



National Aeronautics and Space Administration

John H. Glenn Research Center at Lewis Field, OH 44135

Passive Thermal Design approach for the Space
Communications and Navigation (SCaN) experiment on
the International Space Station (ISS)

DOCUMENT HISTORY LOG

Status (Preliminary/ Baseline/ Revision/ Canceled)	Document Revision	Effective Date	Description
Preliminary	Draft	5/23/2014	Initial Release

SIGNATURE PAGE

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1.0 INTRODUCTION

The SCaN payload provides an on-orbit, adaptable, SDR/STRS-based facility to conduct a suite of experiments to advance the Software Defined Radio (SDR) Space Telecommunications Radio Systems (STRS) Standards, reduce risk (TRL advancement) for candidate Constellation space flight hardware/software, and demonstrate space communication links critical to future NASA exploration missions.

The SCaN Project provides NASA, industry, other Government agencies, and academic partners the opportunity to develop and field communications, navigation, and networking technologies in the laboratory and space environment based on reconfigurable, software defined radio platforms and the STRS Architecture.

The SCaN payload is resident on the P3 Express Logistics Carrier (ELC) on the exterior truss of the International Space Station (ISS). The SCaN payload launched on the Japanese Aerospace Exploration Agency (JAXA) H-II Transfer Vehicle (HTV) and was installed on the International Space Station (ISS) P3 ELC located inboard RAM P3 site.

1.1 Purpose

This paper summarizes the thermal design, analysis, and environmental thermal testing performed for the design and development of the Thermal Control System of the SCaN space flight payload. The analysis and test results were the primary means to show compliance with operational and safety requirements associated with ELC/ISS cargo.

This paper provides thermal analysis and test results showing the thermal performance of the SCaN space flight payload throughout every stage of the mission starting with the JAXA HTV free orbit and on-orbit transfer, and ending with payload operations on the P3 ELC.

2.0 SCaN REQUIREMENTS

It was important that the requirements of the SCaN Thermal Control System (TCS) were defined early in the analysis/design cycle.

SCaN requirements included:

- Launch and Transfer Vehicle (JAXA HTV) requirements.
 - Acceptance and use of approved HTV thermal math model
 - Survival during all phases while in HTV / Heater Design
 - Passive FRAM-Based Cargo Interface Temperature Requirement
 - Incidental Contact Temperatures.
 - Provide SCaN thermal math model to JAXA.
 - Others
- International Space Station (ISS) requirements
 - Acceptance and use of approved ISS thermal math model
 - On-orbit Extra Vehicular Robotics (EVR) HTV to P3 ELC transfer.
 - Incidental Contact Temperatures
 - Heat Rejection to Neighboring Payloads
 - Thermal Exchange to Neighboring Payloads
 - Plume Heating
 - Passive FRAM-Based Cargo Interface Temperature Requirement
 - On-Orbit Survival during Planned 6-hr Power Outage
 - Provide SCaN thermal math model to ISS.
 - Others
- Science requirements
 - SCaN Components Temperature Requirements during Operations mode.
 - SCaN Components Temperature Requirements during Survival mode.

Early meetings and with both ISS and JAXA thermal teams were necessary to establish a set of preliminary requirements for the SCaN TCS because at that time ISS and JAXA requirements were still in flux.

The SCaN TCS team took the initiative and met with the ISS and JAXA thermal teams and generated an Excel spreadsheet that included all ISS and JAXA thermal requirements based on these meetings and based on all ISS and JAXA governing requirement documents. It was understood that several Preliminary Interface Revision Notices (PIRNs) were to follow that would change some of the requirements, but it was agreed that this way a preliminary set of requirements was put in place, with periodic updates as they became available via the PIRNs, for the SCaN thermal team to start preliminary design and analysis of the SCaN TCS.

The SCaN TCS thermal team kept track of any requirement changes till they all became final.

3.0 SCaN TCS DESIGN

3.1 Thermal Control System Description & Design

The SCaN payload is passively cooled. Three of its five sides (Starboard, Zenith, and Ram) function as highly efficient radiators coated with 10 mil Silver Teflon. All heat generated by the SCaN electronics is radiated to space through these three (3) radiators. The Wake and Nadir sides (facing toward other ORUs on the ELC) are non-radiating surfaces and are covered with Multi Layered Insulation (MLI).

During operational periods on ELC active temperature control will be performed by the avionics via heaters. During cold environments the SCaN avionics will actively control the radiator temperatures using heaters and power from the operational ISS power feed (120VDC, 200W).

Contingency power will be used to provide temperature control during periods when the ELC is not powered (ISS 120VDC, 200W) and during the HTV to ELC transfer, HTV (50VDC, 20W), NODE 2 (120VDC, 200W), Japanese Experiment Module (JEM) (120VDC, 200W), SSRMS (120VDC, 200W). This is intended to keep the component temperatures above the minimum storage temperatures. The control would be thermostatic electromechanical switches (Quad configuration, protection for both failed-on and failed-off cases)

The Payload is located on the ISS port P3 ELC, mounted on the starboard side of the P3 ELC on the zenith/ram corner as shown in Figure 3.1-1.



Figure 3.1-1—SCaN Location on ISS

The total surface area of the three radiators (Starboard, Zenith, and Ram) is about $\sim 1.70 \text{ m}^2$, but only about 1.22 m^2 ($\sim 72\%$) of the radiators are covered with 10 mil Silver Teflon as shown in Figure 3.1-2.

This was driven by the requirement to survive on the P3 ELC during times when SCaN was not operating and using the ISS provided heater power, which was limited to about 200 watts. This requirement was key to the design of the SCaN TCS.

The radiators were not sized to reject maximum power during worst case hot environment but instead they were sized to survive and maintain electronics above their survival temperatures during non-operational times, worst case cold environment, and with only the ISS provided heater power. Based on that, it was determined that the maximum available radiator area couldn't be utilized and the area that was covered with 10 mil Silver Teflon was about 72% of the total available radiator area.

Once the radiators were sized to meet the survival requirement, analysis predicted the maximum power SCaN can dissipate during worst case hot environment.

The Wake and Nadir sides are covered with MLI.

