James Webb Space Telescope Integrated Science Instrument Module Thermal Vacuum/Thermal Balance Test Campaign at NASA's Goddard Space Flight Center

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AGENDA

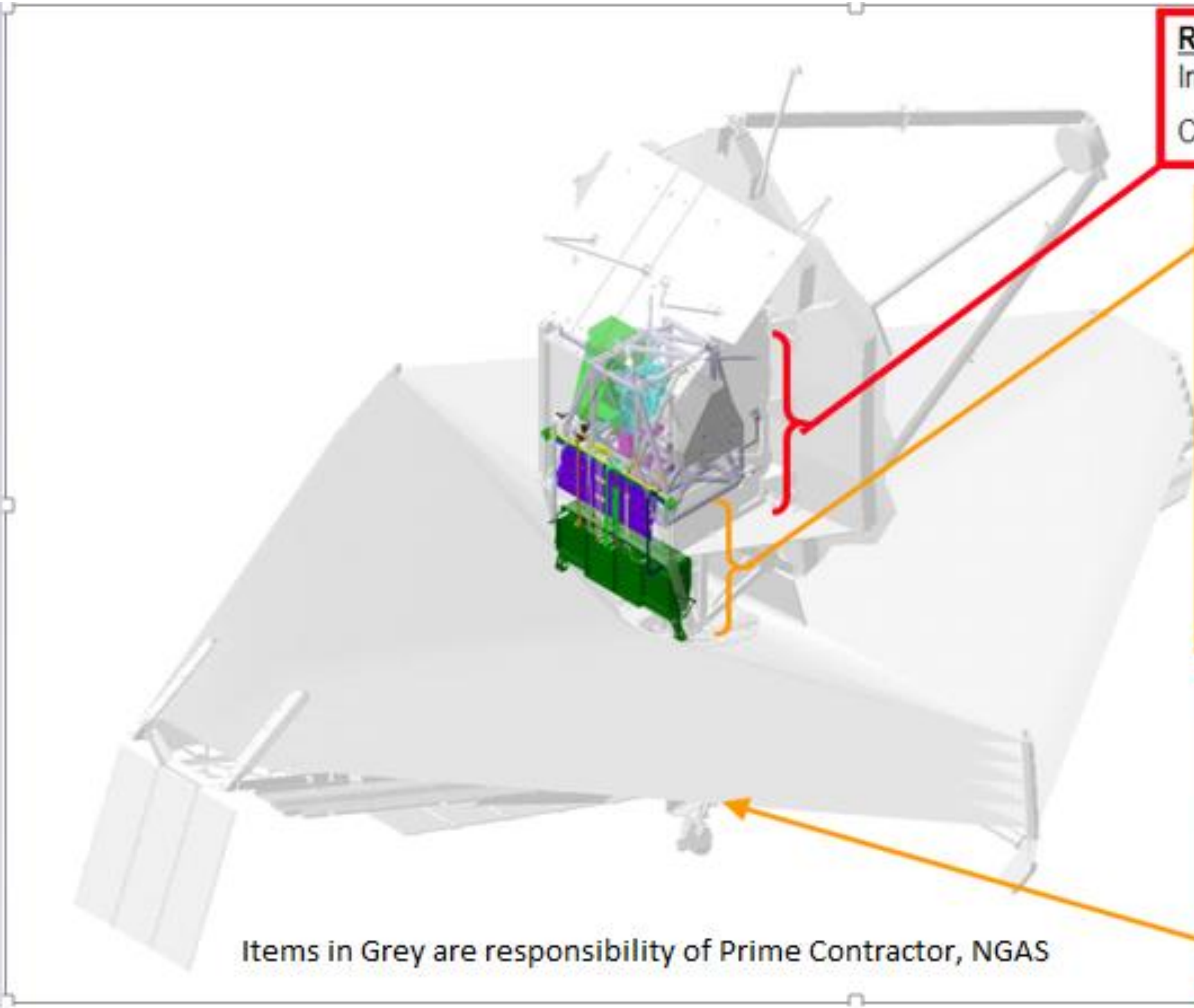
- JWST Background
- Observatory Flight Configuration
- ISIM Configuration
- JWST Facility, ISIM Element Test Program
- ISIM Cryo-Vacuum (CV) Thermal Test Objectives
- Test Complexities
- CV Test Configuration
- Special Equipment Developed for the ISIM CV Tests:
- CV3 Test Profile
- Test Methodology
- Key Test Results
- Lessons Learned
- Acronyms
- Acknowledgements

James Webb Space Telescope - Background

The James Webb Space Telescope (JWST) is a large observatory, designed as a follow-on to the Hubble Space Telescope. Its mission includes study of formation of galaxies and planets following the "Big Bang"

- Launch planned late 2018, into orbit around the second Lagrange point
- Three science instruments passively cooled to 36.5K-43K, located within the cryogenic Region 1
  - Near Infrared Spectrograph (NIRSpec), primarily sponsored by the European Space Agency (ESA) with substantial NASA contribution
  - Fine Guidance Sensor (FGS), provided by the Canadian Space Agency (CSA)
  - Near Infrared Camera (NIRCam), provided by NASA
- One science instrument actively cooled to ~6.2K, also located within Region 1
  - Mid Infrared Instrument (MIRI), jointly sponsored by ESA and the European Consortium (EC). NASA provides the cooler and supplemental hardware for MIRI. The cooler's compressor is located in the ambient temperature spacecraft bus (designated Region 3), outside the cryogenic Region 1
  - Ambient temperature flight electronics located within Instrument Electronics Compartment (IEC), designated as Region 2
- Primary mirror made up of 18 beryllium segments, 6.5-m diameter (deployed)
- NASA's Goddard Space Flight Center (GSFC) is mission lead, and is directly responsible for the Integrated Science Instrument Module (ISIM), including its integration and test
- Northrop Grumman Aerospace Systems (NGAS) is prime contractor, with major contributions also from Ball Aerospace Corporation (BAC).

