James Webb Space Telescope Core 2 Test - Cryogenic Thermal Balance Test of the Observatory's 'Core' Area Thermal Control Hardware

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The James Webb Space Telescope (JWST), successor to the Hubble Space Telescope, will be the largest astronomical telescope ever sent into space. To observe the very first light of the early universe, JWST requires a large deployed 6.5-meter primary mirror cryogenically cooled to less than 50 Kelvin. Three scientific instruments are further cooled via a large radiator system to less than 40 Kelvin. A fourth scientific instrument is cooled to less than 7 Kelvin using a combination pulse-tube Joule-Thomson mechanical cooler. Passive cryogenic cooling enables the large scale of the telescope which must be highly folded for launch on an Ariane 5 launch vehicle and deployed once on orbit during its journey to the second Earth-Sun Lagrange point. Passive cooling of the observatory is enabled by the deployment of a large tennis court sized five layer Sunshield combined with the use of a network of high efficiency radiators. A high purity aluminum heat strap system connects the three instrument's detector systems to the radiator systems to dissipate less than a single watt of parasitic and instrument dissipated heat. JWST's large scale features, while enabling passive cooling, also prevent the typical flight configuration fully-deployed thermal balance test that is the keystone of most space missions' thermal verification plans. This paper describes the JWST Core 2 Test, which is a cryogenic thermal balance test of a full size, high fidelity engineering model of the Observatory's 'Core' area thermal control hardware. The 'Core' area is the key mechanical and cryogenic interface area between all Observatory elements. The 'Core' area thermal control hardware allows for temperature transition of 300K to ~50 K by attenuating heat from the room temperature IEC (instrument electronics) and the Spacecraft Bus. Since the flight hardware is not available for test, the Core 2 test uses high fidelity and flight-like reproductions.

Nomenclature

BSF	Backplane Support Fixture
CERNOX	Lakeshore Trade Name for Thin Film Resistance Cryogenic Temperature Sensors
CJAA	Cryocooler Jitter Attenuator Assembly
CM	Configuration Management

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CQCM	Cryogenic Quartz Crystal Microbalance
Cryo	Cryogenic
CV	Cryo Vacuum
DSR	Deep Space Radiator
DTA	Deployable Tower Assembly
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
GN2	Gaseous Nitrogen
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
He	Helium
IEC	ISIM Electronics Compartment
I&T	Integration and Test
ISIM	Integrated Science Instrument Module
JSC	Johnson Space Center
JWST	James Webb Space Telescope
K	Kelvin
LN2	Liquid Nitrogen
MGSE	Mechanical Ground Support Equipment
MLI	Multi-Layer Insulation
MV1	-V1 Axis
MV3	-V3 Axis
NASA	National Aeronautics and Space Administration
NGAS	Northrop Grumman Aerospace Systems
OTE	Optical Telescope Element
OTIS	Optical Telescope and Integrated Science Instrument Module
PRT	Platinum Resistance Thermometer
PV1	+V1 Axis
PV3	+V3 Axis
RGA	Residual Gas Analyzer
RLDA	Refrigerant Line Deployment Assembly
RTSA	RLDA Thermal Shield Assembly
S/C	Spacecraft
SES	Space Environmental Simulator
Si	Silicon
TAT	Test Advisory Team
TB	Thermal Balance
TBD	To Be Determined
TBR	To Be Reviewed
TC	Thermocouple
TD	Test Director
TQCM	Thermo-Electric Quartz Crystal Microbalance
TV	Thermal Vacuum
TVDS	Thermal Vacuum Data System
VBA	Visual Basic
WOA	Work Order Authorization

I. Introduction

The James Webb Space Telescope (JWST), successor to the Hubble Space Telescope and scheduled for launch in late 2018, will be the largest astronomical telescope sent into space. To observe the very first light of the early universe, JWST requires a large deployed 6.5-meter primary mirror cryogenically cooled to less than 50 Kelvin. Three scientific instruments are further cooled via a large radiator system to less than 40 Kelvin. A fourth scientific instrument is cooled to less than 7 Kelvin using a combination pulse-tube / Joule-Thomson mechanical cooler. Passive cryogenic cooling enables the large scale of the telescope which must be highly folded for launch on an

Ariane 5 launch vehicle and deployed once on orbit during its journey to the second Earth-Sun Lagrange point. Passive cooling of the observatory is enabled by the deployment of a large tennis court sized five layer Sunshield combined with the use of a network of high efficiency radiators. A high purity aluminum heat strap system connects the three near infra-red instrument's detector systems to the radiator systems to dissipate less than a single watt of parasitic and instrument dissipated heat. JWST's large scale features, while enabling passive cooling, also prevent the typical flight configuration fully-deployed thermal balance test that is the keystone of most space missions' thermal verification plans. JWST's fully-deployed size is too large for test facilities and would require complicated off-loading of its delicate deployables for traditional thermal balance testing. As a result, in 2009, National Aeronautics and Space Administration (NASA) began a series of thermal tests consisting of a combination of demonstration, engineering, and flight models. One of those tests was the Core test.

The JWST Core 2 Test is a cryogenic thermal balance test of the Observatory's 'Core' area thermal control hardware. As shown in Figure 1-1, the 'Core' area is the key mechanical and cryogenic interface area between all Observatory elements (Optical Telescope Element (OTE), Spacecraft, Sunshield, and ISIM Electronics Compartment (IEC) (ISIM warm electronics)). The 'Core' area thermal control hardware allows for temperature transition of 300K to ~50 K by attenuating heat from the room temperature IEC and the Spacecraft Bus. A majority of parasitic heat reaching the Optical Telescope and Integrated Science Instrument Module (OTE/ISIM) (OTIS) flows through the 'Core' area.

The Core 2 Test occurred in the Goddard Space Flight Center (GSFC) Space Environment Simulator (SES) facility (Chamber 290) from March through July of 2016. The Core 2 test was added as part of 2011 re-baseline as per Test Advisory Team (TAT) report recommendations. Test objectives were removed from the Johnson Space Center (JSC) OTIS testing to reduce program critical path risk.

Since the flight hardware was not available for test, the Core 2 test used high fidelity and flight-like reproductions. All thermal control features were flight-like utilizing flight drawings and flight I&T teams to install.

The Core 2 test was managed by NASA under Mission Integration and Test (I&T) with Mission Systems Engineering defining test objectives and analysis. Northrop Grumman Aerospace Systems (NGAS) provided flight hardware reproductions and assisted NASA with integration.

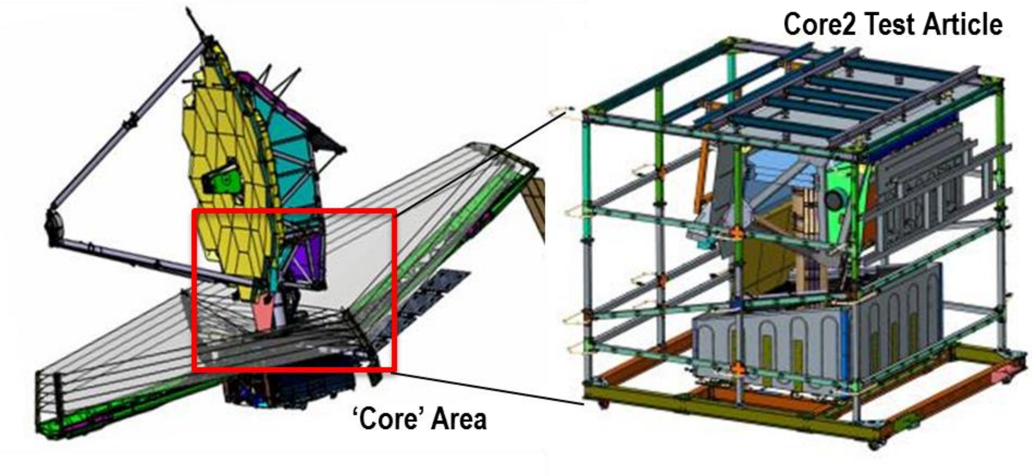


Figure Error! No text of specified style in document.**-1: JWST 'Core' Area and Core 2 Test Article**

II. Test Objectives

The objectives of the Core 2 test were:

1. Core 2 shall verify the final flight 'design' thermal performance and workmanship of critical core area thermal control features.
2. Core 2 shall provide thermal test data for correlation of thermal models of critical core area thermal control features and aggregate core area performance.
3. Core 2 shall provide for the rehearsal, and written and photo documentation of installation of critical core area thermal control features prior to flight unit installation.
4. Test shall determine core area thermal performance sensitivity to IEC and Bus +J3 panel temperatures.

III. Test Configuration

The Core 2 test configuration is illustrated in Figures 3-1 through 3-8. The figures begin with an overview and then proceed to show greater and greater detail of the GSE and test article.