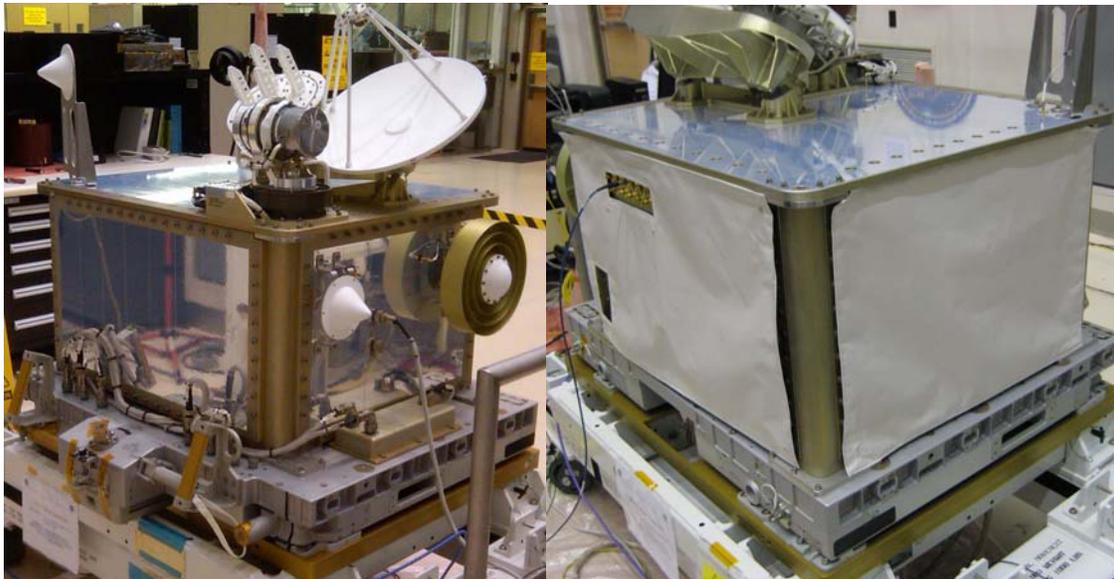


Figure 3.1-2—SCaN Radiators and MLI

The SCaN TCS was designed with guidance from MIL-STD-1540E.

The maximum test-to operating and non-operating temperature limits for all heat dissipating components were de-rated by 11°C for analysis uncertainty margin and 5°C for proto-qualification margin.

The minimum test-to operating and non-operating temperature limits were de-rated by 5°C for proto-qualification margin and a 25% margin on heater capacity was used in lieu of the 11°C for analysis uncertainty margin.

Incorporating MIL-STD-1540E to the component “test” temperature ranges, component analysis temperatures limits are derived, as shown in Table 3.1-1. It should be noted that APS Actuators and Antennas temperatures do not incorporate guidance from MIL-STD-1540E.

Table 3.1-1—SCaN Component Test and Analysis Temperature Ranges

TESTING				
Component	Min. Operating Temps (°C)	Max. Operating Temps (°C)	Min. Non-Operating Temps (°C)	Max. Non-Operating Temps (°C)
Antennas	-89	100	-89	100
APS Actuators	-5	75	-50	75
AVNS	-20	50	-40	85
GCE	-15	45	-35	50
GD	-20	60	-34	85
HARRIS	-30	50	-35	85
JPL (ALL but GPS Mode)	-35	55	-40	80
JPL (GPS Mode)	-18	55	-40	80
RF	-20	70	-40	70
TWTA PSU	-20	80	-50	80
1540E Protoflight Margins *(1)	5	16	5	16
*(1) For min. temps. use 5°C margin and 25% heater margin				
ANALYSIS				
Component	Min. Operating Temps (°C)	Max. Operating Temps (°C)	Min. Non-Operating Temps (°C)	Max. Non-Operating Temps (°C)
Antennas	-84	84	-84	84
APS Actuators	0	65	-45	65
AVNS	-15	34	-35	69
GCE	-10	29	-30	34
GD	-15	44	-29	69
HARRIS	-25	34	-30	69
JPL (ALL but GPS Mode)	-30	39	-35	64
JPL (GPS Mode)	-13	39	-35	64
RF	-15	54	-35	54
TWTA PSU	-15	64	-45	64

3.2 Thermal Analysis Approach

The Thermal Analysis approach was to develop an integrated Thermal Desktop model composed of the ISS model (provided by JSC), the HTV model (provided by JAXA), and P3 ELC with the SCaN model (generated by SCaN Thermal Team).

The Thermal Desktop model is based on the final SCaN flight layout shown in Figure 3.2-1

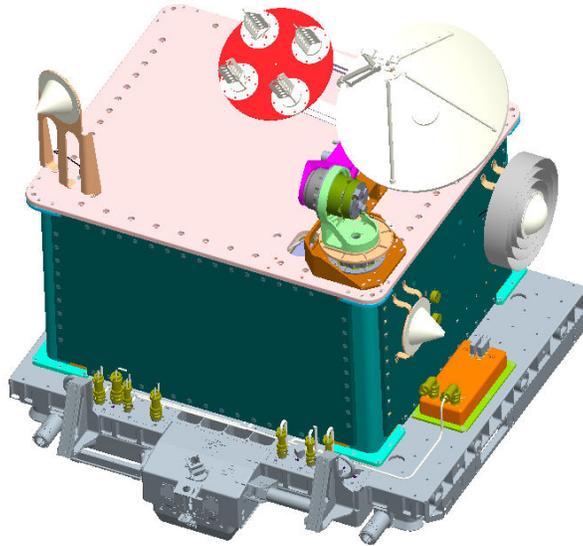


Figure 3.2-1—SCaN Flight Design

There are six (6) key areas to be analyzed.

1. Minimum heater power required for worst case cold environment during non-operating conditions (Design driver).
2. On-orbit operations (% of time operation) for the worst case hot environment.
3. Survival during planned 6 hr power loss for worst case cold environment.
4. HTV to P3 ELC transfer for worst case cold environment.
5. Incidental contact temperatures.
6. Heat rejection to neighboring payloads.

The SCaN on-orbit environment to be used for the Thermal Analysis was dictated by ISS and JAXA requirement documents, such as “SSP 57003” and “SSP 57003-ELC”

The SCaN detailed Thermal Desktop Model was generated per final flight drawings and it is shown in Figure 3.2-2.

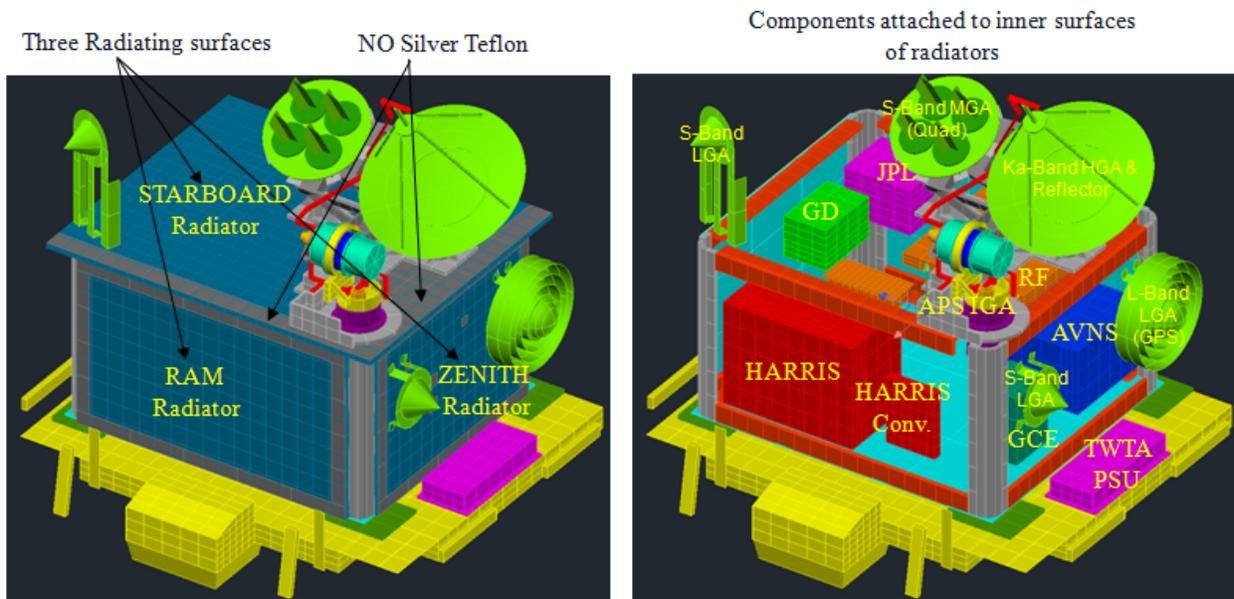


Figure 3.2-2—SCaN Detailed Thermal Desktop Model

A simplified Thermal Desktop model was derived from the detailed model and used for the Orbital Heating Rates analysis.