JWST Design, Thermal Region Definition



Region 1 (~40K) – Instrument Module

Instruments & supporting Hardware

Complex cryogenic environment

Region 2 (~290K) – IEC & HR

ISIM Electronics Compartment:
Instrument ICE & FPE electronics

Traditional Thermal Integration of electronic components within IEC

Harness Radiator:
System for cooling harnessing to reduce parasitics entering Region 1

IEC & HR viewed as "independent" system for purposes of this review

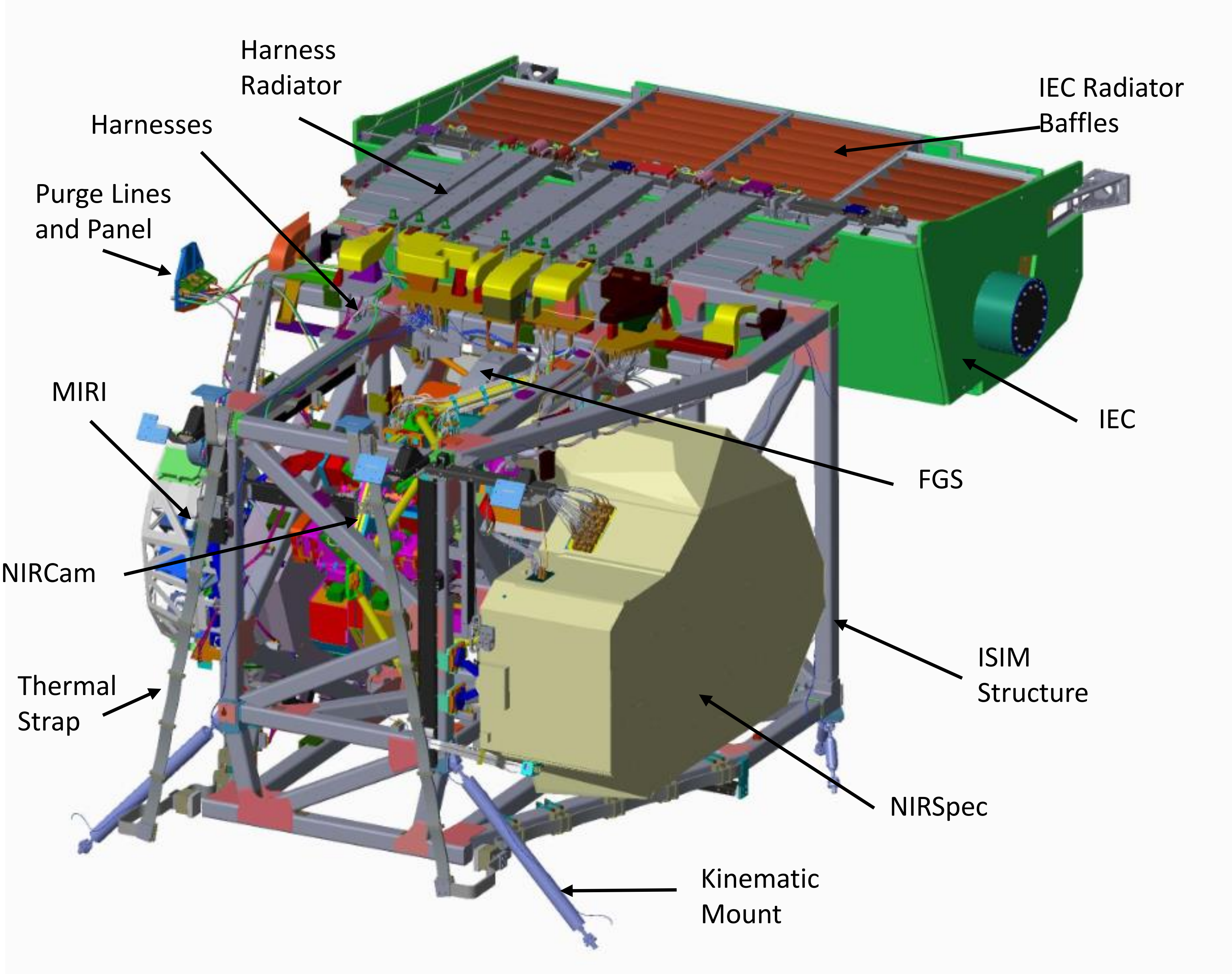
Region 3 (~300K) – S/C Bus

Cryocooler Compressor
Cryocooler Electronics (CCE)
ICDH

Traditional thermal integration of electronic components to NGAS Bus

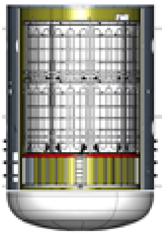
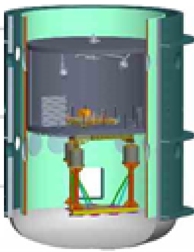
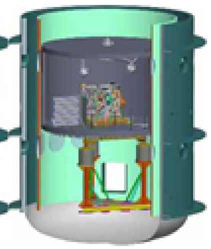
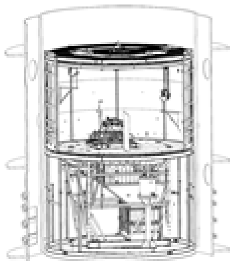
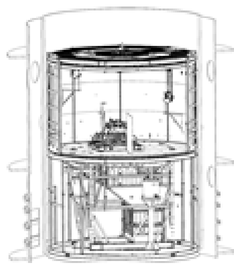
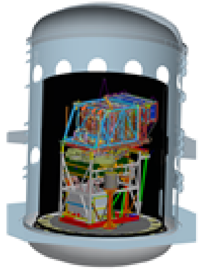
NGAS responsible for integration

Major Design Elements of the ISIM



JWST ISIM Element / Facility Test Program

Test Items – Test Exposure of Items in SES Testing

Tests	 He Shroud Acceptance Test (-03) **COMPLETE 2008**	 Chamber Certification Test (-01) **COMPLETE March 2010**	 ISIM Structure Cryoset Test **COMPLETE May 2010**	 ISIM Structure Cryo-Proof Test **COMPLETE Nov 2010**	 OSIM Cryo-Cal Test 1 **COMPLETE Aug 2012**	 OSIM Cryo-Cal Test 2 **COMPLETE May 2013**	 ISIM Element Cryo-Vacuum Tests (3 tests completed) **CV1: Nov 2013, CV2 Nov 2014 CV3 Feb 2016**
Items in Test	He Shroud (-03)	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP Photogrammetry Fabreeka VIS* MIRI MLI Expmnt Bolometers	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP / MATF Photogrammetry Fabreeka VIS* MIRI MLI Expmnt Bolometers Flight Structure IATF	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP Photogrammetry Fabreeka VIS* Radiometer Flight Structure IATF	He Shroud (-01) Lower GESHA Upper GESHA GIS ITP / MATF Photogrammetry Fabreeka VIS OSIM Baffle OSIM OSIM Shroud BIA SIF/Shroud Support Frame		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
Cycles	1 cycle to 15K B/O to 70C	1 cycle to 15K 1 cycle to 30K B/O to 50C	1 cycle to 39K 1 cycle to 28K B/O to 40C	1 cycle to 28K	1 cycle to 30K (BIA) 1 cycle of OSIM to 100K		CV1: 1 cycle to 43K CV2: 1 cycle to 37K + 43K CV3: 1 cycle to 37K + 43K

* - 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.