Figure 3-1 shows the Core 2 assembly in the SES Chamber and identifies the major elements. Figure 3-2 is a schematic and illustrates the basic temperature regions within the helium shroud for Thermal Balance (TB) #4.

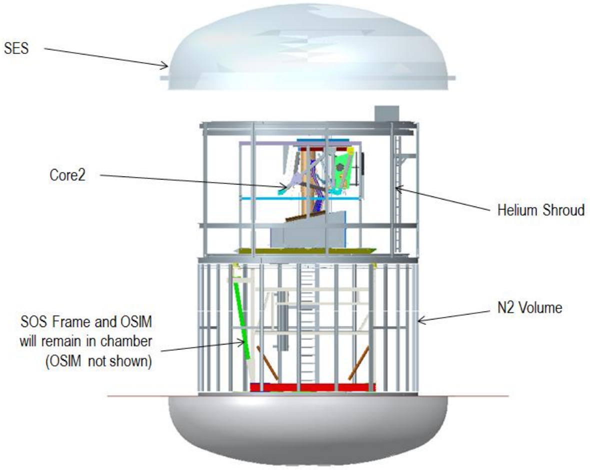
Figure 3-3 shows the Core 2 assembly without the local-encapsulating helium Deep Space Radiators (DSR's) and identifies the major elements of the configuration within the larger helium shroud. Figure 3-4 displays the Ground Support Equipment (GSE) components, along with the DSR's, that makeup the test volume. Figure 3-5 shows the test article overview.

The helium shroud, built specifically for the ISIM CryoVacuum (CV) tests, encloses the upper section of the SES, including Core 2. The Core 2 hardware is a high fidelity replica of the JWST Core area. As a result, temperatures range from the 313K to 30K. The front radiator panels of the IEC, which operate at ~278K, (Region 2) are tented within a thermal enclosure and the heat load from the included heater plates, which simulate the electronics boxes, is rejected to a helium cooled coldplate.

The output of the helium refrigerator skid ran through 9 distinct flow zones, controlled by valves. Figure 3-6 shows the SES Helium System Schematic. These valves were operated as needed throughout the test. Figure 3-2 identifies the individual flow zones. Zones 1-3 were fed to the sides of the facility helium shroud, while zones 8 and 9 cool the floor and roof of the helium volume, respectively; zone 4 cooled the sides of the IEC (DSR); zone 5 cooled the Support Frame for the PV3 and PV1 Assembly as well as the respective Q-meters (thermal boundaries to the targets); zone 6 cooled the Helium Enclosure DSR's; zone 7 provided cooling to the main frame; zone 10 was not used for this test.

Key to the test were the two target assemblies and their associated Q-meters. Figure 3-7 shows the PV3 Target Assembly, which represented the ISIM floor MLI and surrounding area. Figure 3-8 shows the PV1 Target Assembly, which represented the back MLI surface of the primary mirrors. Both of these are key regions and knowledge of the heat flow to these areas is critical.

Core 2 GSE features also included extensive temperature sensor layout (~1078), 197 heater circuits, Two Micro Ion Gauges, a variety of Quartz Crystal Microbalances, and 63 cryopanels.



(Helium Shroud, LN2 Shroud, and Core 2 DSR Panels removed for clarity)

Figure 3-1: Core 2 in the SES Chamber

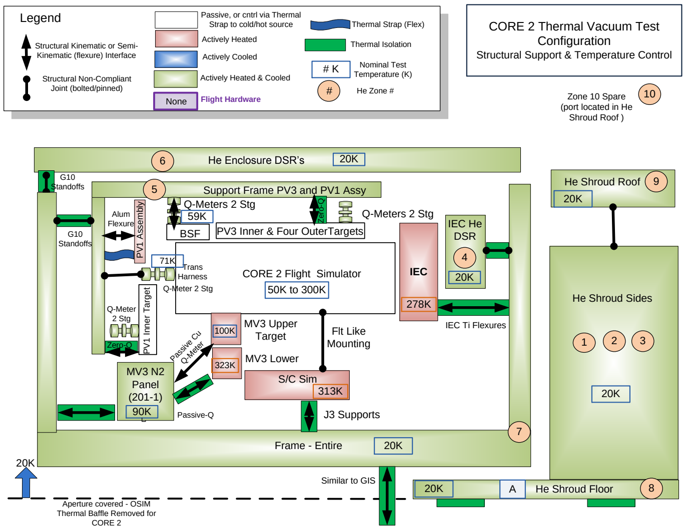


Figure 3-2: Temperature Regimes within Core 2 Test and Helium Zones – Helium Volume TB#4