A variety of combinations of the following parameters were analyzed to determine the worst case hot and cold orbital heating rates for the SCaN payload:

- Beta angles and Altitude with Roll, Pitch and Yaw combinations.
- Hot and Cold Solar & Earth Radiation, and Earth Albedo.
- Some of the cases were analyzed with and without other ORUs on P3 ELC, without seeing any substantial differences.
- Over 100 possible combinations were analyzed.

With the worst case hot and cold environments established the detailed Thermal Desktop model was used to predict SCaN component temperatures and minimum heater power requirements.

As discussed earlier, the minimum heater power available to the SCaN payload during ELC contingency scenarios is ~ 200 watts. In order to maintain the SCaN components above their survival limits with ~ 200 watts of heater power (including 25% margin) the efficiency of the 3 radiators had to be reduced. The total area of the 3 radiators is ~ 1.70 m². It was determined by analysis, and later validated by the TVAC test, that about 28% of the total radiator area, or 0.48 m², will not be covered with 10 mil Silver Teflon.

On-Orbit HTV to P3 ELC Transfer

The HTV to P3 ELC transfer will take place according to the stages shown in Table 3.5-1, and Figure 3.2-4. For each stage final durations and heater power allocations are also included. This timeline and associated heater power available was received from the ISS EVR office and JAXA.

Table 3.2-1—HTV to JEM to P3 ELC Transfer

Ref #	Event	Time Hrs	Total Time Hrs	Power Source	Voltage VDC	Voltage Range VDC	Power Watts (Min. VDC)	Power Watts (Max. VDC)	ANALYSIS Heater POWER
1	HTV Free Flight	15	15	HTV	50	27-52	13.1	48.5	0
2	HTV Free Flight to Node2 Part1 (HTV Rotated 45 deg.)	1.5	16.5	HTV	50	27-52	13.1	48.5	0
3	HTV Free Flight to Node2 Part2 (HTV Fully Rotated Being Docked)	3.5	20	HTV	50	27-52	13.1	48.5	0
4A	HTV Docked on Node2	10	30	HTV	50	27-52	13.1	48.5	0
4	HTV Docked on Node2	20	50	SSRMS	120	106-126	201.6	284.8	201.6
5	EP Node2 to JEM Part1 (SSRMS / EP Extracted from HTV)	1	51	SSRMS	120	106-126	201.6	284.8	0
6	EP Node2 to JEM Part2 (SSRMS / EP half way to JEM EF)	2	53	SSRMS	120	106-126	201.6	284.8	0
7	EP Node2 to JEM Part3 (JEMRMS / EP on the way to JEM EF)	3	56	NA	NA	NA	NA	NA	0
8	EP Node2 to JEM Part4 (EP on JEM EF)	1	57	NA	NA	NA	NA	NA	0
9	EP On JEM EF	30	87	JEM	120	108.5-126.5	211.2	287.1	211.2
10	From JEM EF to SPDMS (SSRMS)	0.62	87.62	SSRMS	120	106-126	201.6	284.8	0
11	Transfer SPDMS to P3 ELC (SSRMS)	2.5	90.12	SSRMS	120	106-126	201.6	284.8	0
12	Install on P3 ELC	1.25	91.37	SSRMS	120	106-126	201.6	284.8	0
12A	Install on P3 ELC Additional time for 6 hr total	1.63	93	SSRMS	120	106-126	201.6	284.8	0