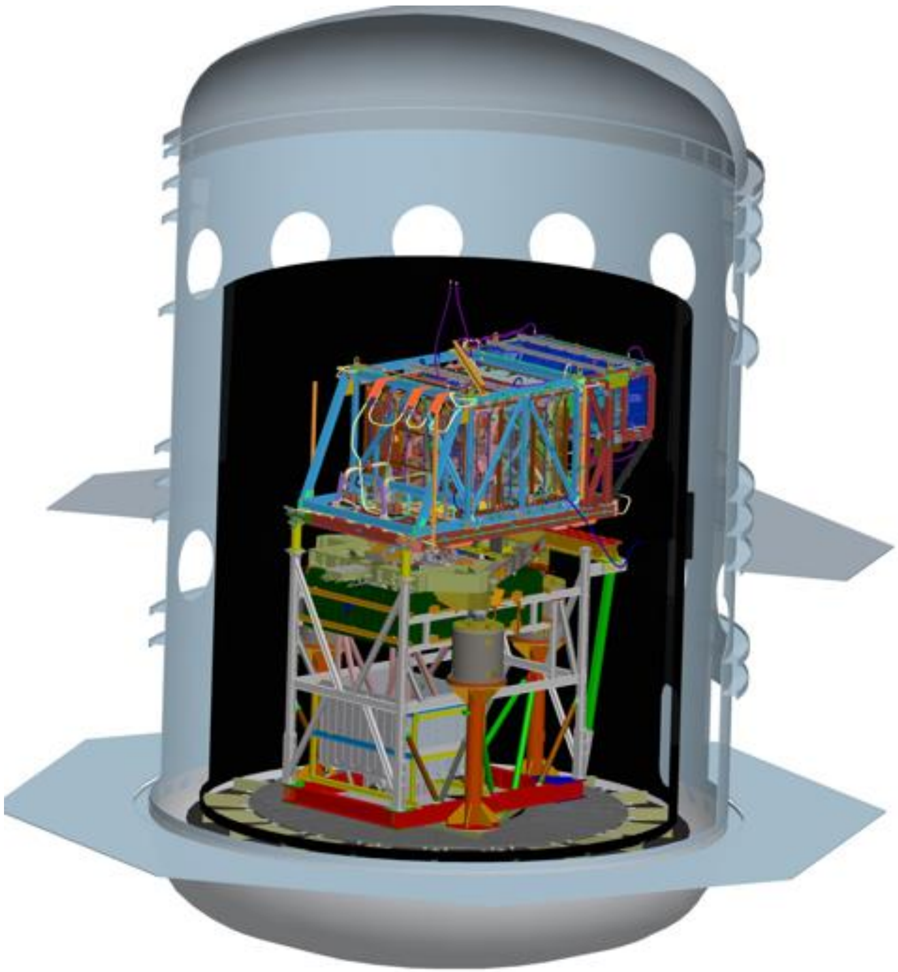
Key ISIM Element Cryo-Vacuum Thermal Test Objectives

- Cryo-Vacuum (CV) tests at GSFC were designed to verify instrument and ISIM optical, electronic, software, and thermal requirements.
- Thermal test objectives of the CV-3 test included:
  - Obtain sufficient data for ISIM detailed thermal model correlation
  - Verify workmanship of Science Instrument (SI) heat straps:
    - Measure thermal conductances, verify they meet requirements
    - Measure temperatures at strap – SI interfaces, verify they meet requirements
  - Verify workmanship of 77/93 flight housekeeping sensors, using the flight ISIM Remote Services Unit (IRSU) and spacecraft simulator
  - Verify NIRSpec, NIRSpec FPA/ASIC, NIRCam, FGS power dissipation in Region 1 meets requirements
  - Verify MIRI optics module (OM) temperature at kinematic mounts (KMs), harness attachment points meets requirements
  - Verify temperatures, gradients at all other SI KMs meet requirements
  - Verify electrical harness heat loads to ISIM from all harnesses meet requirement
  - Verify heat loads through heat straps to all five SI radiators meet high level requirements
  - Verify total heat flow from the harness radiator to the structure meets requirements
  - Measure Cooler heat lift verification of 6K stage
  - Measure MIRI shield heat load
  - Demonstrate functionality of Cooler line decontamination
  - Qualify electronics boxes over operational temperature range (thermal cycling)
  - Observe thermal effect on ISIM from non-nominal conditions and thermal transients:
    - NIRSpec Microshutter anneal
    - Cooler line decontamination

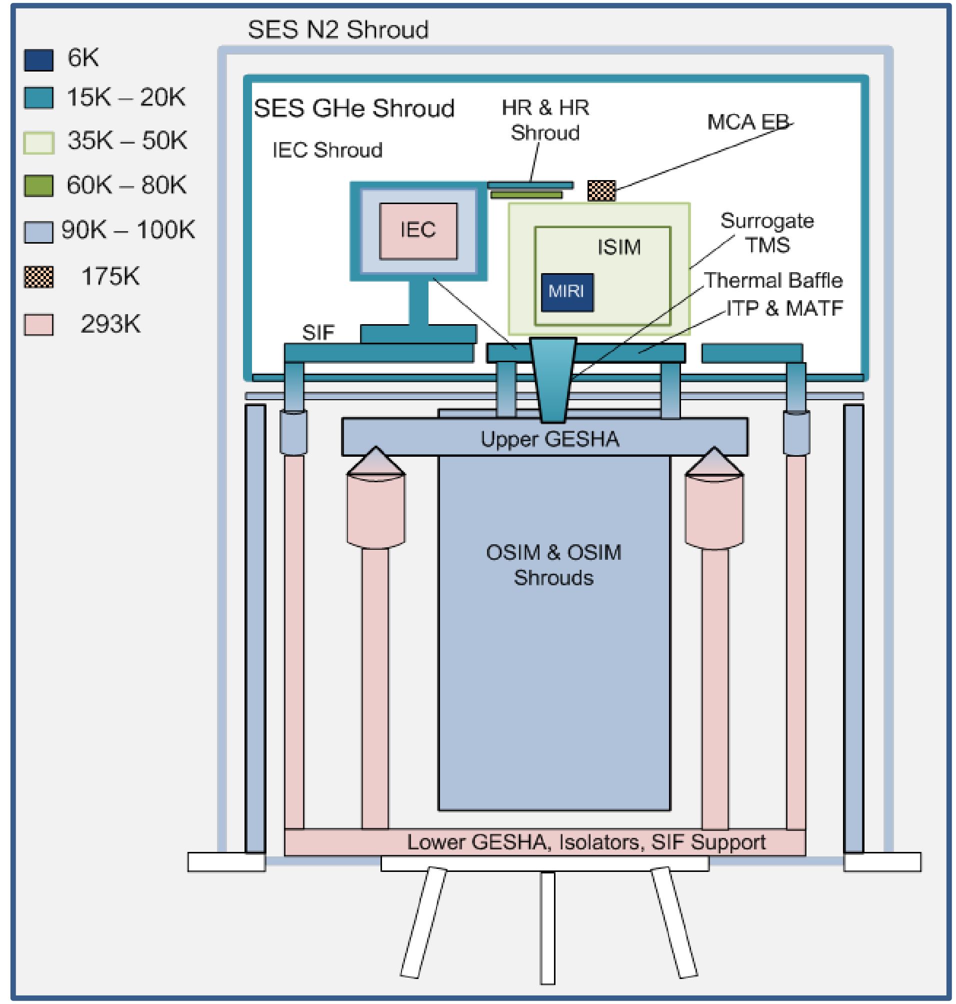
Some Considerations Resulting in Test Complexity