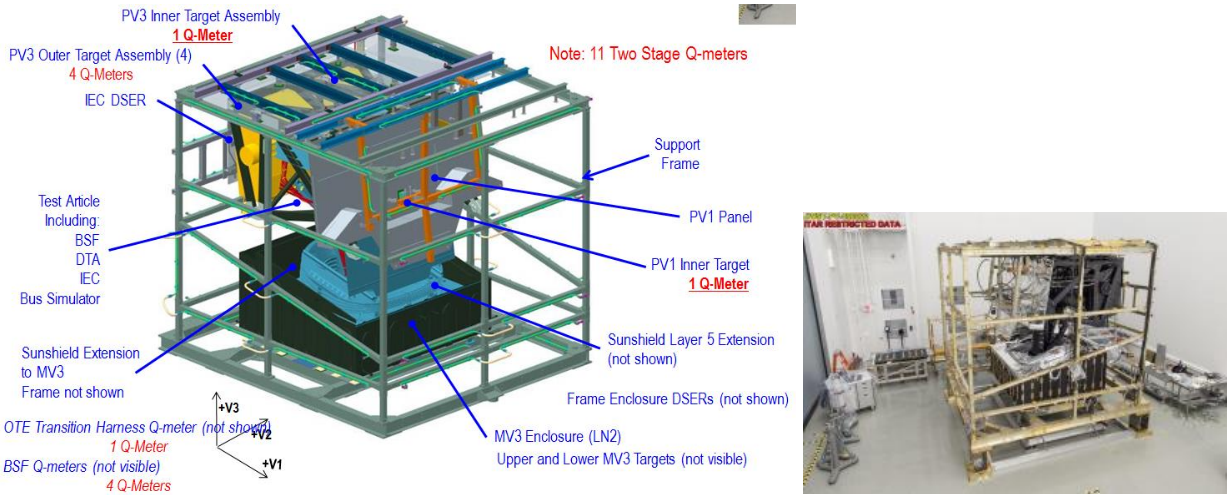


Figure 3-3: Core 2 Assembly Overview without He DSR’s

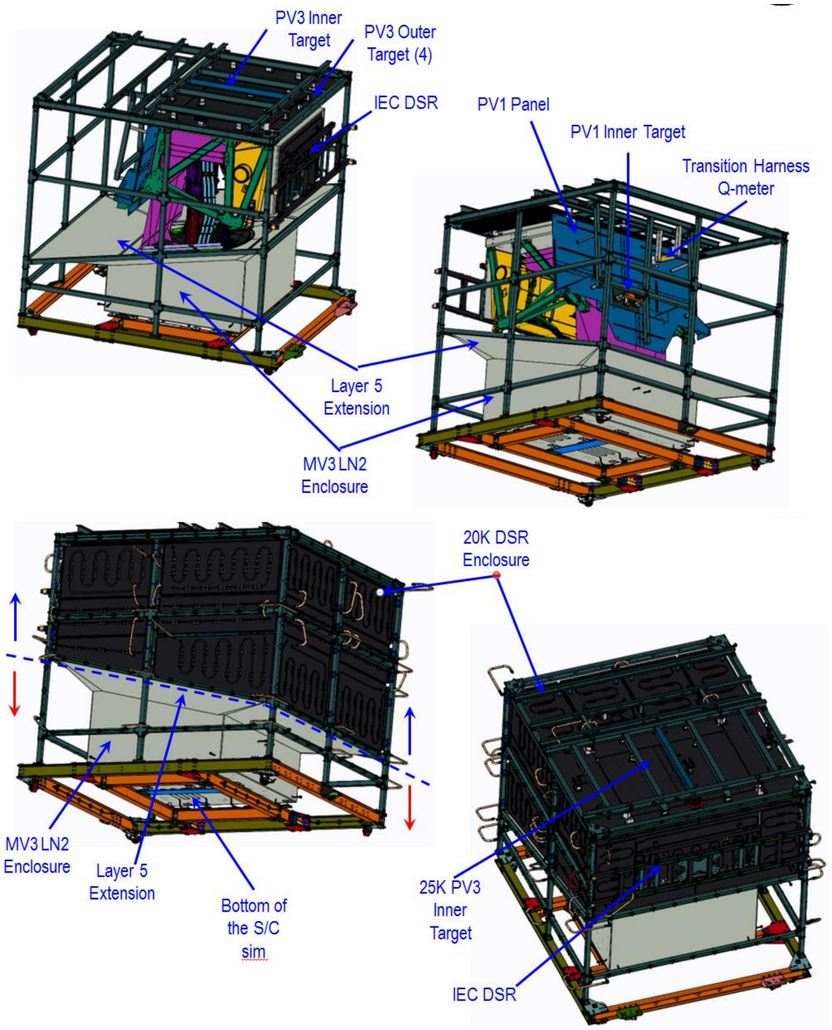


Figure 3-4: Core 2 GSE Components that Makeup the Test Volume

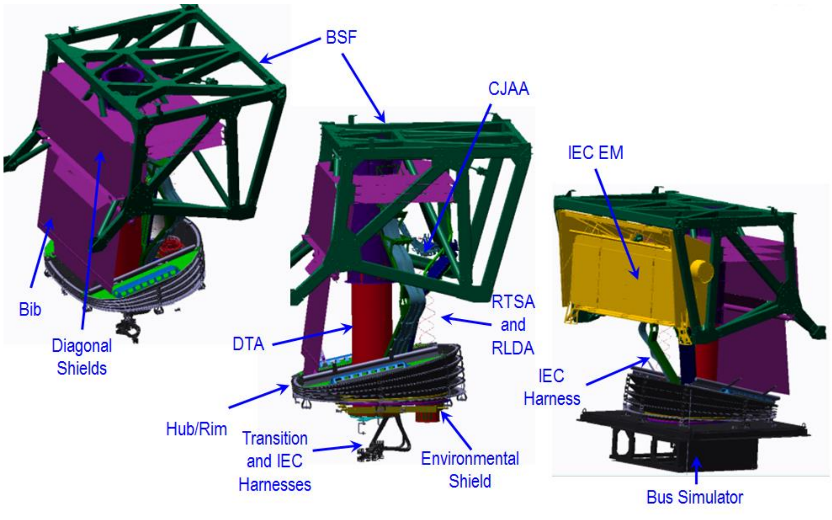


Figure 3-5: Test Article Overview

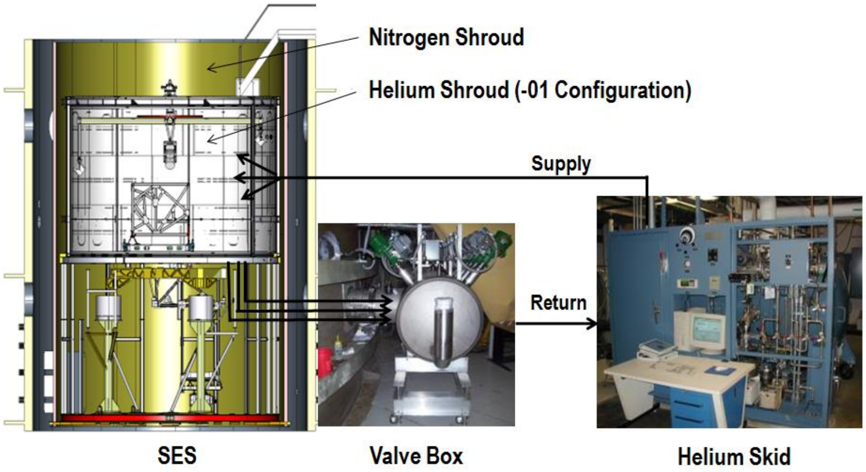


Figure 3-6: SES Helium System Schematic

PV3 Target Assembly

Inner Target matches ISIM Floor footprint

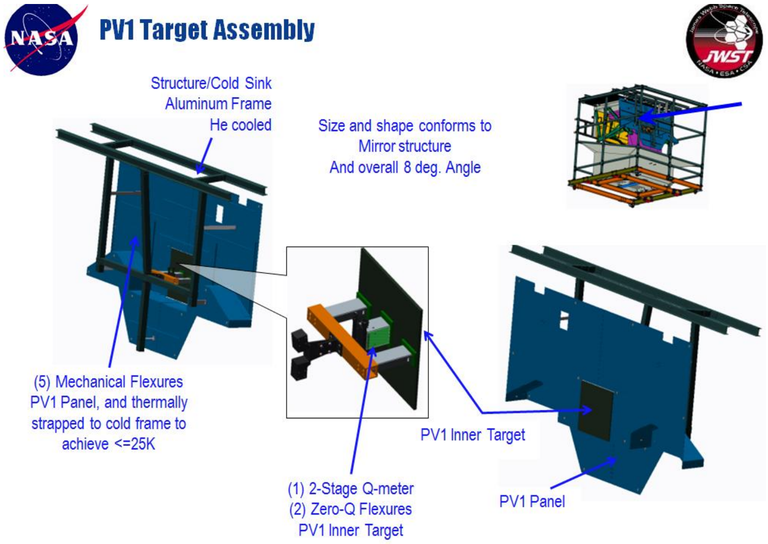
BSF Q-meters (4) pass through PV3 targets, support the BSF, hold the interface at a flight predicted temperature and measure the BSF conducted heat in +V3 direction

2-Stage Q-meter (5)

Zero Q Flexures Provide structural support without significantly affecting heatflows (12)

ISIM Floor Blanket is attached to Inner Target (not shown)

Figure 3-7: PV3 Target Assembly



PV1 Target Assembly

Structure/Cold Sink Aluminum Frame He cooled

Size and shape conforms to Mirror structure And overall 8 deg. Angle

(5) Mechanical Flexures PV1 Panel, and thermally strapped to cold frame to achieve <=25K

PV1 Inner Target

(1) 2-Stage Q-meter
(2) Zero-Q Flexures
PV1 Inner Target

PV1 Panel

Figure 3-8: PV1 Target Assembly

IV. Q-Meters

In addition to extensive instrumentation, Core2 utilized a system of eleven Two Stage Q-meters which are custom designed GSE that function as heat flow meters. Figure 3-3 identifies the locations within the test article.

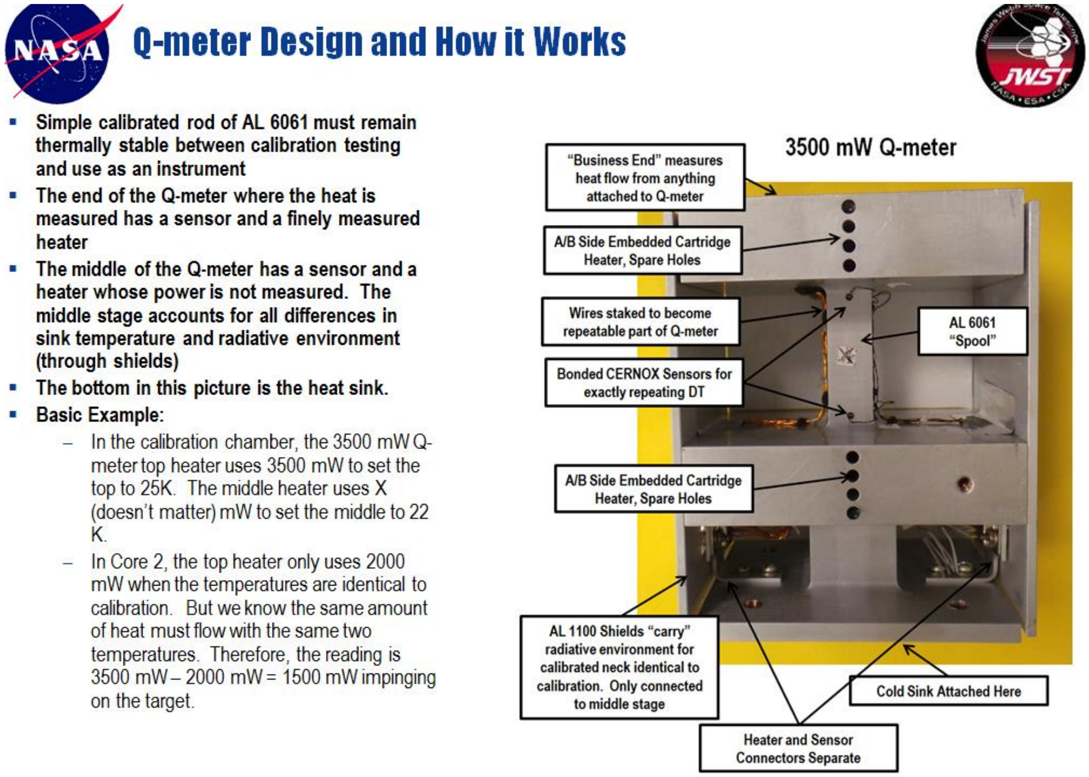
In order to correlate the model, one needs both temperature information and heat flow information. Heat Flow can be calculated from temperatures using a model, but the Q-meter provides a highly calibrated way of directly measuring the heat flow through it, regardless of material properties, optical properties, etc. Also, Q-meters provide command-able temperature values that match calibration points. Q-meters also serve to determine balance status.