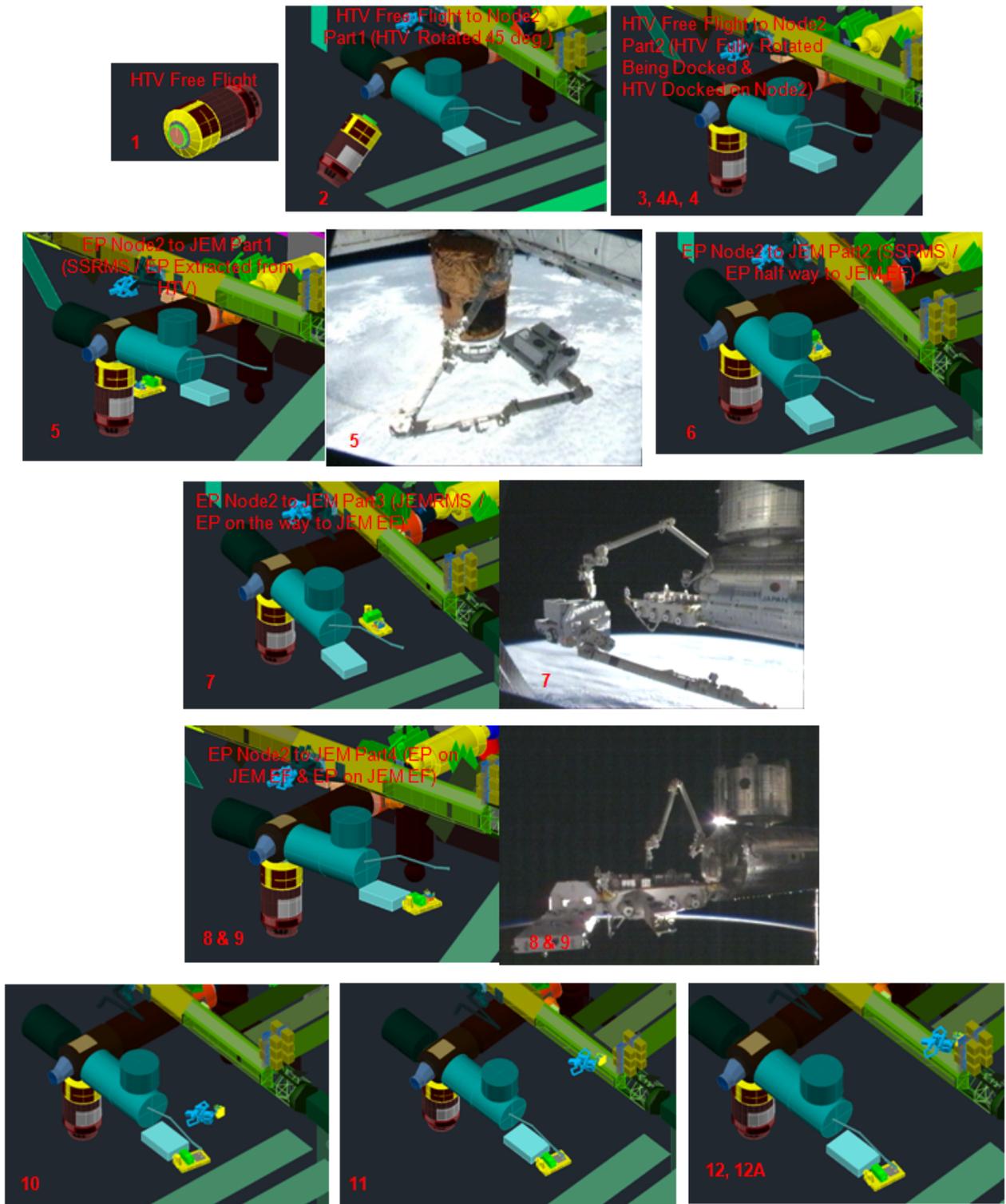


Figure 3.2-4—SCaN HTV to JEM to P3 ELC Transfer

The Thermal Desktop model was updated to include the HTV. The HTV model was provided by JAXA. The model was converted to Thermal Desktop, as shown below in Figure 3.2-5, and incorporated into the ISS/SCaN model shown in Figure 3.2-4.

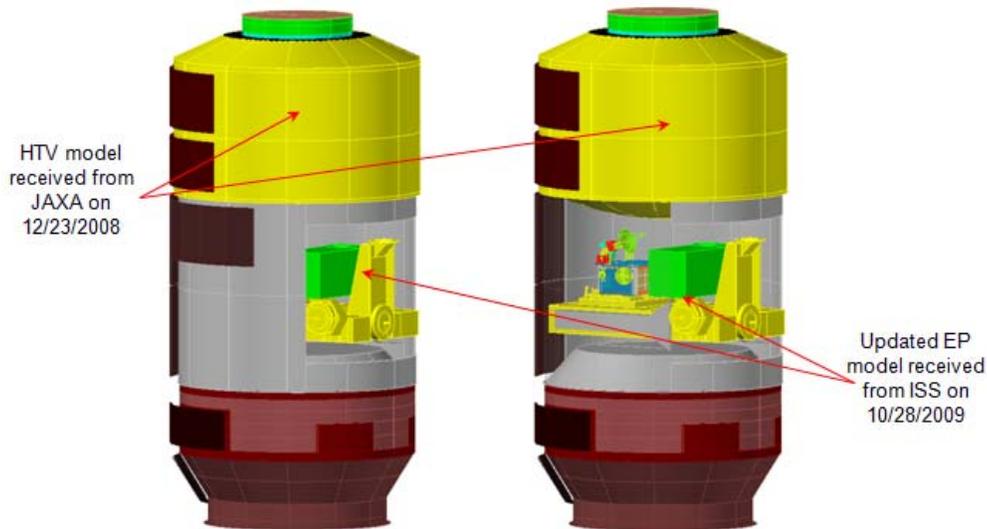


Figure 3.2-5—JAXA Provided HTV Model

For the SCaN HTV to P3 ELC transfer, 3 cases were analyzed. One for Beta +75, one for Beta 0, and one for Beta -75

Figure 3.2-6 shows the temperature profile for each stage in Table 3.2-1 for Beta +75. All SCaN component temperatures are above survival limits.

It must be noted that:

- 1) After HTV berthing with Node 2, SCaN payload could remain inside the HTV without any Heater Power for a long period of time. This necessitates a minimum warm-up time by SSRMS 120V power prior to EP-MP extraction from HTV on the way to JEM-EF
- 2) SSRMS EP-MP extraction from Node 2 and subsequent move to JEM-EF could be up to 7 hours long without any heater power. Once berthed with JEM-EF and due to the 7 hour move without power, SCaN components temperatures will be low. This necessitates a minimum warm-up time by JEM-EF 120V power prior to the move to P3 ELC.

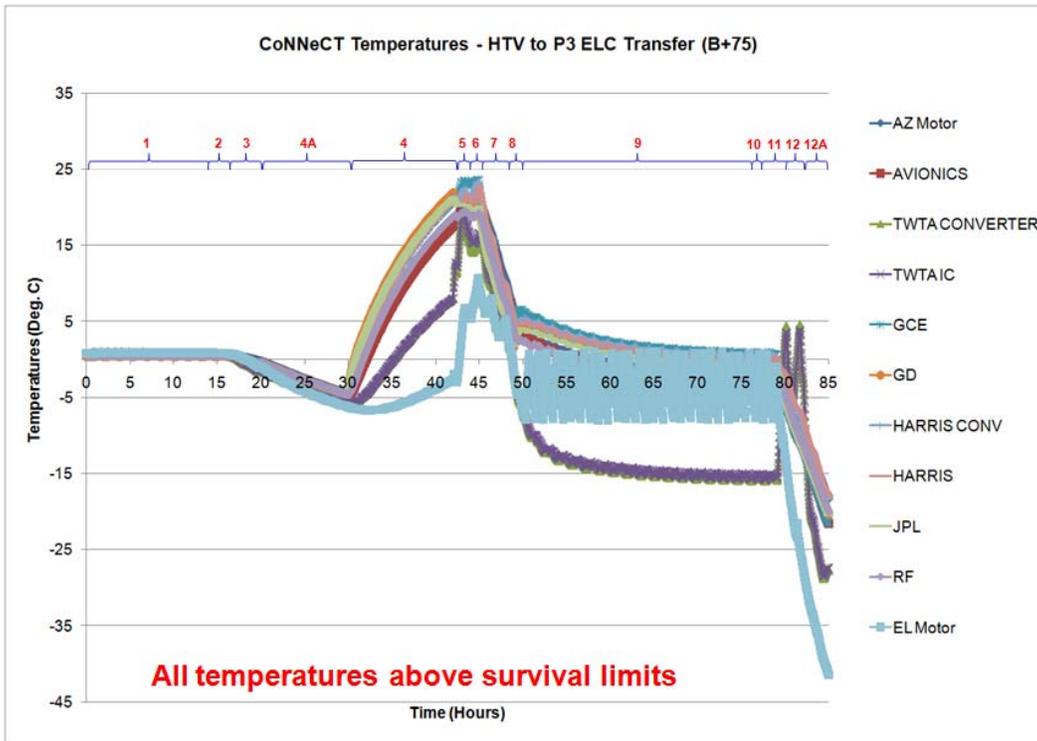


Figure 3.2-6—HTV to P3 ELC SCaN Temperatures – Beta +75

These minimum warm-up times are a function of Beta angle and are shown in Table 3.2-2

Table 3.2-2—SCaN Minimum Warm-up times during Transfer

ISS Beta Angle	Warm-up time from SSRMS 120VDC prior to HTV extraction	Warm-up time from JEM-EF 120VDC prior to P3 ELC move
+75	15 hrs	20 hrs
0	18 hrs	10 hrs
-75	20 hrs	5 hrs

On-Orbit Survival during Planned 6-hr Power Outage

The on-orbit survival during planned 6-hr power loss was analyzed for worst cold case orbital conditions: Beta+75, and for a 10 mil Silver Teflon radiator with BOL $\alpha=0.09$ and $\epsilon=0.88$.