- In transient cool-down, Warmup:
  - Large numbers of constraints and limitations defined:
    - For water, molecular contamination avoidance as instruments passed through specific temperature ranges. These included keeping critical surfaces of SI's within ~5K of each other when water can be released (~140K -170K) during cool-down;
    - Complex strategies developed to control timing of water release from shrouds and cold GSE during warmup, and also nitrogen release (since chamber He shroud and other GSE was operated < 27K). These included operational constraints to prevent arcing by high voltage electronics controlling selected flight heaters during pressure increases caused by water and/or nitrogen release
    - For flight hardware and GSE gradient control
    - Rate limitations on specific elements to control stress due to differential contraction
  - Need to mimic heater algorithms to be used during flight cool-down
  - Control of active, passive cool-down of flight components, GSE with vastly different heat capacities, and in different temperature ranges
- In steady state cryogenic testing / thermal balances:
  - Different temperature ranges and stabilities required (NIR instruments ~40K, MIRI ~6.2K, OSIM ~ 100K, Flight electronics boxes and IEC ~ 278K, He shrouds ~18K)
  - Ability to adjust instrument temperatures as needed during testing with conductive, radiative boundaries, accommodate instrument heat loads without flight radiators
  - Heat loads to radiators are 5 mW < Q < 200 mW, leading to need for measurement accuracy of ~ 2 mW in test
- Overall test duration of 108 days actual

ISIM CV Test Configuration: Overview



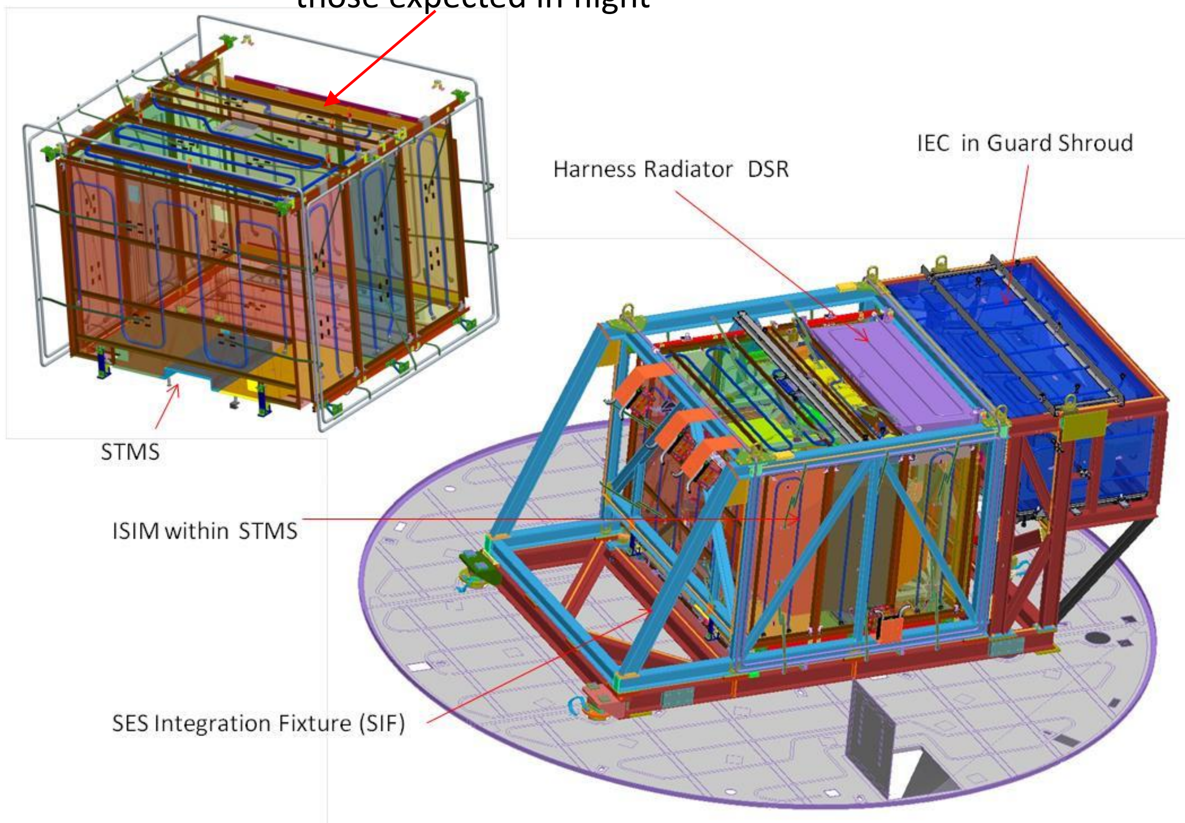
ISIM Payload, GSE, Plus Optical Simulator (OSIM), inside GSFC 8.2m dia., 12.2 m tall Space Environmental Simulator (SES)



General Temperature Ranges Held in ISIM Cryo-Vacuum Testing

ISIM CV Test Configuration: Radiative Boundary

Surrogate Thermal Management System (STMS), provides 12 individually controlled radiative thermal boundaries (zones) around the science instruments (Region 1) to provide thermal gradients similar to those expected in flight