There were a total of eleven Two Stage Q-meters (High Accuracy, High Complexity, Calibration Required) which measured heat flow by difference in heater power to the calibration test. The Two Stage Q-meters were designed to provide an accuracy of +/- 2 mW.

Figure 4-1 shows a picture of a 3500 mW Two-Stage Q-Meter and describes how it works.

As mentioned before, the eleven Two Stage Q-meters served as the primary tool for establishing thermal balance. Figure 4-2, which was taken from the test procedure, shows the criteria used for each balance point. The eleven Q-meters had to meet certain energy criteria and the temperatures of the 95 test-article control sensors had to change less than 0.015K/Hour.

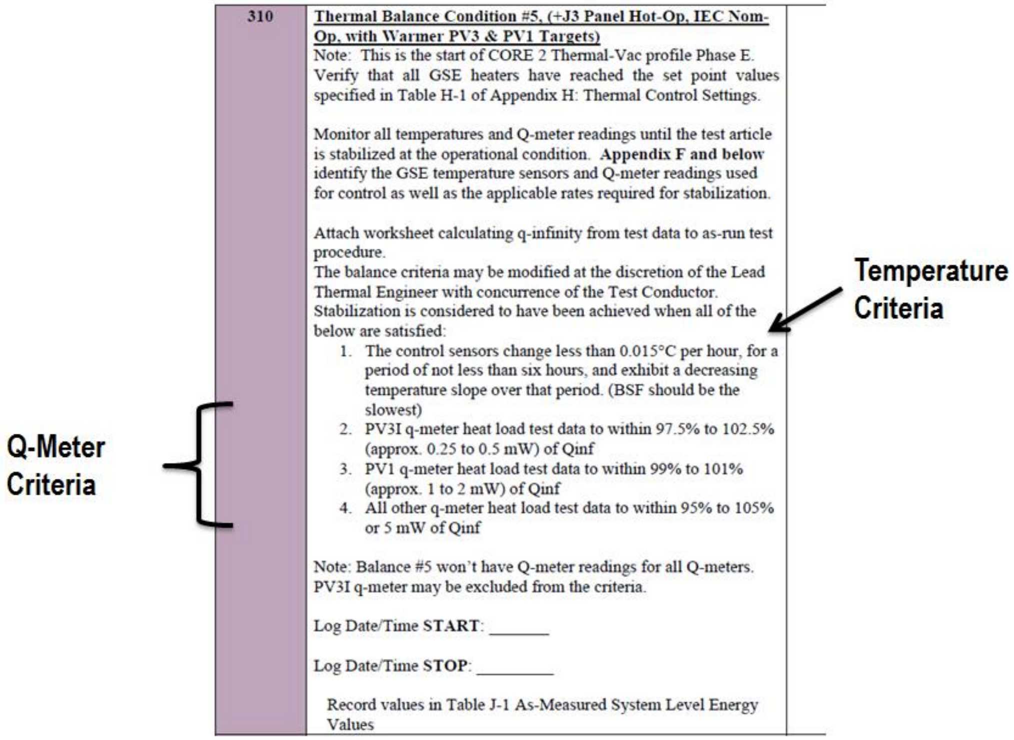
In addition, Core 2 incorporated fourteen Single Stage Q-meters and a number of Zero-Q flexures.



Q-meter Design and How it Works

- Simple calibrated rod of AL 6061 must remain thermally stable between calibration testing and use as an instrument
- The end of the Q-meter where the heat is measured has a sensor and a finely measured heater
- The middle of the Q-meter has a sensor and a heater whose power is not measured. The middle stage accounts for all differences in sink temperature and radiative environment (through shields)
- The bottom in this picture is the heat sink.
- Basic Example:
  - In the calibration chamber, the 3500 mW Q-meter top heater uses 3500 mW to set the top to 25K. The middle heater uses X (doesn't matter) mW to set the middle to 22 K.
  - In Core 2, the top heater only uses 2000 mW when the temperatures are identical to calibration. But we know the same amount of heat must flow with the same two temperatures. Therefore, the reading is 3500 mW – 2000 mW = 1500 mW impinging on the target.

Figure 4-1: Two Stage Q-Meter Design and How it Works



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Thermal Balance Condition #5, (+J3 Panel Hot-Op, IEC Nom-Op, with Warmer PV3 & PV1 Targets)
Note: This is the start of CORE 2 Thermal-Vac profile Phase E. Verify that all GSE heaters have reached the set point values specified in Table H-1 of Appendix H: Thermal Control Settings.

Monitor all temperatures and Q-meter readings until the test article is stabilized at the operational condition. **Appendix F and below** identify the GSE temperature sensors and Q-meter readings used for control as well as the applicable rates required for stabilization.

Attach worksheet calculating q-infinity from test data to as-run test procedure.
The balance criteria may be modified at the discretion of the Lead Thermal Engineer with concurrence of the Test Conductor.
Stabilization is considered to have been achieved when all of the below are satisfied:

1. The control sensors change less than 0.015°C per hour, for a period of not less than six hours, and exhibit a decreasing temperature slope over that period. (BSF should be the slowest)
2. PV3I q-meter heat load test data to within 97.5% to 102.5% (approx. 0.25 to 0.5 mW) of Qinf
3. PV1 q-meter heat load test data to within 99% to 101% (approx. 1 to 2 mW) of Qinf
4. All other q-meter heat load test data to within 95% to 105% or 5 mW of Qinf

Note: Balance #5 won't have Q-meter readings for all Q-meters. PV3I q-meter may be excluded from the criteria.

Log Date/Time **START**: _______

Log Date/Time **STOP**: _________

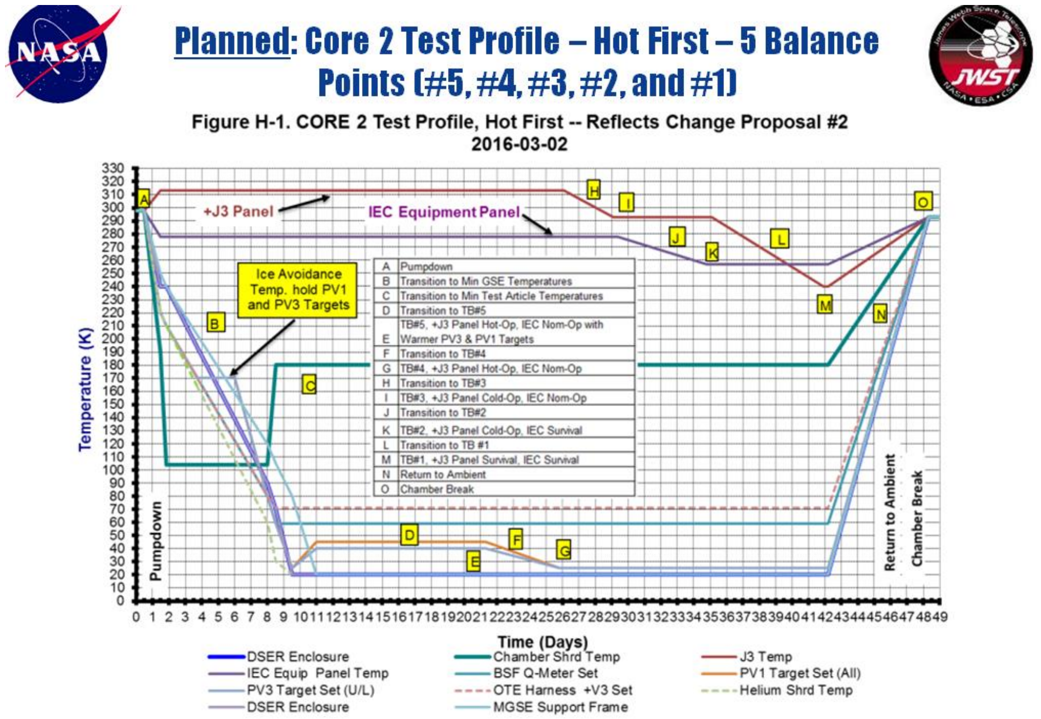
Record values in Table J-1 As-Measured System Level Energy Values

Figure 4-2: Balance Criteria

V. Test Profile

Figure 5-1 shows the Planned Core 2 Thermal Vacuum / Thermal Balance (TV/TB) Test profile. The test consisted of five Thermal Balance (TB) points (#5, #4, #3, #2, #1) each of which provided temperature and /or Q-meter data. The planned test started with the warmest boundary conditions first, thus providing the largest thermal signal-to-noise ratio, and proceeded temperature wise downward. Table 5-1 lists the TB points along with the data gathered and a description of the balance point.

