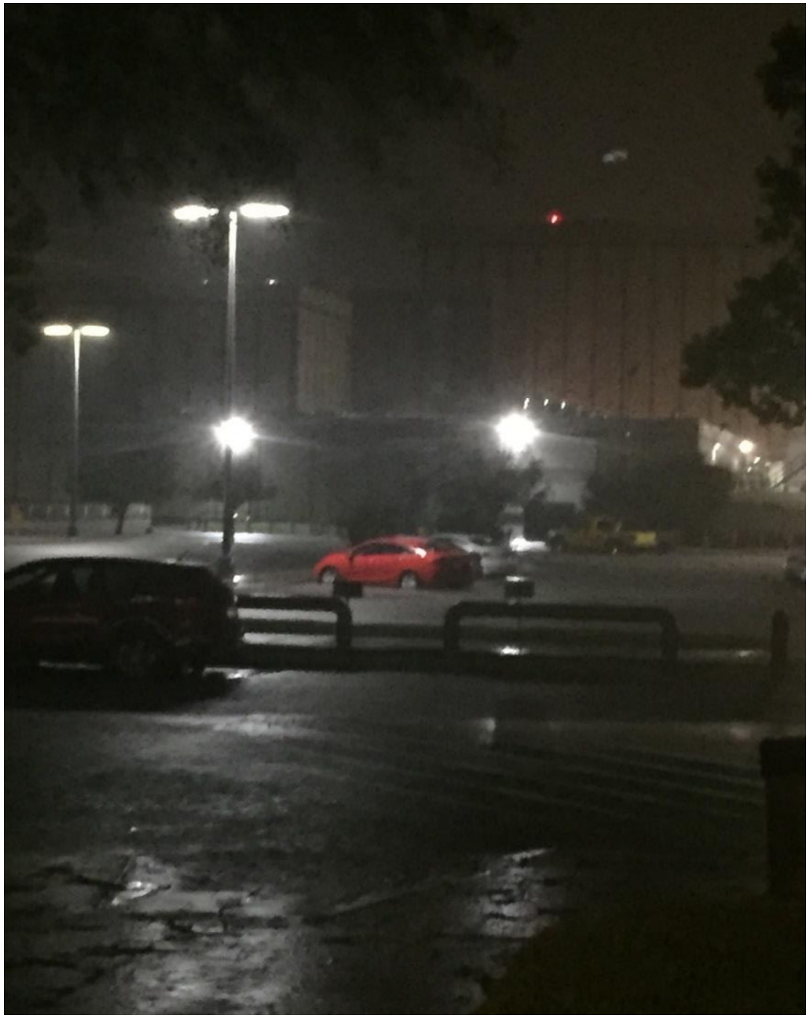
- ~20 inches of rain ***overnight*** at JSC, 45-50 inches total in Houston area (over 4 days)
- Flash flooding, storm, and tornado warnings all night

Impacts to personnel, JSC

- Extremely hazardous travel, several experienced test support personnel called in to JSC prior to landfall in case Center access became impossible
- Only JSC entrance was closed for several hours due to flooding

Impact to Test

- OTIS test continued, but optical testing temporarily curtailed



JSC Parking Lot B32 (Photo Credit: L. Feinberg)