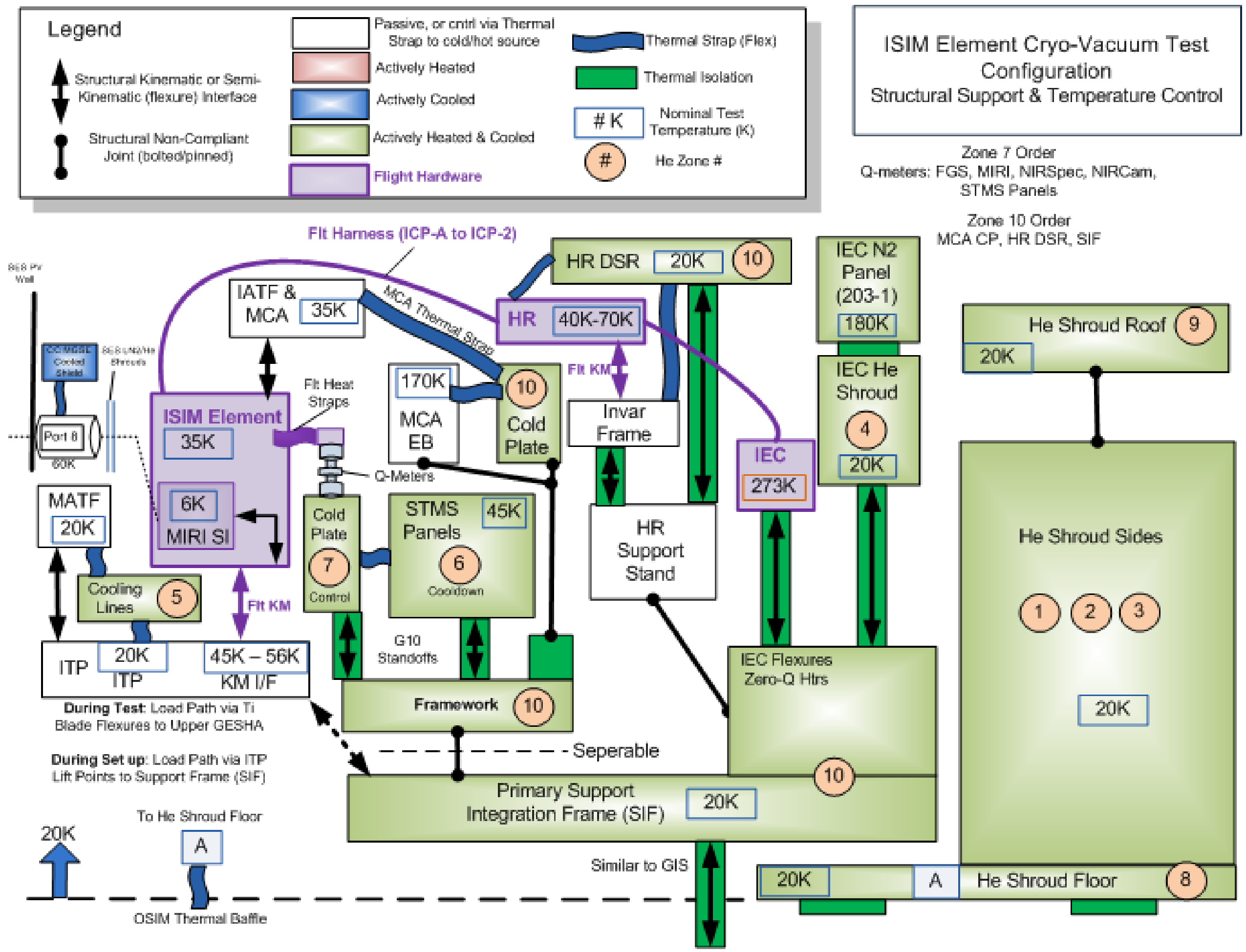


Individual STMS zones plumbed with GHe lines for rapid cool-down, warmup. GHe flow stopped during steady state testing, temperature controlled to within +/- 50 mK of specified temperature using heaters, controllers

"Q-meters" (not shown here) attach to ends of flight heat straps where flight radiators would be located, providing constant temperature conductive thermal boundaries to each instrument, while simultaneously measuring heat flow

ISIM CV Test Configuration: He Flow Zones

- Helium Refrigerator System in SES has 1000W cooling capacity at 20K
- GHe Flow is divided into 10 zones, adjustable from 0% to 100% open in real time
- Primary He shroud uses 5 of those zones, the remainder are assigned to cool key GSE in a manner to facilitate and enhance transient cool-down, warmup, and steady state boundary thermal control



ISIM CV Test Special Equipment: Q-meter

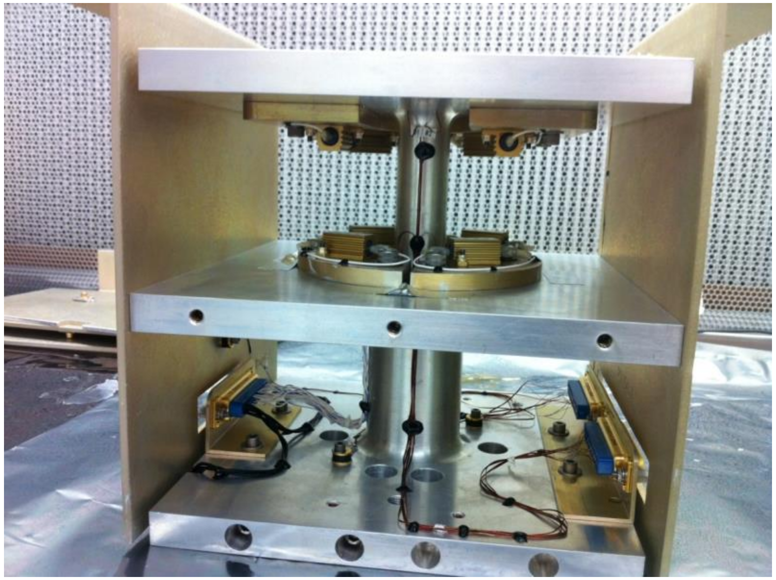
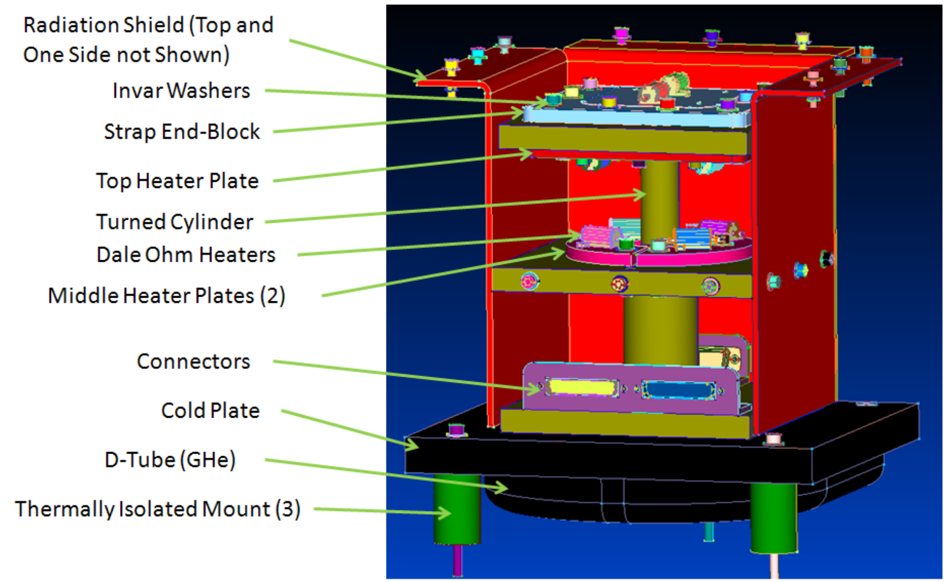
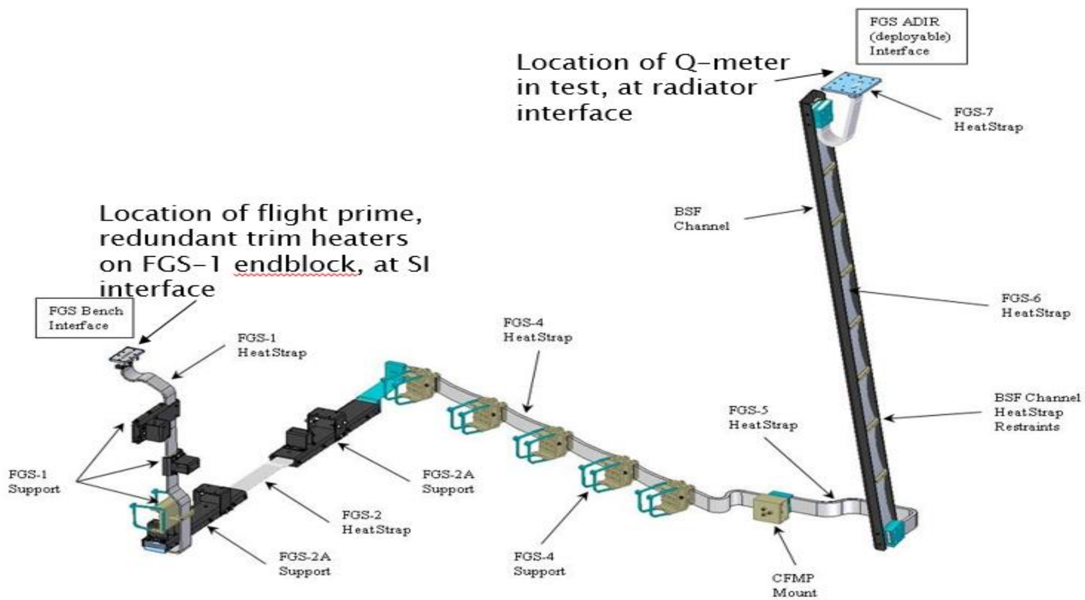