During the initial thermal balance point, TB #5, it was noted that there were higher than expected negative heat readings on two of the 100mW Q-meters (PV3 Inner and PV3 Outer SN01 100 mW). These two Q-meters represented the two structurally weakest i.e. thinnest necks (1/4" square), of the eleven. The team performed two sub-balances i.e. in-situ calibrations, on every Q-meter. An in-situ calibration can measure the conductance of the Q-meter while the test article is stable by changing the middle stage temperature and measuring the power difference. During the troubleshooting between TB #5 and TB #4 on cycle 1, no other Q-meter besides the two 100 mW Q-meters showed a significant difference between a backed-out in-situ heat load reading and the reading using the fully calibrated value from the calibration tests. Table 5-2 shows the heat flow comparisons. Note that these in-situ readings were rough ones. The test article wasn't as stable as when we did the real ones that compared so favorably to Cycle 2. These were diagnostic and just to check for potential touching.



Planned: Core 2 Test Profile – Hot First – 5 Balance Points (#5, #4, #3, #2, and #1)

Figure H-1. CORE 2 Test Profile, Hot First -- Reflects Change Proposal #2
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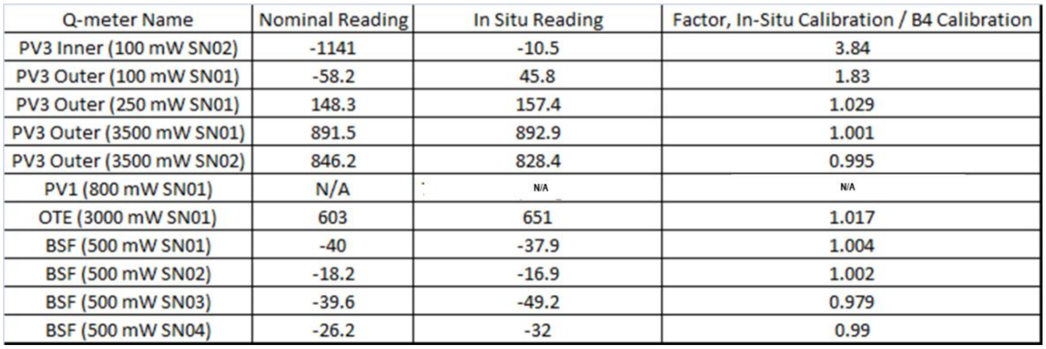
A	Pumpdown
B	Transition to Min GSE Temperatures
C	Transition to Min Test Article Temperatures
D	Transition to TB#5
E	TB#5, +J3 Panel Hot-Op, IEC Nom-Op with Warmer PV3 & PV1 Targets
F	Transition to TB#4
G	TB#4, +J3 Panel Hot-Op, IEC Nom-Op
H	Transition to TB#3
I	TB#3, +J3 Panel Cold-Op, IEC Nom-Op
J	Transition to TB#2
K	TB#2, +J3 Panel Cold-Op, IEC Survival
L	Transition to TB #1
M	TB#1, +J3 Panel Survival, IEC Survival
N	Return to Ambient
O	Chamber Break

Figure 5-1; Planned Core 2 Test Profile

Table 5-1: Planned Five Thermal Balance Points

#	Data Gathered	Description & Purpose
TB #5	Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating with Warmer PV3 & PV1 Targets Represents flight-like hot case Largest thermal signal-to-noise ratio Excellent for thermal model correlation
TB #4	Q-Meter and Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating: Represents hot case, Largest thermal signal-to-noise ratio
TB #3	Q-Meter and Temperature	Spacecraft +J3 Panel Cold-Operating, IEC Nominal-Operating
TB #2	Q-Meter and Temperature	Spacecraft +J3 Panel Cold-Operating, IEC Survival-Operating
TB #1	Q-Meter and Temperature	Spacecraft +J3 Panel Cold-Operating, IEC Survival-Operating

Table 5-2: Q-Meter Nominal Vs. In-Situ Readings



Q-meter Name	Nominal Reading	In Situ Reading	Factor, In-Situ Calibration / B4 Calibration
PV3 Inner (100 mW SN02)	-1141	-10.5	3.84
PV3 Outer (100 mW SN01)	-58.2	45.8	1.83
PV3 Outer (250 mW SN01)	148.3	157.4	1.029
PV3 Outer (3500 mW SN01)	891.5	892.9	1.001
PV3 Outer (3500 mW SN02)	846.2	828.4	0.995
PV1 (800 mW SN01)	N/A	N/A	N/A
OTE (3000 mW SN01)	603	651	1.017
BSF (500 mW SN01)	-40	-37.9	1.004
BSF (500 mW SN02)	-18.2	-16.9	1.002
BSF (500 mW SN03)	-39.6	-49.2	0.979
BSF (500 mW SN04)	-26.2	-32	0.99

After much deliberation, it was determined that the two 100 mW Q-meters had experienced bending which caused a thermal short between the top Q-meter “business end” and the middle stage via the shields. The Q-meters were intended to withstand very low forces in the Core 2 test set-up. By design, they were removed from the load path between the beams and the targets, and were replaced structurally by the Zero-Q flexures. The Q-meters were installed on top of the targets, with cold plates and flex lines to cool them. However, the weight of the flex lines and their routing was not fully considered in the bending analysis, causing an unexpected load that was high enough to cause a touch between the shield and the colder target stage.

Due to the issues with the 100 mW Q-meters, the team decided to “break chamber” i.e. warm-up and open the chamber, to repair the two Q-meters. This demonstrated the importance of the PV3 Inner 100 mW Q-meter reading to the success of the test. Prior to that, though, the team decided to complete TB #5, TB #4 and added in two additional cases. This plan was a risk mitigation strategy in case the repair effort was not successful and the test could not be continued.

One benefit of the in-situ calibrations was that they provided an estimate of the 100mW Q-meter thermal shorts. This estimate could then be removed from the actual measurement reading to provide a projection for the Q-meter reading during the first cycle, before any fix was made.

In the end, the repair effort was successful and the test was divided into two segments, 2A and 2B.

Figure 5-2 shows the Actual Core 2A TV/TB Test profile. Test 2A consisted of a single cycle test with four TB points (#5, #4A, #X, and #Y), each of which, provided temperature and/or Q-meter data, as well as two High Resolution Cross-Talk tests that were part of the diagnostic effort. Test 2A lasted 40 days. Table 5-3 lists the TB points along with the data gathered and a description of the balance point. TB #5 and TB #4A were as planned. TB #X was implemented to see the impact on Core 2 heat flows and temperatures of a 20K increase in the IEC panel temperature. TB #Y was implemented to see the impact on Core 2 heat flows and temperatures of a 20K decrease in the Spacecraft +J3 panel temperature.

Figure 5-3 shows the Actual Core 2B TV/TB Test profile. Test 2B consisted of a single cycle test with three TB points (#4B, #D, and #E), each of which, provided temperature and Q-meter data, as well as a OTE Harness Sensitivity Study that was part of the diagnostic effort. Test 2B lasted 33 days. Table 5-4 lists the TB points along with the data gathered and a description of the balance point. TB #4B was a repeat of TB #4A but with the two repaired 100 mW Q-meters. Amazingly, the PV3 Inner 100 mW Q-meter reading was 38.82 mW for 4A (estimated via in-situ calibration) and 43.2 mW for 4B (repaired Q-meter). The in-situ calibration and the Q-meter re-work validated each other and verified that the 100 mW Q-meters had provided accurate readings for correlation of the test article. TB #D was implemented to see the impact on PV3 Inner Q-meter heat flows and temperatures for an increase in the BSF Q-meter temperatures (59K to 74K). TB #E was implemented to see the impact on PV3 Inner Q-meter heat flows and temperatures for an increase in the BSF Q-meter temperatures (74K to 84K).