Prior to planned 6 hour power loss, components are turned on to warm-up. In addition heater power is applied in strategic areas. Total power required for component warm-up is ~552 Watts.

Thermal Analysis results with SCaN component mounting temperatures after the 6-hr power outage are shown below in Figure 3.2.3. After a 30 hour warm-up, at the end of the 6 hour planned power outage, ALL SCaN Radio Components are WITHIN their non-operating temperature limits with an average margin of $\sim 18^{\circ}\text{C}$. Results also showed that a 20 hour warm-up will also be sufficient.

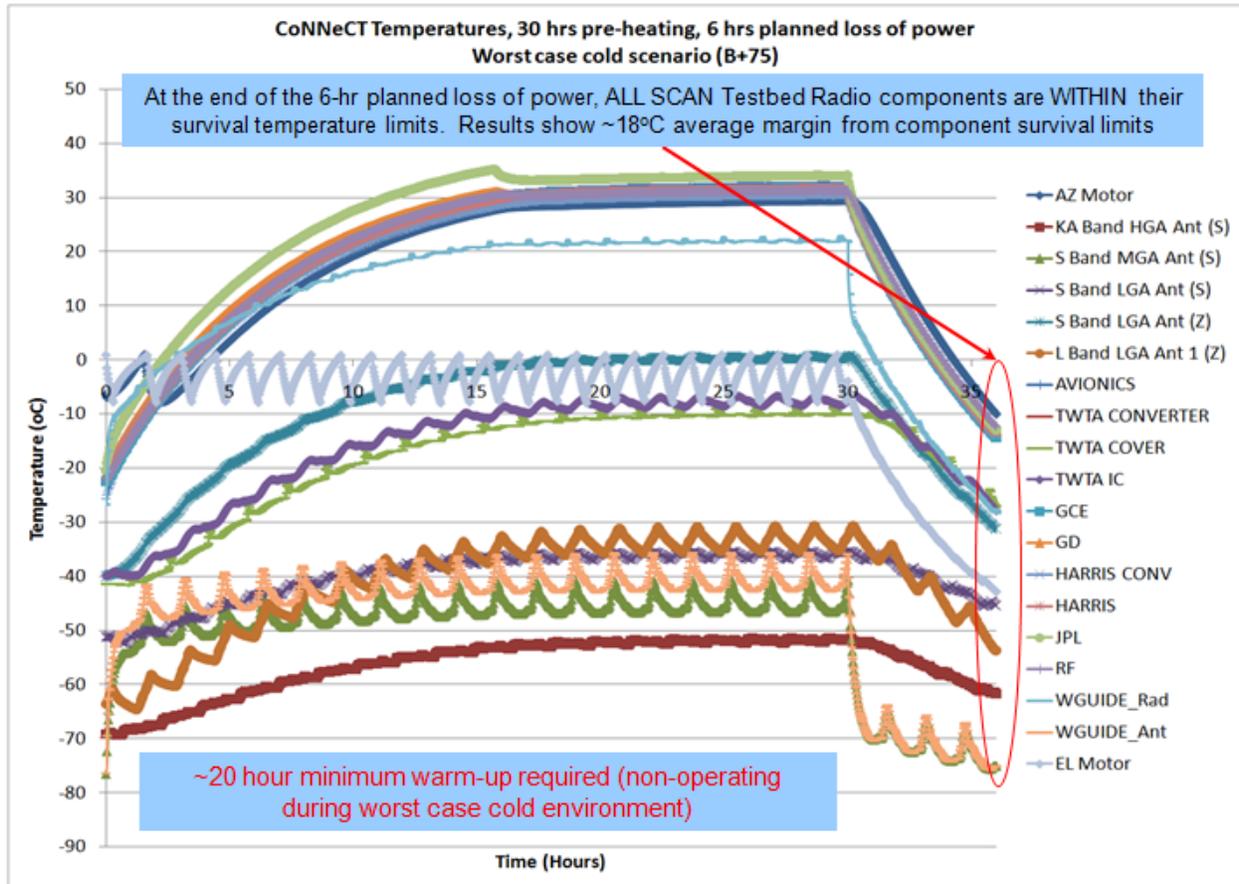


Figure 3.2-3—SCaN Temperatures after 6-hr Power Outage

The analysis was repeated with at least one radio failed, which implies less warm-up power, and results showed that ALL SCaN Radio Component temperatures are still well within their non-operating limits.

SCaN On-Orbit Operations

The SCaN radiators must reject all internal heat loads while maintaining all components at or below their maximum operating temperatures in the warmest environment.

As seen earlier, the SCaN radiators were designed to survive the worst case cold environment with the minimum heater power available, in order to maintain SCaN components above their non-operating/survival temperatures.

Using the TVAC test validated Thermal Desktop model, analysis was performed for all 37 modes of operation over the full range of Beta angles (-75° to +75°) and for both Beginning-of-Life (BOL) and End-of-Life (EOL & EOL) values.

For any mode of operation with its corresponding power dissipation, the maximum transient operating temperature of the radiator surface at the component interface was predicted for the full range of Beta angles. Subsequently, the range of Beta angles out of the full -75° to +75° range that the component was at or below its maximum operating temperature was calculated as days of operation per year or % operating time.

This analysis was repeated for all operating modes and results are shown in Figure 3.3-3