Dealing with Harvey: During, after Landfall

Water Damage in B32 OTIS Control Room, despite pre-test roof repairs

Plastic Sheeting installed to Protect control computers and data stations

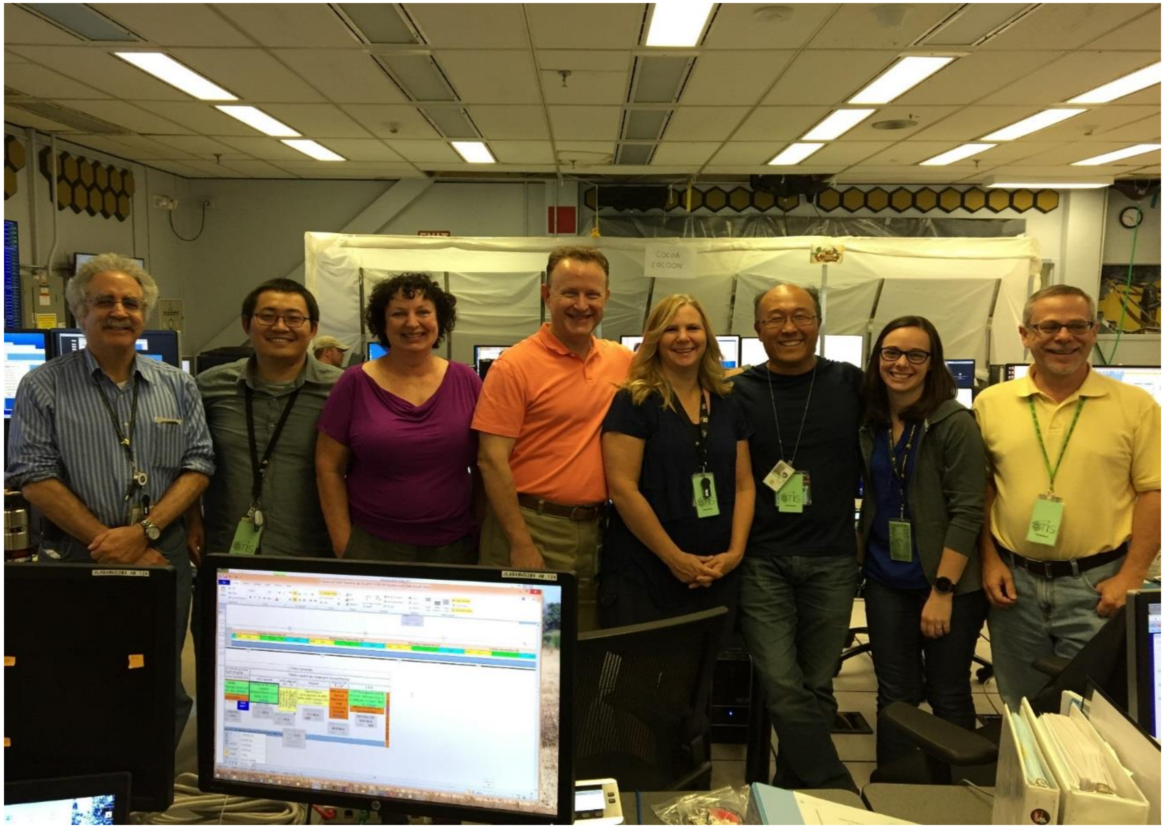
Dealing with Harvey: Several Days after Landfall

- Hurricane was slow moving, bands of intense rainfall, winds persisted for 4 days
- Carpools organized using high ground clearance trucks/SUV's to ferry personnel to/from hotels because of local road flooding
- 12 hour shifts until local flooding eased
- Road flooding in Houston prevented timely LN2 deliveries for ~ 3 days (only had 5 days reserve on-hand before LN2 shroud would warm, causing premature test warmup). Great efforts made to bring in LN2 from alternate supplier
- Fortunately, JSC area did not lose commercial power, which would have resulted in premature test end
- Commercial air travel from local airports was impacted for several days after the hurricane. NASA GSFC, NGAS, BATC made special arrangements to provide replacement test support crews

(Photos Credit: L. Feinberg)

Acknowledgement for All Test Teams

- The authors wish to acknowledge the hard work and dedication of the Project and Test Directors, Payload Thermal, GSE Thermal, Contamination, Cryo Support, Instrument, Optics, Facilities, and all other support teams for a successful test.
- Payload Thermal support team on shift during Hurricane Harvey shown below



Recommendations for Off-Nominal Test Planning

Enhance personnel and flight hardware safety with appropriate planning:

- Low hanging fruit should always be addressed:
    - Provide spares for critical GSE power supplies, make sure personnel trained to replace them
    - Provide/install redundant sensors for controlled heaters, and redundant GSE heater circuits
    - Provide/install backup power supply for critical thermal boundaries, power supplies, test measurement equipment, data systems, control electronics, facilities, to allow continued testing or safe test end (UPS, diesel generator)
    - Make sure well trained test support personnel available to replace scheduled shift personnel in case of illness, accidents
    - Prior to major thermal vacuum tests, projects should list potential events and their effects, and evaluate risks of failures of GSE, flight hardware, flight software, facilities, utilities, personnel evacuations, etc. in terms of impact to flight hardware damage and potential programmatic impact for repairs; schedule; cost. Project must be willing to accept remaining risks.

Make as many facility, utility provisions as robust as possible. Demonstrate pre-test (without risking flight hardware).

Even if certain potential facility or utility failures cannot be prevented, evaluate potential damage, devise test workarounds or emergency procedures