Photo of Q-meter during Initial Assembly



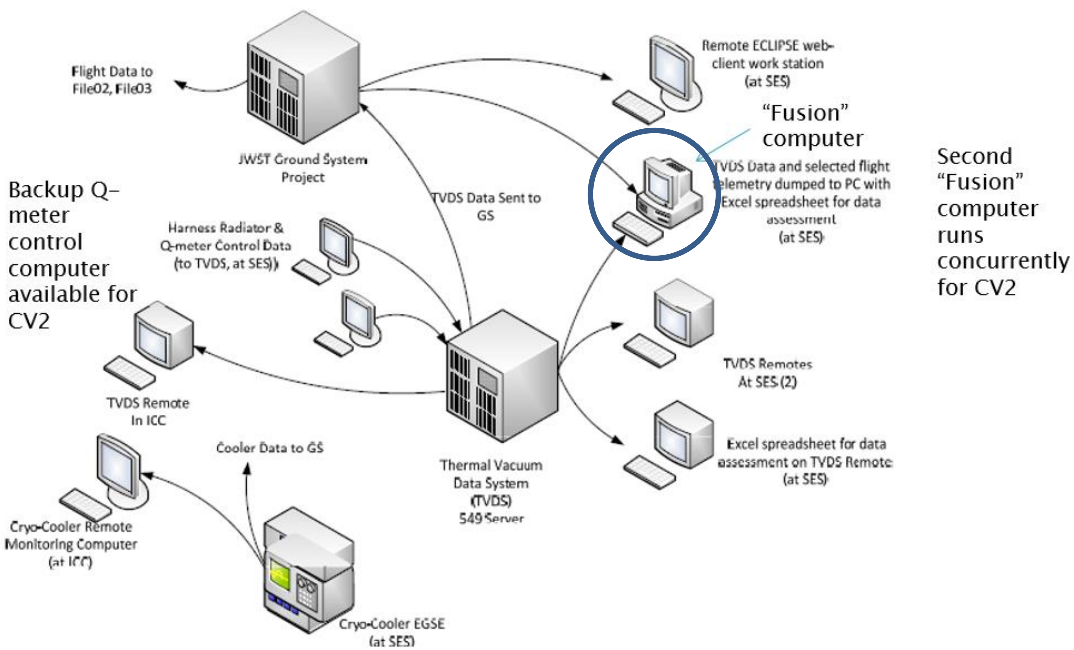
Q-meter Components

Typical mounting location of Q-meters in test (to heat strap at radiator interfaces), and location of trim heaters (on heat strap at instrument interfaces)



ISIM CV Test Special Equipment: Fusion Computer System

- CV tests needed to continually monitor > 1700 sensors, other parameters;
  - Flight sensors, voltages, instrument status, etc. read through S/C simulator and displayed on Eclipse data system;
  - Facility, other GSE temperatures, pressure read out and displayed by TVDS system;
  - Special GSE developed for CV tests: Q-meter instrumentation, harness radiator control and instrumentation read and displayed on local displays
  - Fusion Computer system developed in Excel, to read all data every 2 minutes, monitor compliance with over 100 constraints and limitations pertaining to gradients, rates, and relative temperatures, and if needed, recommend mitigations. The system is extremely flexible and powerful, providing capabilities not available with the older TVDS facility test software. The Fusion software permits plotting in real time, and allows remote monitoring (with VPN).