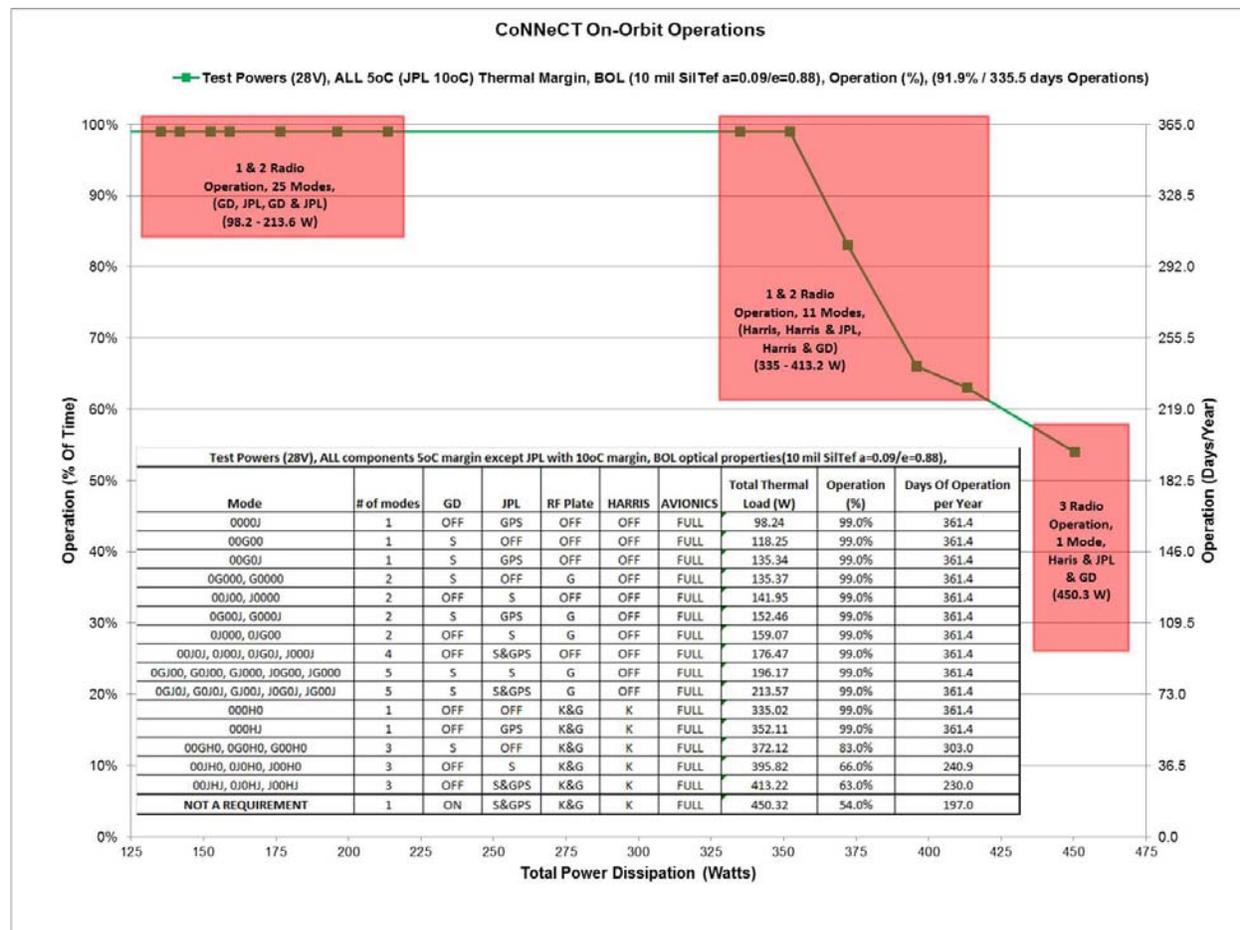


Figure 3.3-3—SCaN On-Orbit Operations

Results show that with a 5°C margin incorporated for all components except JPL, and a 10°C incorporated for JPL, SCaN can operate close to 334 days per year (91.9% of the time) during the initial years assuming there is no contamination of the optical properties of the 10 mil Silver Teflon.

Based on the results of the System TVAC test, it is recommended to use a 5°C margin for all components except JPL and 10°C (5°C + 5°C) margin for JPL (JPL requested the additional 5°C margin to account for their thermal analysis uncertainties)

The 5°C margin is incorporated to account for:

- The temperature difference between the mounting surface under the baseplate of each component and the approximate location of the Thermistor or RTD monitoring that component.
- The temperature sensor accuracy/error.
- The temperature drop across the thermal interface material between each component baseplate and the radiator surface.

Thermal analysis results (confirmed by TVAC test data) showed that the TOTAL offset of the temperature limits due to the above, varied between 1°C and 4°C for the different SCaN components.

Incorporating the 5°C margin for all components except JPL and 10°C margin for JPL, SCaN can operate up to 334 days per year or 91.9% of the time.

4.0 SCAN TVAC TESTING

4.1 SCaN STA TVAC Testing

Early in the design phase, the SCaN thermal team decided to utilize the existing Structural Test Article (STA), which was built for structural testing, and perform a TVAC test and define the test setup necessary to simulate the on-orbit environment of the SCaN radiators. The setup of these environments (hot and cold) may require numerous changes to the arrangement and intensity of lamps being used to dial-in the correct thermal environment for each of the three radiators. By using the Structural Test Article (STA) to define this test setup in advance, the project will reduce time needed for thermal vacuum cycling and performance verification of the Flight payload.

Additionally, by simulating the operational heat loads on the STA, the project will obtain an early report on the performance of the thermal control system, specifically, the effectiveness of the radiators. This will allow more time for design adjustments if needed. For example, the most likely adjustment would be the percentage of radiator coverage with silver/teflon (Ag/FEP). The test data will also provide some validation of the thermal model used to predict the on-orbit performance. The results of this test may allow reduction in the current thermal margin (16°F) used in the design analyses of the radiators. This would provide higher duty cycles for payload operations

4.1.1 IR Lamps setup

The VF6 facility is equipped with a LN2 cold wall that operates at 85K (-188°C). This is far below the environmental sink temperatures of the SCaN radiators. Therefore heat flux must be added to the radiators to achieve the designated sink thermal environment. IR lamps are commonly used for this purpose.

The heat flux values that the lamps are required to produce was calculated from the SCaN detailed Thermal Desktop model.

Given the Thermal Desktop generated target heat fluxes for the incident surfaces, a number of lamps, and a mathematical description of the lamp energy output, it was possible to find satisfactory lamp arrays and predict the intensity of the lamps required to produce the necessary fluxes.

The infrared lamp array thermal radiation heat transfer model involved both a combination of trial and error and batch runs of 32-bit GWBASIC programs VERTSCAN.BAS and HORTSCAN.BAS (originally written by R. Ziemke and described in NASA/TM-2004-212332, *Infrared Heater Used in Qualification Testing of International Space Station Radiators*, May 2004).

The lamp intensity will be varied (voltage regulation) to bring the radiator to temperatures predicted by the on-orbit SCaN thermal model.

After the successful completion of the STA TVAC, the lamp voltages for both hot and cold worst case environments were recorded and were used as the starting point during the SCaN TVAC of the flight payload.

4.2 SCaN Flight System TVAC Testing

System TVAC Testing (3/25/2011 – 4/4/2011)

The SCaN Flight System was TVAC tested in Vacuum Facility #6 (VF6), in Building 301, at NASA GRC.

“Flight System Thermal Vacuum (TVAC) Test Report”, GRC-CONN-RPT-0781 is available for review. The report includes validation of the Thermal Desktop model.

A synopsis of the TVAC test results is included in this report.