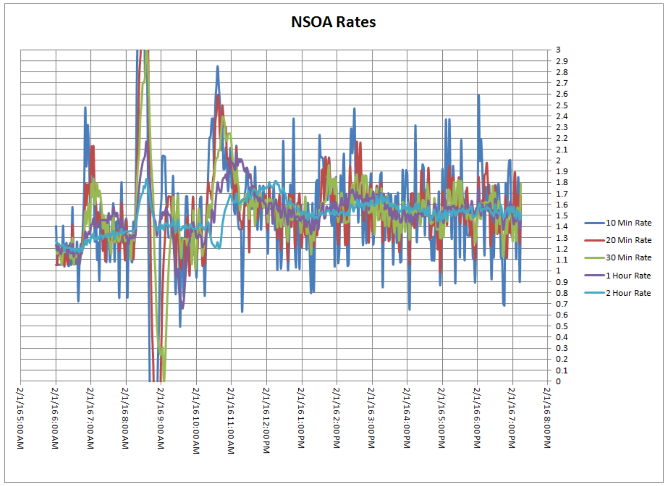
Lessons Learned and Applied

Lessons Learned and Applied: Hardware

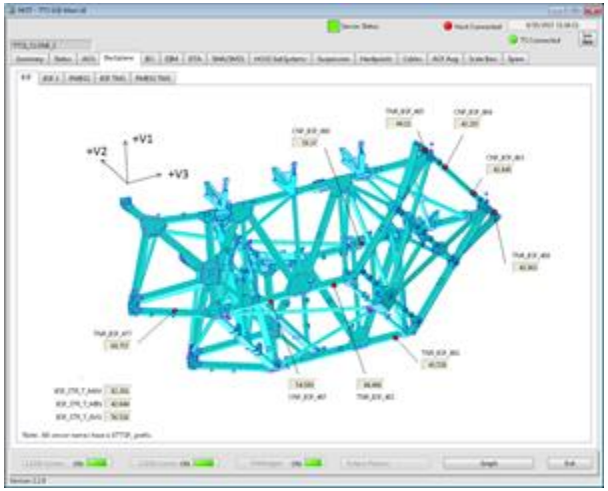
- In large tests such as this one, ensure there are enough sensors to evaluate thermal stresses, provide thermal distortion model crosschecks, and understand the heat flows and physical phenomena at thermally-critical interfaces
- Critical components (especially ones where L&Cs are based upon) should always have temperatures sensors
- Flight heater setpoints should be made as easily modifiable as possible in the flight software
- When possible, heaters on mirrors should be placed directly on the mirror structure itself
- A cryogenic flight system with on-off heater control (“bang-bang”) should be avoided

Lessons Learned and Applied: Thermal Analysis and Monitoring Software

- In cryogenic test transient cooldown and warmup predictions, use of a greater number of temperature-dependent emissivity sets is critical to accurately predict hardware behavior
- Plan for high gas load contingencies in modeling, analysis, and test design, and especially analyze for the effects of gas heat transfer during GHe backfill, critical points in the test (such as the “burp”), and unexpected chamber leaks
- User-friendly test monitoring software is critical for tests as complex as OTIS CV



Screenshot of Fusion Software
Source: Genesis ESI/Brian Comber



Screenshot of L3Harris TTS Data Acquisition System
Source: NASA/L3Harris Corp.

Lessons Learned and Applied: Test Planning and Management

- **Train your team on what to monitor, and ensure that this is all properly captured and documented while on shift**
  - For example, a runaway heater can have devastating consequences if not captured early!
- **Test limitations & constraints should always be defined based on measurable data, and it is absolutely necessary that every temperature sensor needs to have a red and yellow limit preprogrammed in**
- **Define test management rules when hardware is near red and yellow limits**
- **Develop a test plan that rigorously burns down risk**

Post-Test Milestones

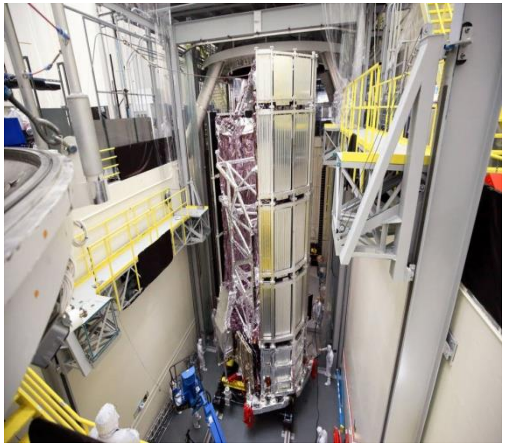
POST-CRYOGENIC TEST GLAMOUR SHOT

JWST's OTIS at NASA's Johnson Space Center Chamber A

Source: NASA/JWST/ Chris Gunn

Final Integration and Testing

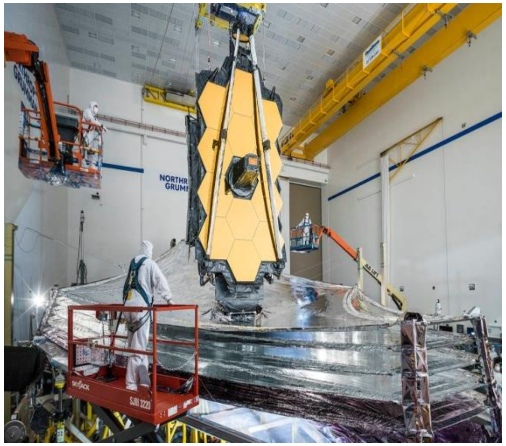
Feb 2018: OTIS is transported from Houston, TX to Redondo Beach, CA for final JWST integration