ISIM CV Test Special Equipment: Fusion Computer System

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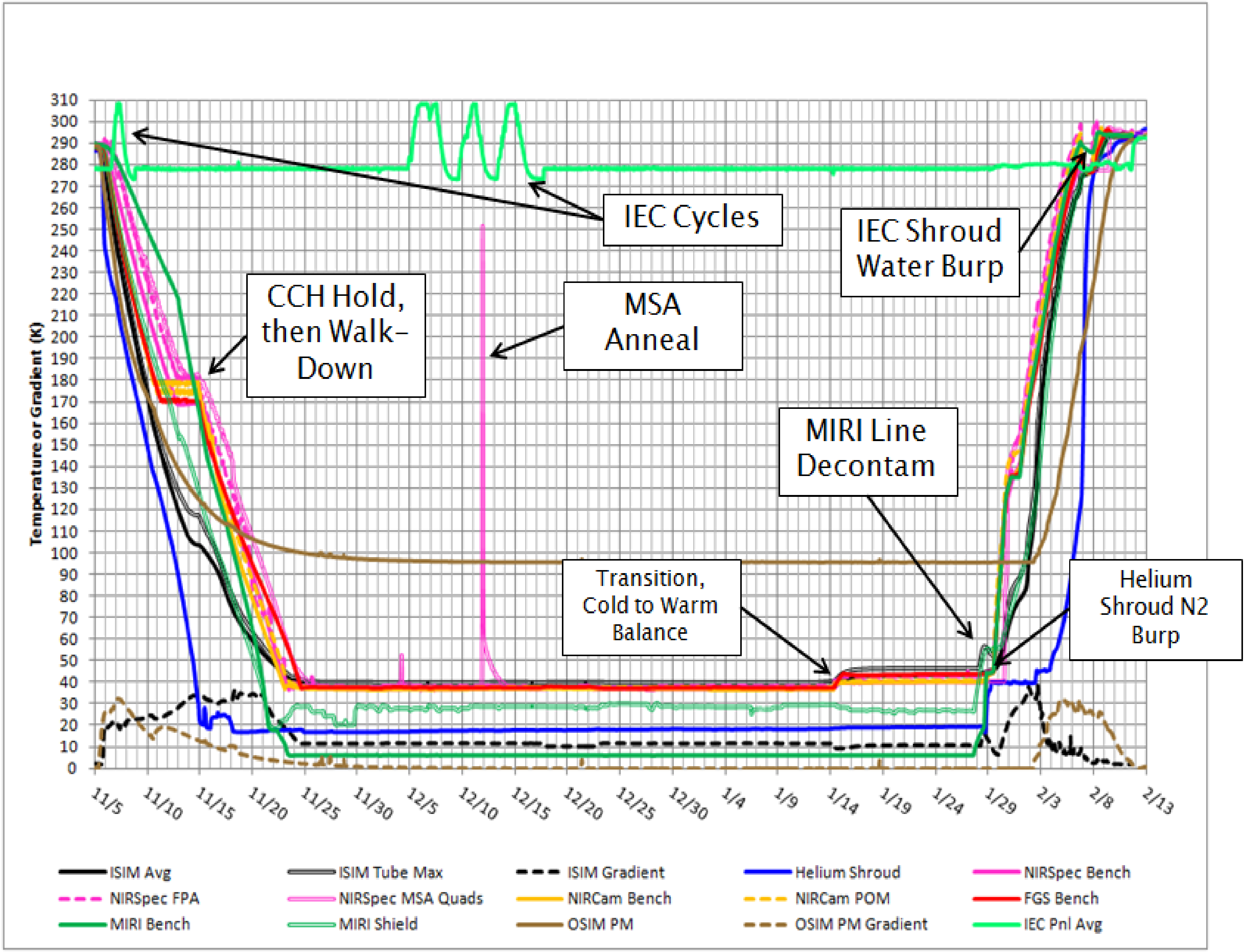
	A	B	C	D
1	No Broken Temperature Limits	Yellow Gradient Squelched		
2	CV3 Monitoring, as of (TVDS):	February 1, 2016	6:16 PM	Eclipse:
3	Remove or add a sensor to the list	Avg (K)	Min (K)	Max (K)
2	IEC NIRSpec Panel 2	279.13	279.13	279.13
3	IEC Shell Temperatures	263.25	244.31	283.59
4		OSIM Items		
5	IATF Structure	91.16		
6	OSIM Primary Mirror (TCs, run cold)	95.72		
7	Mirror Center (PRT - should remain >95K)	97.05		
8	Optical Bench	100.23		
9	FM1	100.35	99.94	100.75
0	FM2	99.00	98.72	99.34
1	FM3	101.38	99.08	104.66
2	PM Bulkhead	101.17	100.11	103.12
3	PM Bulkhead near Spherical Joint Mounts	96.75	96.45	97.03
4	PMB near Spherical Joints	101.58	101.19	102.67
5	PIM Electronics	170.01	170.01	170.01
6	PIM Detector	160.00	160.00	160.00
7	PDI Detector	93.81	93.81	93.81
8	ADM Internal Temperature	296.23	294.09	297.75
9	PDI ASIC Electronics	170.00	170.00	170.00
00	DEB PSM	159.94	159.94	159.94
01	DEB SPM	160.02	160.02	160.02
02	DEB PTM	159.96	159.96	159.96
03	DEB FM3	159.82	159.82	159.82
04	PSM Encoder, Outboard Side (1) - sensor bad, use 4-6 for temps	112.67	112.67	112.67
05	PSM Encoder, Outboard Side (2) - TMP4-6	112.67	112.67	112.67
06	PSM Encoder, Facing PTM (Endboard)	110.61	109.99	111.23
07	PM to Bulkhead Flexure I/F, +V3	97.42	96.73	98.12
08	PM to Bulkhead Flexure I/F, +V2	96.88	96.73	97.03
09	PM to Bulkhead Flexure I/F, -V3	96.69	96.45	96.93

T_Avg_PTE-1017,PTE-1018,PTE-1019

Typical display of part of 1 Fusion system page. Flight and GSE rates, gradients, relative temperatures (min/max) are shown in real time. Control logic and limits can be changed during the test with proper authority. Sensors lost can be deleted from equations in real time.

ISIM CV3 Test Profile



ISIM CV3 Test Methodology

- Complex, highly choreographed cool-down relied on extremely detailed thermal modeling of flight payload, test GSE, chamber, to comply with all constraints and limitations and cool-down objectives.
- At steady state, ISIM radiative thermal boundaries (STMS panels), and ISIM conductive boundaries set to flight predicted temperatures for cold, warm conditions. Q-meters (radiator surrogate) set to temperatures required by instruments in cold, warm flight
- Heat strap conductances, instrument power dissipation determined by set of 3 balances (cold) and 2 balances (warm), which can be done instrument by instrument when convenient:
  - 1. nominal quiescent SI operation, measure Q-meter heat load
  - 2. add known amount of heat with trim heater at SI interface, measure Q-meter heat load. Calculate fraction of heat that transfers to the Q-meter (usually 95-100%, by design)
  - 3. turn off trim heater and instrument.
  - Heat strap conductance = Difference between Q-meter readings of balance #1 and 2, divided by SI temperature rise
  - Instrument dissipation = Difference between Q-meter readings of balance #1 and 3, divided by fraction of known heat that transfers to the Q-meter
  - MIRI heat load to cooler determined with SI off, taking series of steady state balances measuring enthalpy of cooling fluid versus heat load, then extrapolating to determine load with no added heat load.
- Harness heat loads to ISIM measured using GSE embedded sensors within harness bundles, with conductance versus temperature having been measured in test facility pre-test.
- Q-meters also used to determine heat loads during selected events, such as NIRSpec microshutter anneal, and MIRI cooler line decontamination event
- Complex, highly choreographed warmup relied on extremely detailed thermal modeling of flight payload, test GSE, chamber, to comply with all constraints and limitations and warmup objectives. Pressure rise, coinciding with release of water, nitrogen, carefully planned.