The as tested hardware is shown in Figure 4.2-1

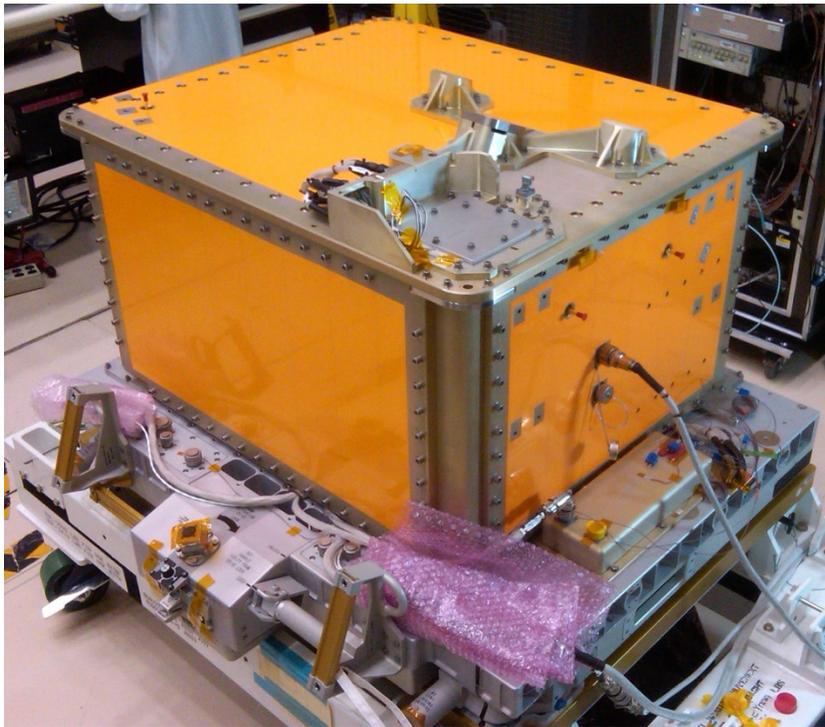


Figure 4.2-1—System TVAC as Tested Hardware

The as tested hardware with the necessary support hardware in VF6 is shown in Figure 4.2-2

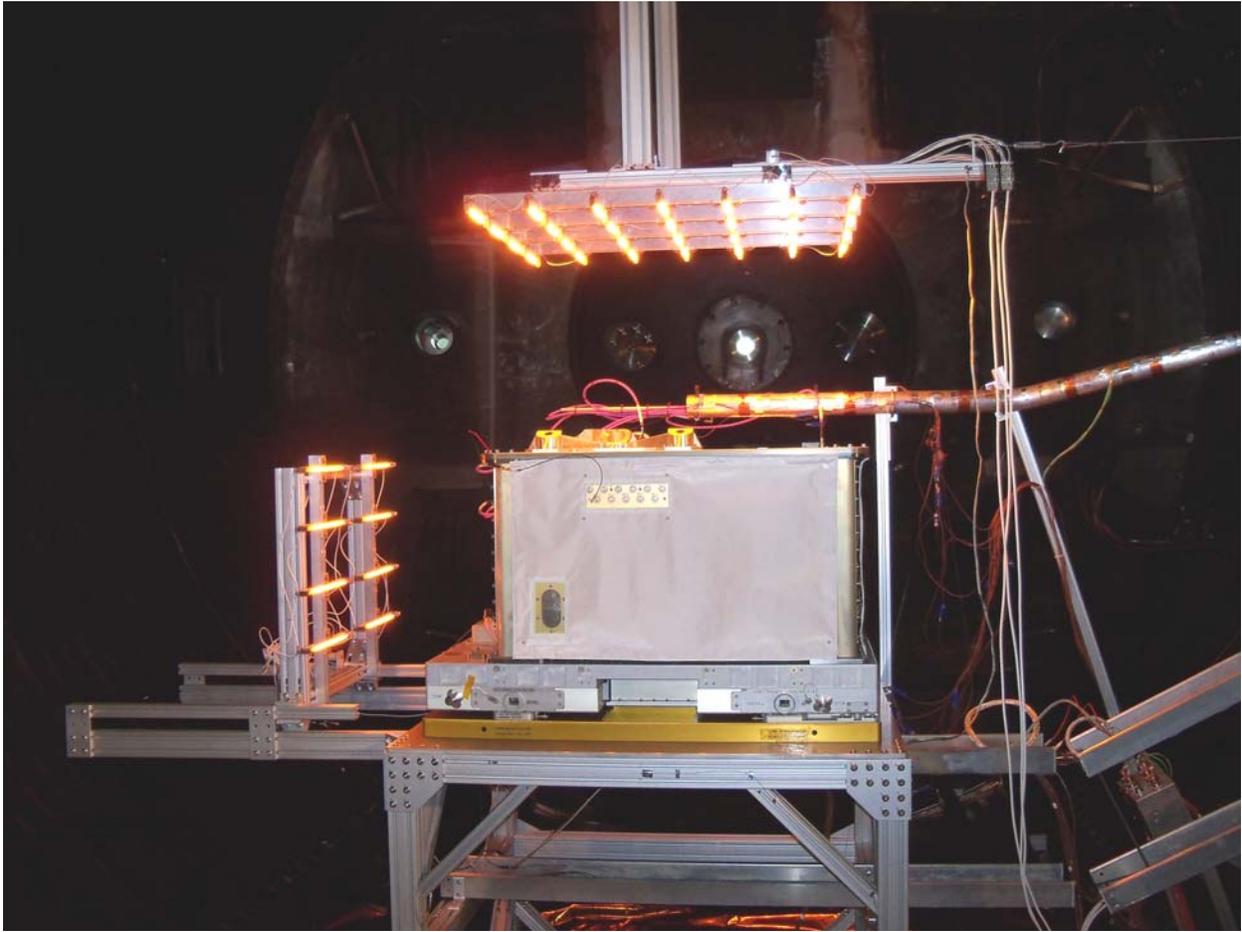


Figure 4.2-2—System TVAC as Tested Hardware in VF6

A picture of the hardware during the TVAC test in VF6 is shown in Figure 4.2-3 (Taken from the North East window of the chamber).