May 2019: Spacecraft Element Thermal Vacuum Testing Complete

Aug 2019: OTIS is joined to the Sunshield and SCE, completing the assembly of the JWST observatory

Oct 2020: Acoustic and Vibrational Testing complete for JWST Observatory



Dec 2020: Final sunshield deployment test complete

Mar 2021: Final Comprehensive Systems Test (CST) Complete

All pictures courtesy of : NASA,/JWST/Chris Gunn

Preparations for Launch!

- JWST arrived at the launch site in Kourou, French Guiana via ship on October 12th, 2021!
- JWST was folded up to fit inside the Ariane 5 Launch Vehicle fairing
  (“The world’s most complex piece of origami”)

Arianespace’s ELA-3 launch complex

near Kourou, French Guiana

The MN Colibri Arrives with JWST in the port of Kourou, French Guiana
Source: NASA/Chris Gunn

JWST is unloaded from the MN Colibri
Source: NASA/Chris Gunn

86

Launch and Orbit

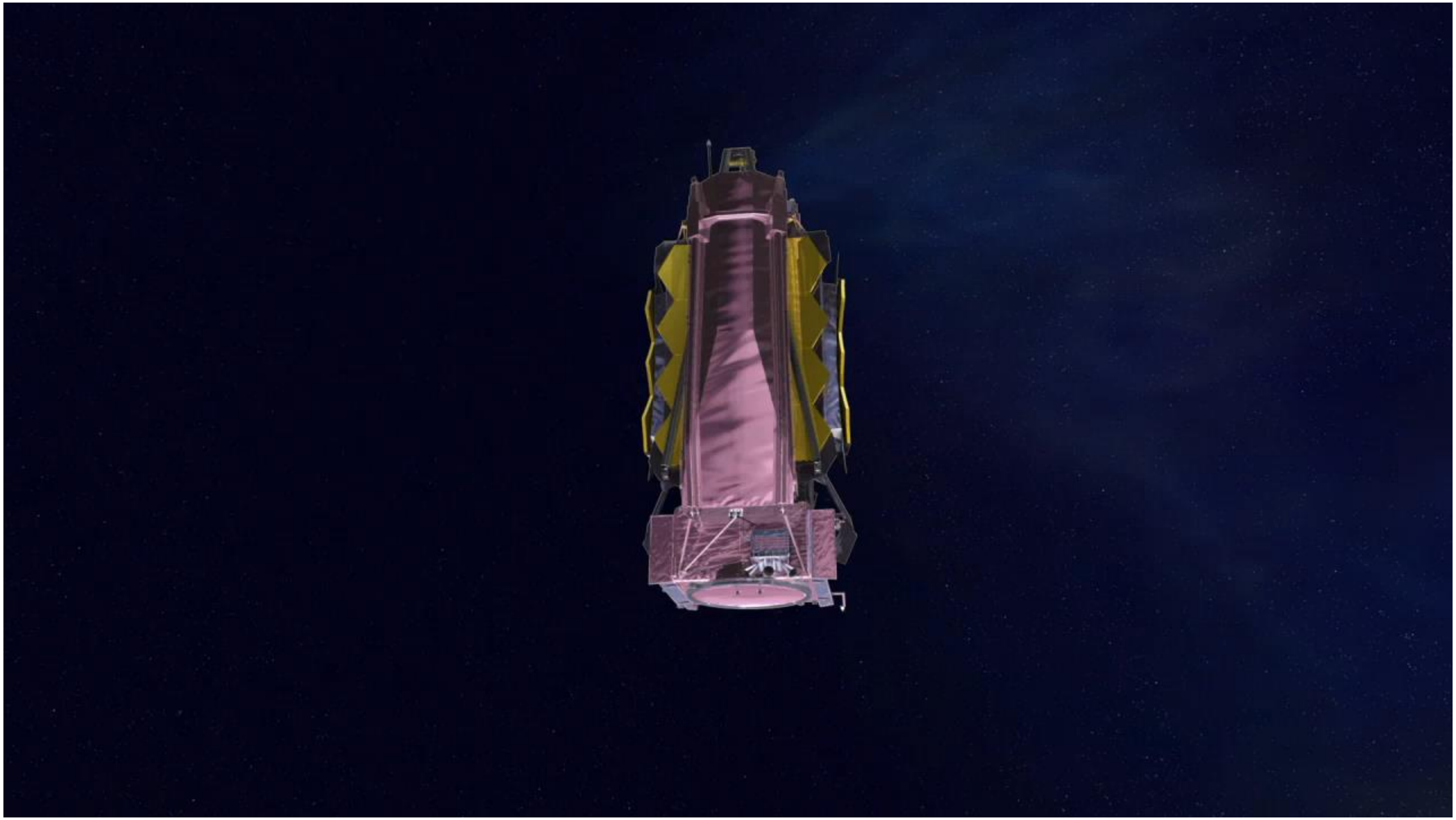
Webb was launched on top of ESA's Ariane 5 on December 25th, 2021