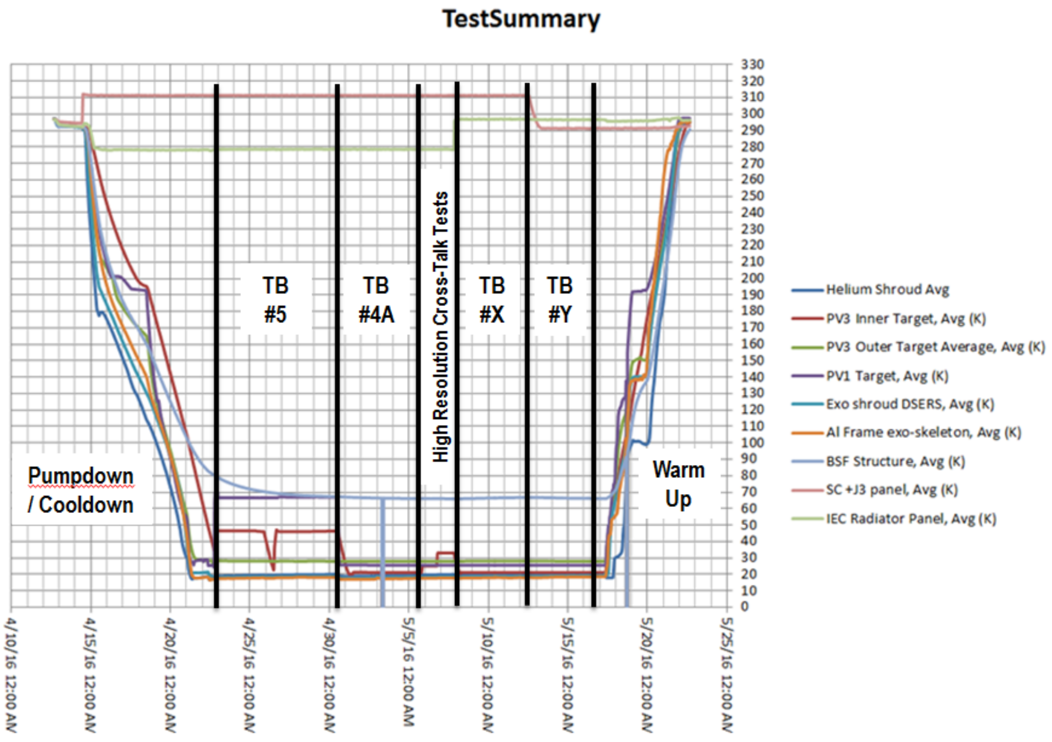


Figure 5-2: Actual Core 2A Test Profile (40 Day Duration)

Table 5-3: Actual 2A Four Thermal Balance Points and Cross-Talk Tests

#	Data Gathered	Description & Purpose
TB #5	Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating with Warmer PV3 & PV1 Targets Represents flight-like hot case Largest thermal signal-to-noise ratio Excellent for thermal model correlation
TB #4A	Q-Meter and Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating: Represents hot case, Largest thermal signal-to-noise ratio
Cross-Talk	Q-Meter and Temperature	High Resolution Cross-Talk Tests (2X) – 12 hours each. Raised the PV3 Inner Panel temperature 2X (21K to 25K) and then (25K to 33K) to see impact on four surrounding PV3 panels. See if any direct coupling
TB #X	Q-Meter and Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Hot-Operating: Determine impact on Core 2 temperatures from increased IEC temperature
TB #Y	Q-Meter and Temperature	Spacecraft +J3 Panel Cold-Operating, IEC Hot-Operating: Determine impact on Core 2 temperatures from decreased S/C +J3 Panel temperature

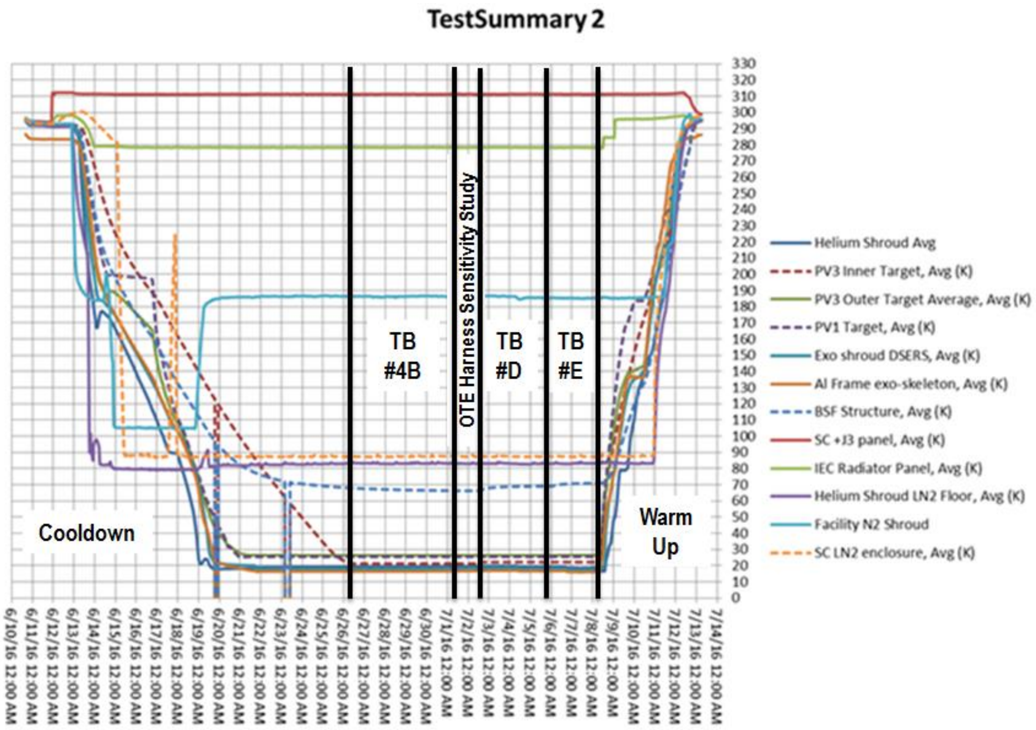


Figure 5-3: Actual Core 2B Test Profile (33 Day Duration)

Table 5-4: Actual 2B Three Thermal Balance Points and OTE Harness Sensitivity Study

#	Data Gathered	Description
TB #4B	Q-Meter and Temperature	Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating: Verify Q-meter fix and compare data to Core 2A, 4A data; Represents hot case, Largest thermal signal-to-noise ratio
OTE Harness Sensitivity	Temperature	OTE Harness Sensitivity Study - Raise OTE Harness Q-meter from 69K to 75K (Waited 24 hours): See impact on PV3 Inner target and four outer targets of a warmer OTE Harness Q-meter
TB #D	Q-Meter and Temperature	BSF Warm (59K to 74K), Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating: Determine impact on Core 2 temperatures from increased BSF temperature
TB #E	Q-Meter and Temperature	BSF Warm (74K to 84K), Spacecraft +J3 Panel Hot-Operating, IEC Nominal-Operating: Determine impact on Core 2 temperatures from increased BSF temperature

VI. Real Time Data Processing

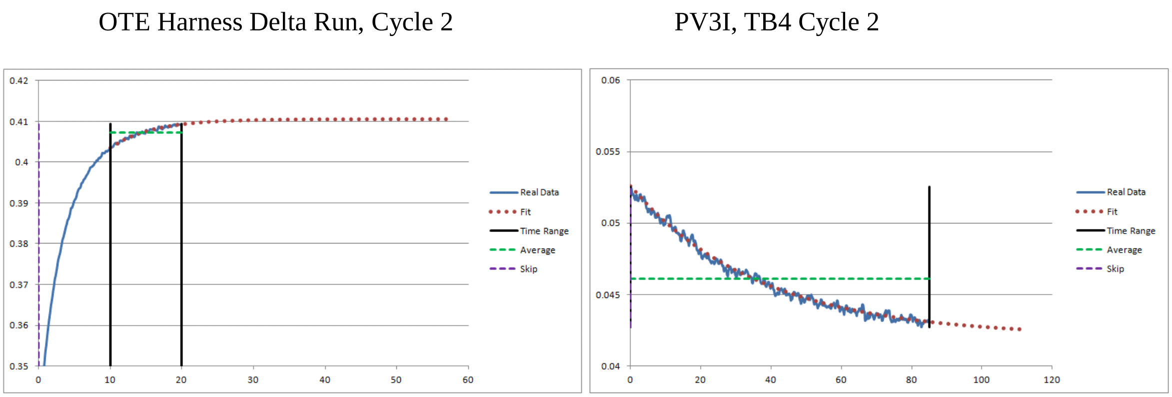
One of the interesting features of the Core 2 test was the use of the Fusion computer system along with its capability of curve fitting test data.

The “Fusion” computer program was so named because in the past, it has “Fused” data from multiple systems into one monitoring platform. Built on Excel VBA, it is a program that reads a .CSV file every two minutes. In addition, it monitors Limits and Constraints and provides audible alarms and conditional formatting for visual alarms, a graphing tool, color plots, and remote access to near real-time test data.

For the Core 2 test, it also provided information on the balance status. Added to the program was the functionality to retrieve X hours of data starting from Y hours ago and to fit the data to an exponential decay curve. With the curve equation, it provided predictions on when balance criteria would be met. It smoothed out noise in sensors and provided a noiseless equation for rate calculations. It was used for Q-meter readings and for BSF temperatures. The exponential fit of test data was based on two methods which were often compared.

The first method was called the “Harpole Method”, after George Harpole from Ball Aerospace. Fusion would write the input files, run Harpole’s exe file, and read the output file. It was “smarter” than the Excel version and much faster. However, many times, it returned an error if the data were not “exponential” enough. Harpole method fit data to T=Tinf + (To-Tinf)*e^(-t/tau).