Key results from CV testing

Heat Strap Thermal Conductances

Strap Name	Original SDL Requirement @40K (mW/K)	Calculated from SDL Segment Measurements, Normalized to 40K (mW/K)	CV2 Measured, Normalized to 40K (mW/K)	CV3 Measured, Normalized to 40K (mW/K)	MIRI Shield Test 3 Measured Near 20K (mW/K)
NIRCam	269.3 - 336.7	343.2	331.4	333.4	
FGS	98.0 - 158.8	133.2	99.5	92.1	
NIRSpec OA	171.9 - 214.7	336.8	283.3	286.7	
NIRSpec FPA/ASIC	119.1 - 149.9	277.6	198.7	221.7	
MIRI SIIP - Radiator	66.5 -	SIIP 1 to Radiator: 92	N/A	89.4	
		SIIP 2 to Radiator: 58	N/A	57.2	
		SIIP 3 to Radiator: 57	N/A	53.3	
MIRI SIIP - Harness	80 -				
MIRI Shield @ 20K	1000 -				419.0

Electrical Harness Heat Loads to ISIM (Structure plus Instruments)

Harness	Cold Balance (mW)	Warm Balance (mW)	Warm Balance
	CV3	CV3	Allocation (mW)
NIRSpec FPE	5.8	7.7	12.0
NIRSpec ICE	5.1	7.2	6.4
NIRSpec MCE	5.3	9	
NIRCam FPE	5.2	12.7	61.0
NIRCam ICE	16.4	23.5	
MIRI FPE	4.9	7.1	25.0
MIRI ICE	12.9	19.3	
FGS FPE	7.3	9.1	25.0
FGS ICE	10.1	13.2	
IRSU	13.4	21.8	25.0
Total	86.4	130.6	154.4

Instrument Nominal Power Dissipation

Instrument	SI estimate (2011), mW	CV2 Measurement, mW	CV3 Measurement, mW
NIRCam	139.5 – 177.3	148.3	152.7
FGS	44.5 – 53.5	45.3	48.4
NIRSpec OA	~ 4.5	4.5	4.4
NIRSpec FPA/ASIC	31.6 – 35.9	35.1	35.2

Workmanship: 1 of 77 IRSU sensors found to be intermittent, was replaced post CV3 test

Testing Lessons Learned

- **High accuracy heat flow measurement is extremely valuable in hardware design validation, requirement verification. Pay special attention to design detail, careful pre-test calibration. Use instrumentation that provides alternating current to read sensors, to eliminate Seebeck effects**
- **Use/develop test monitoring system so all flight and test sensors and heaters, are monitored, and Constraints and Limitations can be evaluated in real time, and plots/graphs can be made quickly**
- **Perform pre-test checkout of key facilities hardware (He refrigerator, vacuum pumps, chamber shrouds, data Acquisition System), and all temperature sensors and measurement systems. Verify that all sensors with individual calibration curves (by serial number) have them input into the appropriate instrumentation, and check all setpoints are set correctly. Recommend use of Cernox sensors for critical temperature measurements, as uniqueness of resistance versus temperature calibration permits quick pre-test check at ambient that correct calibration curves are used**
- Prepare pre-test temperature and heat load predictions and clear success criteria
- Develop a large, well trained staff for thermal shift support, flexible enough to provide support in the event of illnesses, bad weather, and other emergencies. Identify test “floaters” (experts on various test aspects) in combination with regularly scheduled thermal test support to provide 24/7 continuity. Conduct multiple comprehensive pre-test training sessions, with a written curriculum
- Make thermal test program flexible and robust, to accommodate short notice changes to testing schedule
- Prepare pre-test plans, procedures, including safing of the payload, to deal with unexpected problems.
- Have the thermal test modeler/analyst involved during integration, and make test configuration inspections to confirm that models accurately represent the test
- Input to overall test planning to prioritize thermal tests, participate in key test decision points to proceed
- Coordinate with contamination control personnel to verify test procedures meet cleanliness requirements
- Have available redundant key GSE units (computers, controllers, temperature measurement instrumentation, etc)

Acronyms

ASIC	Application Specific Integrated Circuits
BAC	Ball Aerospace Corporation
BIA	Beam Image Analyzer
BSF	Backplane Support Fixture
CCE	Cryocooler Electronics
CCH	Contamination Control Heater
CSA	Canadian Space Agency
CV	Cryo-Vacuum
DM	Development Model
DSR	Deep Space Radiator
EC	European Consortium
ESA	European Space Agency
ETU	Engineering Test Unit
FGS	Fine Guidance Sensor
FM	Flight Model
FPA	Focal Plane Arrays
GESHA	Goddard Equipment Support Hardware Assembly
GHe	Gaseous Helium
GN_2	Gaseous Nitrogen
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HR	Harness Radiator
HSA	Heat exchanger stage assembly
IEC	ISIM Electronics Compartment
I/F	Interface
IHR	ISIM Harness Radiator
IOS	ISIM to OTE and Spacecraft Requirements Document
ISIM	Integrated Science Instrument Module
IRSU	ISIM Remote Services Unit
ITP	ISIM Test Platform
JSC	Johnson Space Center
JWST	James Webb Space Telescope
K	Kelvin
KM	Kinematic Mount
LN_2	Liquid Nitrogen
MATF	Master Alignment Test Fixture
MCA	Monitor and Calibration Assembly
MIRI	Mid Infrared Instrument
MLI	Multilayer Insulation
NGAS	Northrop Grumman Aerospace Systems
NIRCam	Near Infrared Camera
NIRSpec	Near Infrared Spectrograph
OA	Optics Assembly
OM	Optics Module
OSIM	OTE Simulator
OTE	Optical Telescope Element
OTIS	Optical Telescope / ISIM
PG	Photogrammetry
PMBSS	Primary Mirror Backplane Support Structure
SES	Space Environment Simulator
SI	Science Instrument
SIF	SES Integration Frame
SIIP	Science Instrument Interface Plate
STMS	Surrogate Thermal Management System (for use in test)
TB	Thermal Balance
TCU	Thermal Conditioning Unit
TMS	Thermal Management System (flight)
TV	Thermal Vacuum
TVDS	Thermal Vacuum Data System
VIS	Vibration Isolation System
VM	Verification Model
W	Watt

Acknowledgements

- Thermal Control during the CV3 test was an effort of many people, including Test Directors, conductors, operators, Systems, contamination control personnel, and scientists
- Brian Comber provided most of the test thermal modeling and helped write the procedures. He also calibrated the Q-meters. Dharmendra Patel used the detailed TMG model to answer detailed questions for flight and test, Paul Cleveland provided support on IEC, and Jim Tuttle supported harness radiator testing and harness heat load measurement effort. Kim Banks and her team of cryogenics experts provided coverage and support of the GSE cooler used for MIRI in the testing.
- The following people provided thermal shift coverage for the duration of the 108 day test:

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Dharmendra Patel	Amil Mann
Stuart Glazer	