It journeyed 940,000 miles / 1.5 million km to its destination at L2, four times the distance from the Earth to the Moon

Webb went through 178 separate motions to unfold in space while it was on its way to L2

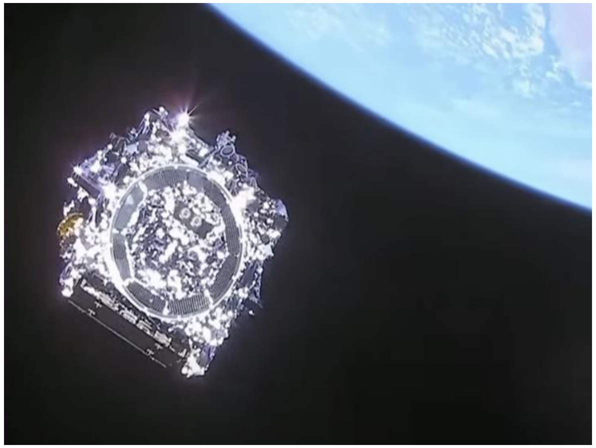
Photo credit: ESA

On-Orbit Deployment



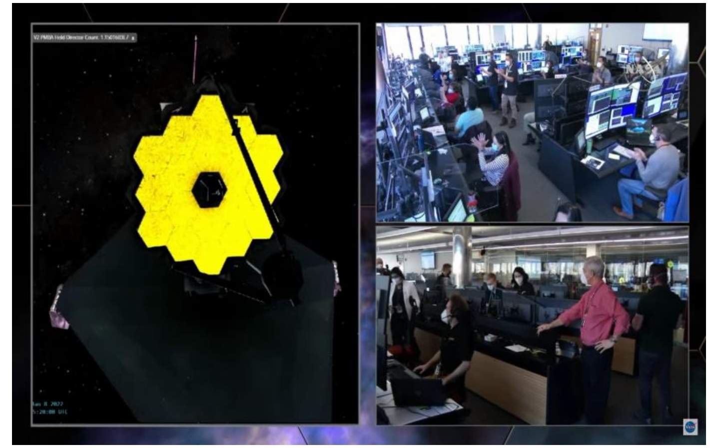
Source: NASA/JWST

Highlights from JWST Commissioning

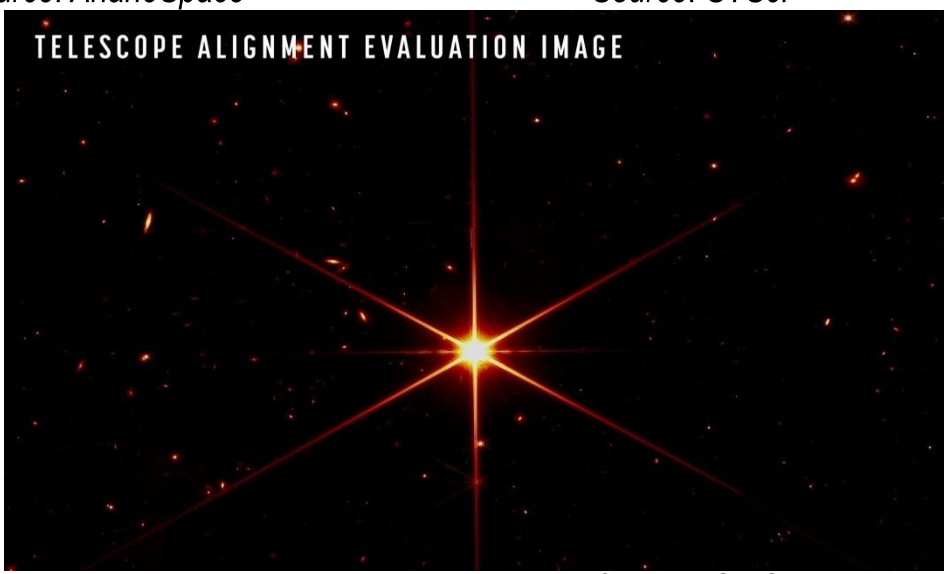


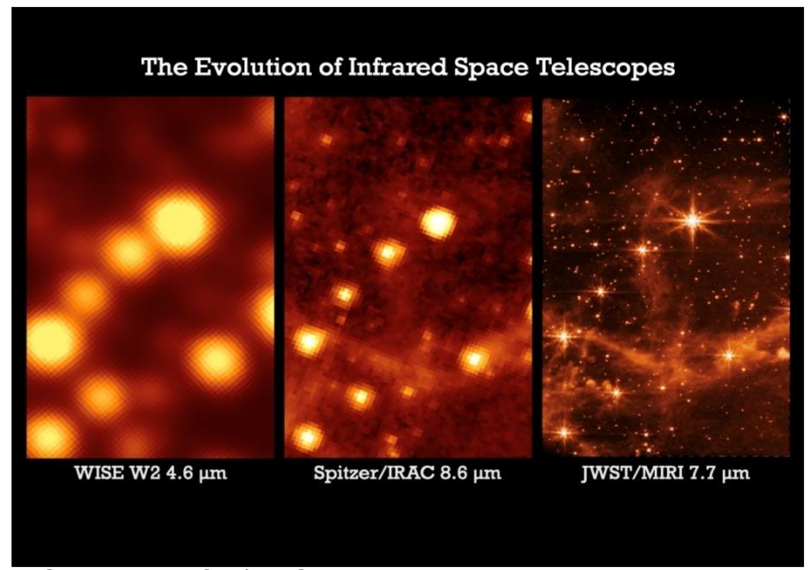
Separation from the Ariane 5 Launch Vehicle, Dec 25th, 2021