The second method was written in Excel. In an Excel window, Fusion printed out the curve fit next to the real data, and calculated a chi squared for each time step. It then used Excel’s solver to find the best A, k, and C to minimize Chi Squared in the equation: T = C+A(1-e^(-k*t)). Following this it graphed the result on top of the original data. It is very important to note that a human needs to be in the loop to determine if the algorithm has provided an appropriate fit. At the end of a transition, the data can behave more linearly and noise can throw off the true exponential nature of the data. Fusion will always try to minimize Chi Squared, no matter what the condition of the data. Additional features include allowing the user to select a different time period for the fit and to skip spurious data. Figure 6-1 shows exponential fit examples.


OTE Harness Delta Run, Cycle 2

PV3I, TB4 Cycle 2

Figure 6-1: Exponential Fit Examples

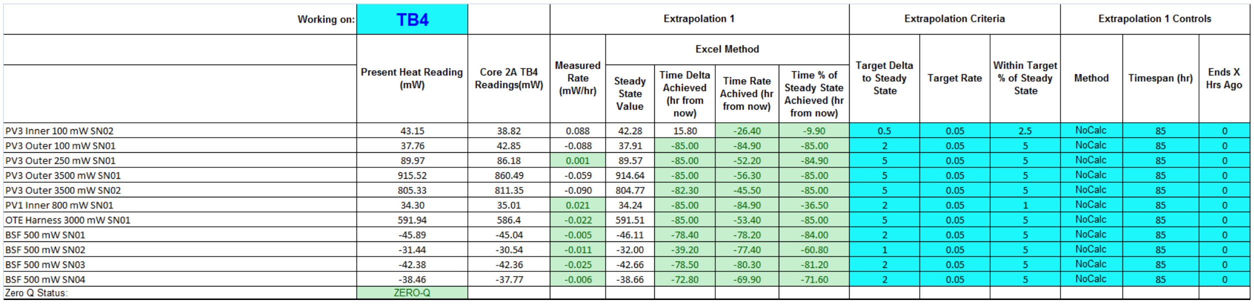
VII. Test Results

For six of the seven thermal balance conditions (Test 2A: #5, #4A, #X, #Y; and Test 2B: #4B, #D and #E), the eleven Q-meters served as the primary tool for establishing balance i.e. the Q-meters had to be within a certain percentage of estimated steady state values. The one exception to this was TB #5, which was a flight like temperature condition with the warmer PV3 and PV1 targets, in which the 95 control sensors had to be changing less than 0.015K/hour. The 95 control sensor list reflects key flight-like hardware that were essential for thermal model correlation.

For both the Q-meter readings and the 95 control senor temperature readings, the extrapolation techniques within Fusion severed as the deterministic mechanism. In actuality, Q-meter readings and control sensor temperature readings were gathered for each balance point. However, in TB#5, some of the boundary condition heater setpoints were outside of the originally planned Q-meter calibration ranges and thus temperatures served as the controlling data for balance.

As an example, Table 1-5 shows the balance data for Test 2B TB #4B. In Table 7-1, in the first column, Fusion presents the heat reading for the eleven Q-meters and the status of the Zero-Q flexures. Extrapolation 1 is to the right. It shows: measured rate (which is the slope of the final 2 hours), projected steady state value, and the time when each of the criteria was met: Delta to Steady State, Rate, and Percentage of Steady State. The light green indicates that the criteria have been met i.e. green is good; the negative number indicates the time at which it was met in the past i.e. 9.90 hours ago for PV3 Inner for the Percentage of Steady State.

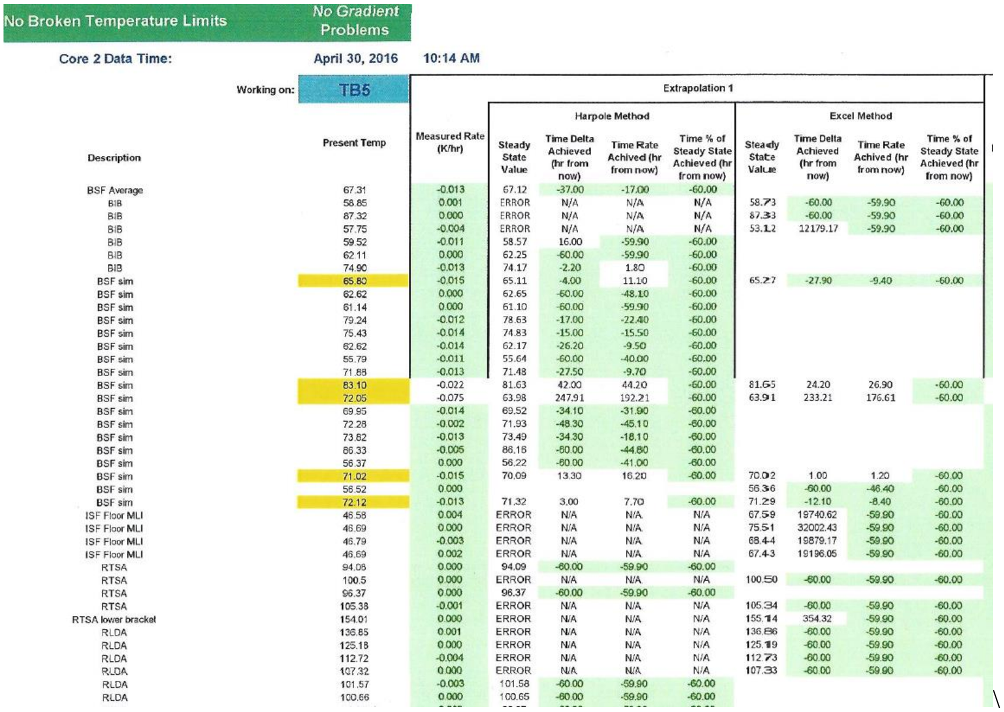
Table 7-1: Real-Time Q-Meter Extrapolations Outputs, Test 2B TB #4



Working on:	TB4		Extrapolation 1					Extrapolation Criteria			Extrapolation 1 Controls		
				Excel Method									
	Present Heat Reading (mW)	Core 2A TB4 Readings(mW)	Measured Rate (mW/hr)	Steady State Value	Time Delta Achieved (hr from now)	Time Rate Achived (hr from now)	Time % of Steady State Achieved (hr from now)	Target Delta to Steady State	Target Rate	Within Target % of Steady State	Method	Timespan (hr)	Ends X Hrs Ago
PV3 Inner 100 mW SN02	43.15	38.82	0.088	42.28	15.80	-26.40	-9.90	0.5	0.05	2.5	NoCalc	85	0
PV3 Outer 100 mW SN01	37.76	42.85	-0.088	37.91	-85.00	-84.90	-85.00	2	0.05	5	NoCalc	85	0
PV3 Outer 250 mW SN01	89.97	86.18	0.001	89.57	-85.00	-52.20	-84.90	5	0.05	5	NoCalc	85	0
PV3 Outer 3500 mW SN01	915.52	860.49	-0.059	914.64	-85.00	-56.30	-85.00	5	0.05	5	NoCalc	85	0
PV3 Outer 3500 mW SN02	805.33	811.35	-0.090	804.77	-82.30	-45.50	-85.00	5	0.05	5	NoCalc	85	0
PV1 Inner 800 mW SN01	34.30	35.01	0.021	34.24	-85.00	-84.90	-36.50	2	0.05	1	NoCalc	85	0
OTE Harness 3000 mW SN01	591.94	586.4	-0.022	591.51	-85.00	-53.40	-85.00	5	0.05	5	NoCalc	85	0
BSF 500 mW SN01	-45.89	-45.04	-0.005	-46.11	-78.40	-78.20	-84.00	2	0.05	5	NoCalc	85	0
BSF 500 mW SN02	-31.44	-30.54	-0.011	-32.00	-39.20	-77.40	-60.80	1	0.05	5	NoCalc	85	0
BSF 500 mW SN03	-42.38	-42.36	-0.025	-42.66	-78.50	-80.30	-81.20	2	0.05	5	NoCalc	85	0
BSF 500 mW SN04	-38.46	-37.77	-0.006	-38.66	-72.80	-69.90	-71.60	2	0.05	5	NoCalc	85	0
Zero Q Status:	ZERO-Q												

As an example of temperature stabilization, Table 7-2 shows the temperature stabilization data for Test 2A, TB #5. The first column shows a partial listing of the 95 control sensors. This is followed by the present temperature, the measured rate (which is the slope of the final 2 hours), projected steady state value, and the time when each of the criteria were met. For temperature stabilization, the “Time Delta” indicates when it was within 1.0K of the steady state value and the “Time Rate Achieved” indicates when it met 0.015K/Hour. As before, Green designates it was satisfied. For the “BSF Average”, a negative number means it was satisfied 60 hours ago. The first several columns show results from the Harpole Method. If the data was not appropriate enough for Harpole, then the slower EXCEL method was used.