Source: ArianeSpace

JWST Mission Operations Center in Baltimore, MD
Source: STScI



Completion of all major deployments at the Mission Operations Center on January 8th, 2022
Source: NASA TV





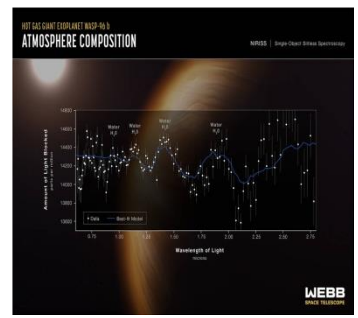
Pictures from JWST Commissioning, Source: NASA/JWST

JWST First Images: July 12th, 2022!

“Cosmic Cliffs” in the Carina Nebula

Stephan’s Quintet

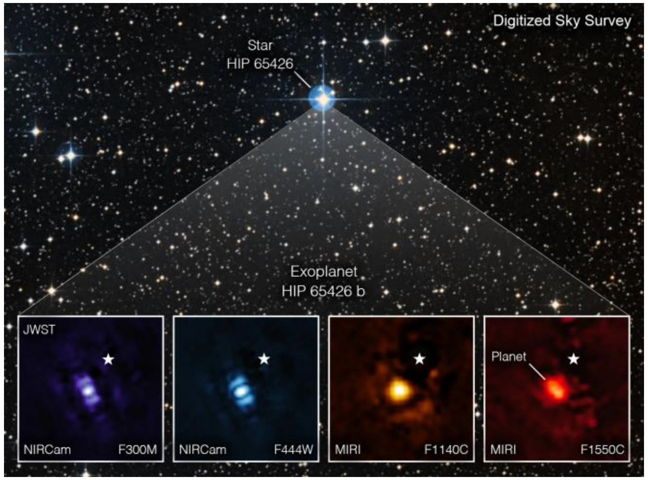
Southern Ring Nebula



WASP-96b

SMACS 0723

The Year Since!



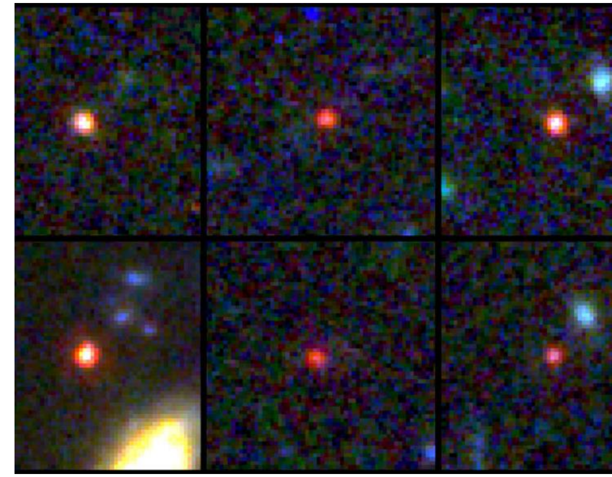
Exoplanet HIP 65426 b


The New York Times

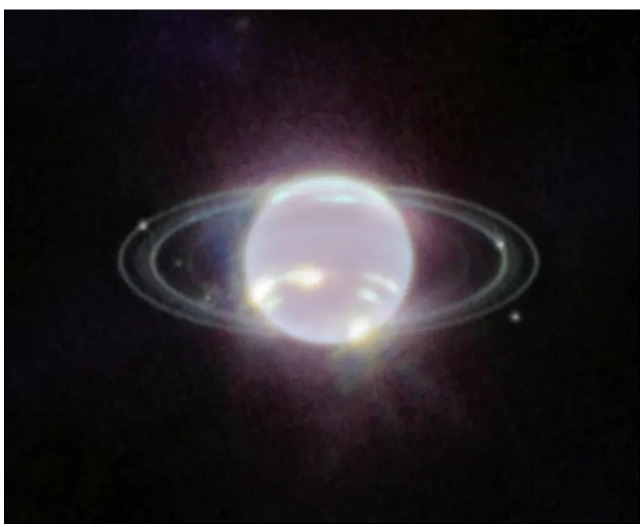
From the Depths of Space to the Walls of a Gallery

The artist Ashley Zelinskie is helping NASA scientists share their work with wider audiences.

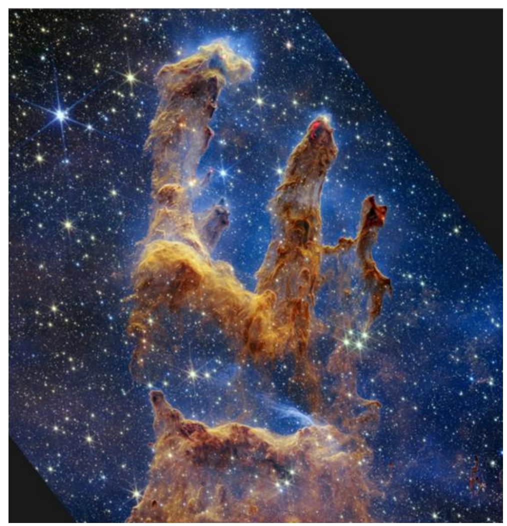
JWST Art Exhibit Feature in the New York Times



Six of the most distant galaxies, which appear too massive based on current models