Table 7-2: Real-Time Temperature Extrapolations Outputs, Test 2A TB #5



No Broken Temperature Limits *No Gradient* Problems

Core 2 Data Time: April 30, 2016 10:14 AM

Working on:	TB5	Extrapolation 1								
			Harpole Method				Excel Method			
Description	Present Temp	Measured Rate (K/hr)	Steady State Value	Time Delta Achieved (hr from now)	Time Rate Achived (hr from now)	Time % of Steady State Achieved (hr from now)	Steady State Value	Time Delta Achieved (hr from now)	Time Rate Achived (hr from now)	Time % of Steady State Achieved (hr from now)
BSF Average	67.31	-0.013	67.12	-37.00	-17.00	-60.00				
BIB	58.85	0.001	ERROR	N/A	N/A	N/A	58.73	-60.00	-59.90	-60.00
BIB	87.32	0.000	ERROR	N/A	N/A	N/A	87.33	-60.00	-59.90	-60.00
BIB	57.75	-0.004	ERROR	N/A	N/A	N/A	53.12	12179.17	-59.90	-60.00
BIB	59.52	-0.011	58.57	16.00	-59.90	-60.00				
BIB	62.11	0.000	62.25	-60.00	-59.90	-60.00				
BIB	74.90	-0.013	74.17	-2.20	1.80	-60.00				
BSF sim	65.80	-0.015	65.11	-4.00	11.10	-60.00	65.27	-27.90	-9.40	-60.00
BSF sim	62.62	0.000	62.65	-60.00	-48.10	-60.00				
BSF sim	61.14	0.000	61.10	-60.00	-59.90	-60.00				
BSF sim	79.24	-0.012	78.63	-17.00	-22.40	-60.00				
BSF sim	75.43	-0.014	74.83	-15.00	-15.50	-60.00				
BSF sim	62.62	-0.014	62.17	-26.20	-9.50	-60.00				
BSF sim	55.79	-0.011	55.64	-60.00	-40.00	-60.00				
BSF sim	71.88	-0.013	71.48	-27.50	-9.70	-60.00				
BSF sim	83.10	-0.022	81.63	42.00	44.20	-60.00	81.65	24.20	26.90	-60.00
BSF sim	72.05	-0.075	63.98	247.91	192.21	-60.00	63.91	233.21	176.61	-60.00
BSF sim	69.95	-0.014	69.52	-34.10	-31.90	-60.00				
BSF sim	72.28	-0.002	71.93	-48.30	-45.10	-60.00				
BSF sim	73.82	-0.013	73.49	-34.30	-18.10	-60.00				
BSF sim	86.33	-0.005	86.16	-60.00	-44.80	-60.00				
BSF sim	56.37	0.000	56.22	-60.00	-41.00	-60.00				
BSF sim	71.02	-0.015	70.09	13.30	16.20	-60.00	70.02	1.00	1.20	-60.00
BSF sim	56.52	0.000					56.36	-60.00	-46.40	-60.00
BSF sim	72.12	-0.013	71.32	3.00	7.70	-60.00	71.29	-12.10	-8.40	-60.00
ISF Floor MLI	46.58	0.004	ERROR	N/A	N/A	N/A	67.59	19740.62	-59.90	-60.00
ISF Floor MLI	46.69	0.000	ERROR	N/A	N/A	N/A	75.51	32002.43	-59.90	-60.00
ISF Floor MLI	46.79	-0.003	ERROR	N/A	N/A	N/A	68.44	19879.17	-59.90	-60.00
ISF Floor MLI	46.69	0.002	ERROR	N/A	N/A	N/A	67.43	19196.05	-59.90	-60.00
RTSA	94.08	0.000	94.09	-60.00	-59.90	-60.00				
RTSA	100.5	0.000	ERROR	N/A	N/A	N/A	100.50	-60.00	-59.90	-60.00
RTSA	96.37	0.000	96.37	-60.00	-59.90	-60.00				
RTSA	105.38	-0.001	ERROR	N/A	N/A	N/A	105.34	-60.00	-59.90	-60.00
RTSA lower bracket	154.01	0.000	ERROR	N/A	N/A	N/A	155.14	354.32	-59.90	-60.00
RLDA	136.85	0.001	ERROR	N/A	N/A	N/A	136.86	-60.00	-59.90	-60.00
RLDA	125.18	0.000	ERROR	N/A	N/A	N/A	125.19	-60.00	-59.90	-60.00
RLDA	112.72	-0.004	ERROR	N/A	N/A	N/A	112.73	-60.00	-59.90	-60.00
RLDA	107.32	0.000	ERROR	N/A	N/A	N/A	107.33	-60.00	-59.90	-60.00
RLDA	101.57	-0.003	101.58	-60.00	-59.90	-60.00				
RLDA	100.66	0.000	100.65	-60.00	-59.90	-60.00				

For all balance cases, the test results were predominately in-family with expectations. Where there were discrepancies with original predictions, reasonable explanations were identified.

VIII. Compliance Matrix

The Core 2 test has so far successfully completed three of its four test objectives. Table 8-1 shows the compliance matrix, lists the test objectives, and identifies where in the test they were satisfied.

The status of the fourth objective is "Pending" due to its link with the Thermal Model Correlation effort. However, one major accomplishment is that the test showed that there were no design flaws with the current flight design and implementation i.e. there were no "show stoppers" or items requiring redesign. All results were in-family with expectations. This result is supportive of the verification of the final flight "design" thermal performance.

Table 8-1: Core 2 Compliance Matrix

#	Status	Test Objective	
1	Pending	Core2 shall verify the final flight 'design' thermal performance and workmanship of critical core area thermal control features.	Flight design is conditionally verified pending final model correlation. There are no design changes required for thermal performance based on preliminary review of Core2 data. MLI/SLI is being modified in certain areas based on Core2 integration lessons learned. Verification of the final flight "design" thermal performance will be via analysis with correlated flight model. Thermal model correlation efforts are underway with an estimated completion date of 2016-09-30. A Thermal Model Correlation review is planned for 2016-10-05.
2	Completed	Core2 shall provide thermal test data for correlation of thermal models of critical core area thermal control features and aggregate core area performance.	Completed via three thermal balance cases: TB #5, TB4A, and TB4B. TB #5: Represents flight-like hot case with largest thermal signal-to-noise ratio. Excellent for thermal model correlation. Stringent temperature criteria met. TB #4: Represents hot case with Q-meter readings. Largest thermal signal-to-noise ratio. Stringent Q-meter and temperature criteria met.
3	Completed	Core2 shall provide for the rehearsal, and written and photo documentation of installation of critical core area thermal control features prior to flight unit installation.	Completed via extensive photo documentation as well as development and implementation by the NGAS flight-installation crew.
4	Completed	Test shall determine core area thermal performance sensitivity to IEC and Bus +J3 panel temperatures.	Completed via two thermal balance cases: TB #X and TB #Y. TB #X: Spacecraft +J3 Panel Hot-Operating, IEC Hot-Operating. Determined impact on Core 2 temperatures from increased IEC temperature (278K to 298K). Stringent Q-meter and temperature criteria met. TB #Y: Spacecraft +J3 Panel Cold-Operating, IEC Hot-Operating. Determined impact on Core 2 temperatures from decreased S/C +J3 Panel temperature (313K to 293K). Stringent Q-meter and temperature criteria met.

IX. Anomalies

As in any thermal vacuum test, anomalies occur. The team identified fourteen note-worthy items. The two most significant were:

- The PV3 Inner 100 mW Q-meter thermal short to shield (discussed previously)
- The inner PV3 blanket droop and short to BSF+V3 bumpers and blanket

Concerning the second anomaly, the ISIM floor blanket is suspended from the PV3 target with very thin nylon fishing lines. (The flight design uses x-shaped tensioned diagonal wires under the ISIM floor blanket.) During test it was deduced that this blanket was contacting the BSF floor blanket below it. After removal from the chamber, external visual observation confirmed the blanket had sagged significantly onto the BSF floor blanket. This drooping is considered the source of the higher PV3 Inner Q-meter heat loads seen in the various thermal balance cases.

X. Conclusions

The Core 2 test successfully completed three of its four test objectives. The fourth objective is conditionally met and is expected to be fully completed pending the Thermal Model Correlation Review

With the completion of Core 2, the critical thermal design of the Observatory ‘Core’ area has been demonstrated to be adequate for flight. Lessons learned during the integration of Core 2 are being applied to the integration procedures for the flight article.

Core2 test success represents a significant milestone in the overall verification program for JWST. NASA has now completed three of the five major cryogenic/thermal vacuum tests required for thermal verification. In 2017 the thermal verification program will complete with cryogenic tests of the telescope/instruments (OTIS) and a thermal vacuum test of the Spacecraft Bus with stowed Sunshield.