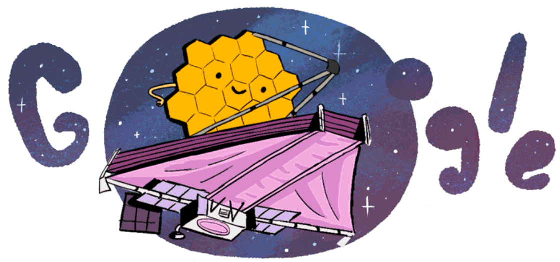
Neptune

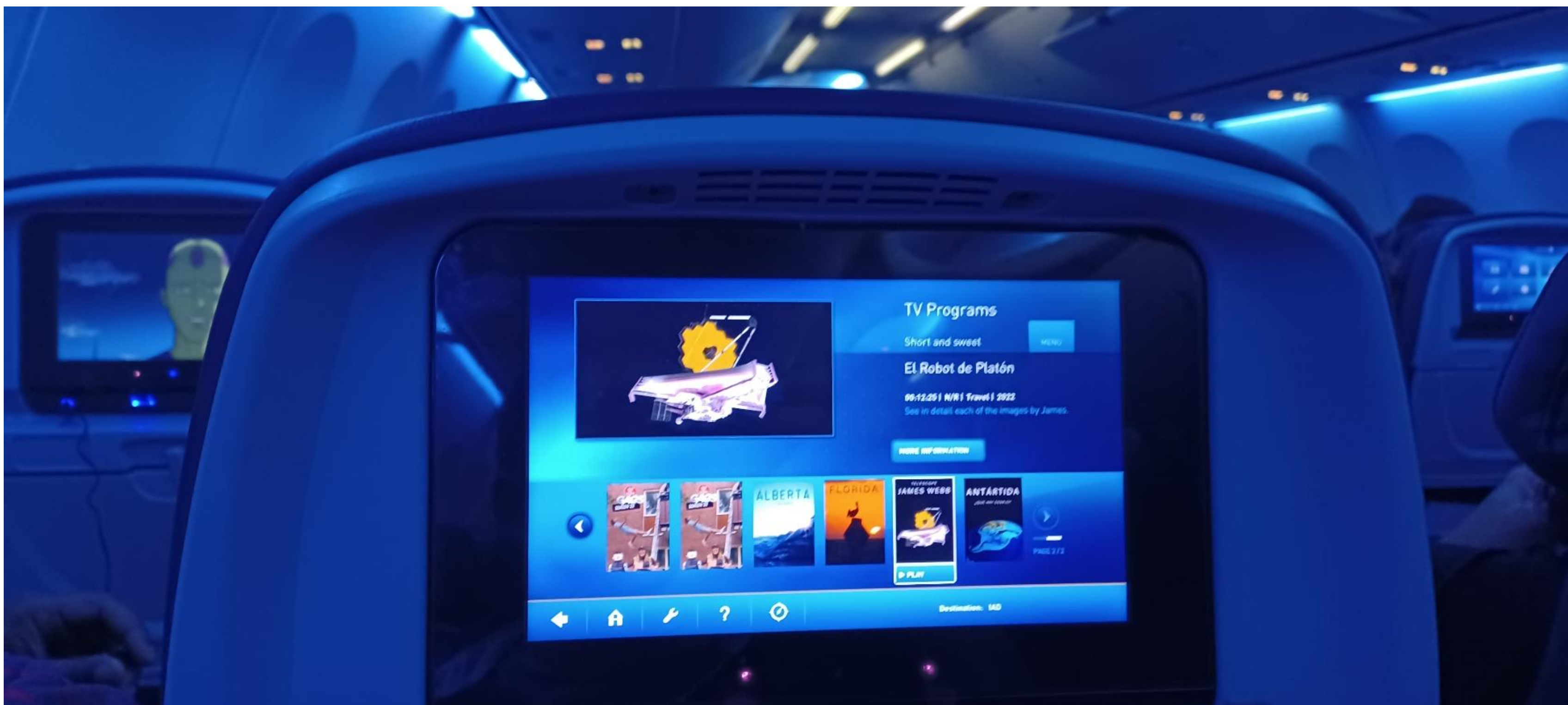


"Pillars of Creation"

JWST 1st Anniversary Image: Rho Ophiuchi

JWST's Widespread Impact





Thank You!

Questions?

Reference: Acronyms (Page 1)

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 (Page 2)

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

References (Page 1)

1. Feinberg, L., Voyton, M., Lander, J., Keski-Kuha, R., and Matthews, G. “James Webb Space Telescope Optical Telescope Element/Integrated Science Instrument Module (OTIS) Status.” *Proceedings of the SPIE.* Volume 9904, id. 990407. 2016.
2. Kimble, R., Apollo, P., Feinberg, L., Glazer, S., Hanley, J., Keski-Kuha, R., Kirk, J., Knight, S., Lambros, S., Lander, J., McGuffey, D., Mehalick, K., Ohl, R., Ousley, W., Reis, C., Reynolds, P., Begoña Vila, M.; Voyton, M., Waldman, M., Whitman, T. “Cryo-Vacuum Testing of JWST’s Integrated Telescope & Scientific Instrument Suite.” *American Astronomical Society.* AAS Meeting 229, id. 238.14. 2016.
3. Kimble, R. “Cryo-Vacuum Testing the James Webb Space Telescope.” Presented at the NASA Goddard Space Flight Center Engineering Colloquium. March 26, 2018.
4. Yang, K., et al. “Thermal Model Performance for the James Webb Space Telescope OTIS Cryo-Vacuum Test .” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018
5. Homan, J. Cerimele, M., and Montz, M. “Creating the Deep Space Environment for Testing the James Webb Space Telescope at NASA Johnson Space Center's Chamber A.” *43rd International Conference on Environmental Systems.* Vail, CO, July 14-18, 2013.
6. Havey, K., Cooke, D., Huguet, J., and Day, R. “Thermal Management of JWST Cryo-Vacuum Test Support Equipment.” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018
7. Huguet, J., Day, R., Havey, K., and Cooke, D. “Thermal Control of Boundaries for JWST Infrared Tests in Cryogenic Vacuum Configuration.” *48th International Conference on Environmental Systems.* Albuquerque, NM, July 8-12, 2018

References (Page 2)

8. Glazer, S., and Comber, B. "James Webb Space Telescope Integrated Science Instrument Module Thermal Vacuum/Thermal Balance Test Campaign at NASA's Goddard Space Flight Center." *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016
9. Park, S., Brinckerhoff, P., Franck, R., Schweickart, R., Thomson, S., Burt, W., and Ousley, W. "Successful Completion of the JWST OGSE2 Cryogenic Test at JSC Chamber-A while Managing Numerous Challenges." *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016.
10. Ousley, W., Burt, W., and Davis, A. "James Webb Space Telescope Cryogenic Thermal Pathfinder Test" *44th International Conference on Environmental Systems.* Tucson, AZ, July 13-17, 2014.
11. Davis, A., Ousley, W., Burt, W., and Cottingham, C. "James Webb Space Telescope Thermal Pathfinder Test Development." *46th International Conference on Environmental Systems.* Vienna, Austria, July 13-17, 2016.
12. Davis, A., Ousley, W., and Burt, W. "James Webb Space Telescope Thermal Pathfinder Test Results." *47th International Conference on Environmental Systems.* Charleston, SC, July 17-20, 2017.