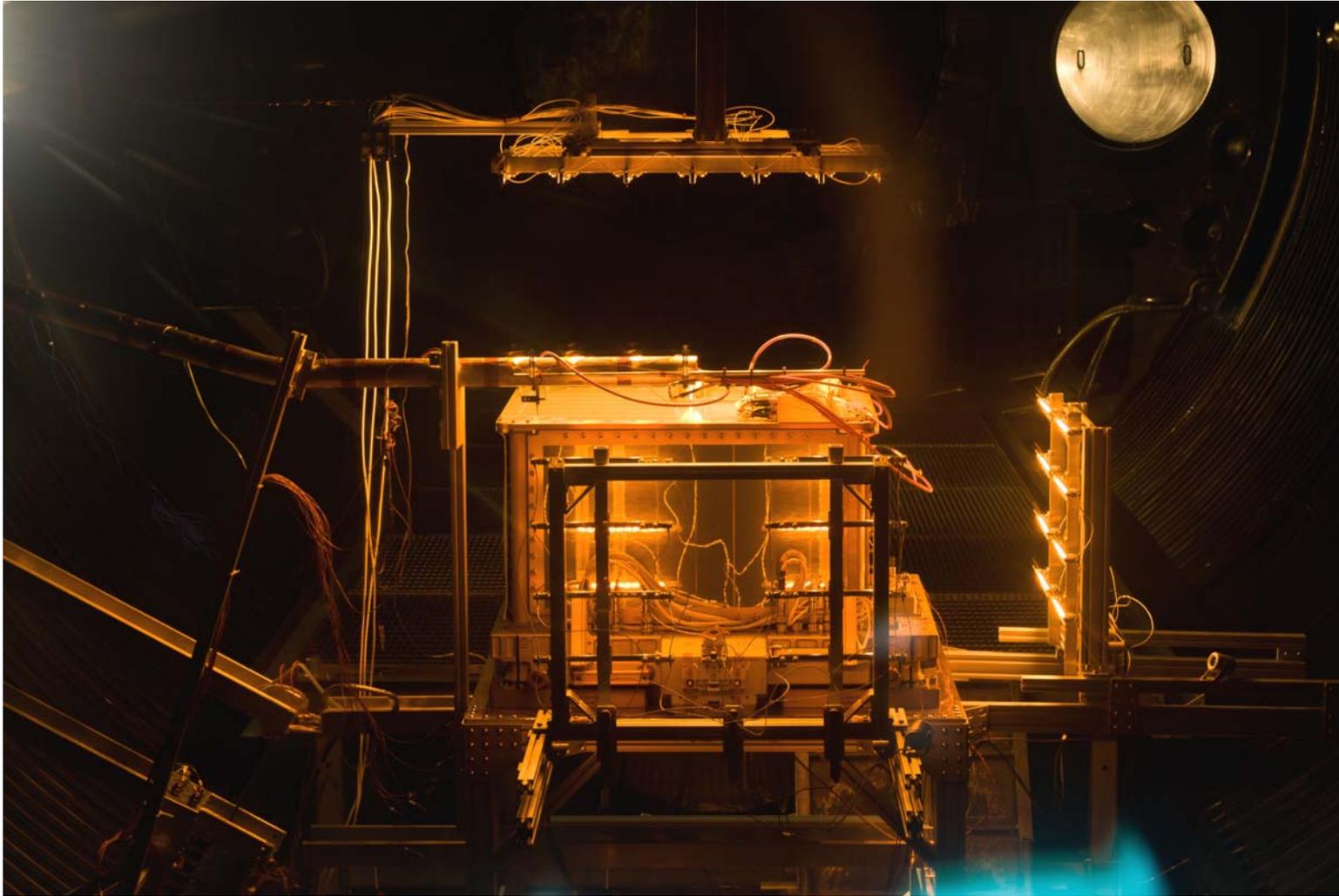


Figure 4.2-3—System TVAC Hardware being tested in VF6

The as tested temperature profile of the temperature control sensors is shown in Figure 4.2-4

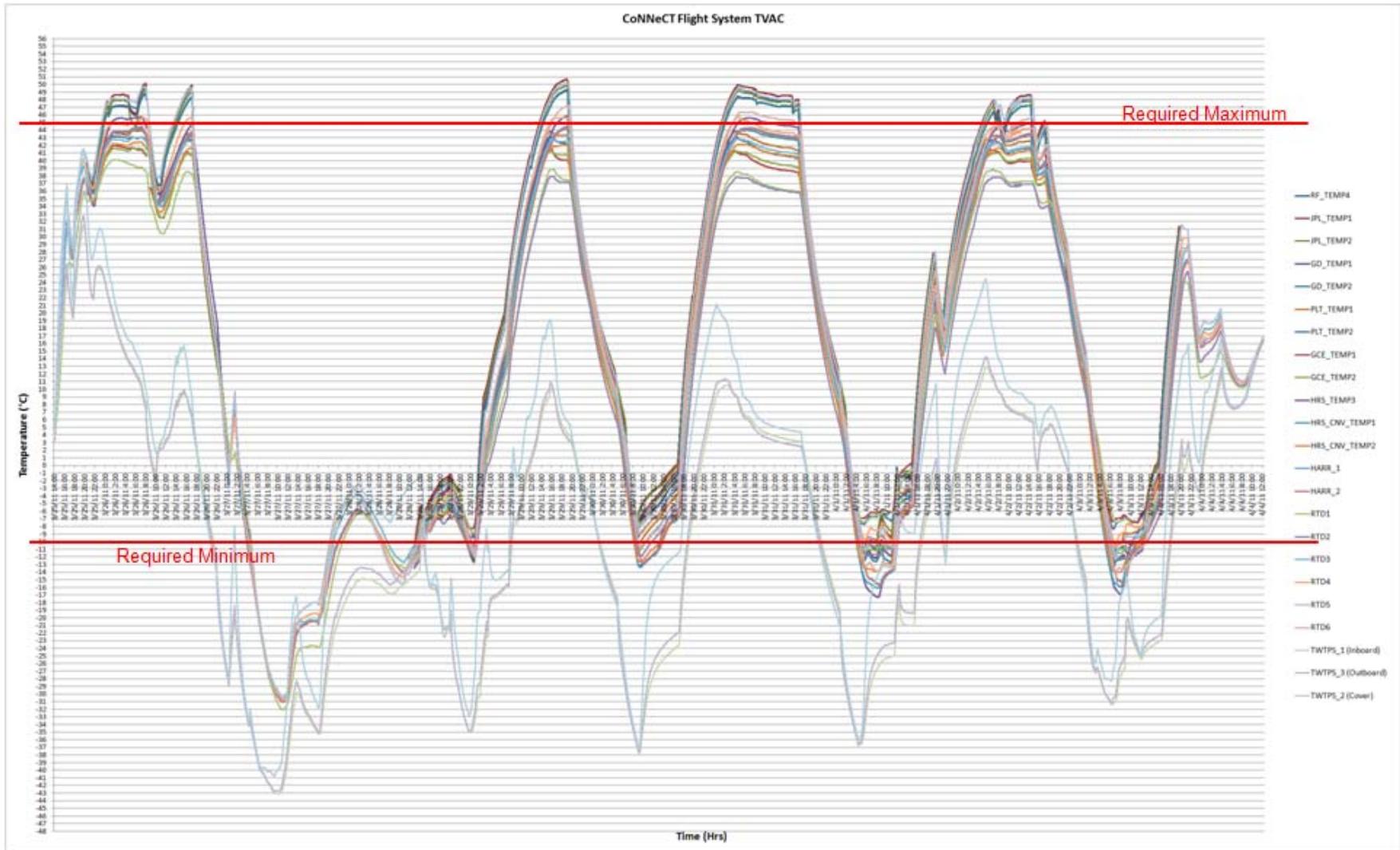


Figure 4.2-4—System TVAC Actual Temperature Profile

5.0 SCAN ON-ORBIT TRANSFER

The SCaN Payload was launched on-orbit aboard the JAXA HTV3 on Friday, August 20th, 2012.

The HTV3 docked with ISS Node 2 on Friday, August 27th, 2012. The SCaN Payload remained inside the HTV3 for about 10 days.

On Monday August 6, 2012, at 3:10 am the 1st part of the on-orbit EVR transfer from the HTV3 to the JEM EF started and was completed 5 hours and 7 minutes later, at 8:17 am, when heater power from JEM-EF to SCaN Payload was confirmed.

On Tuesday August 7, 2012, at 1:30 am the 2nd part of the on-orbit EVR transfer from the JEM EF to the P3 ELC started:

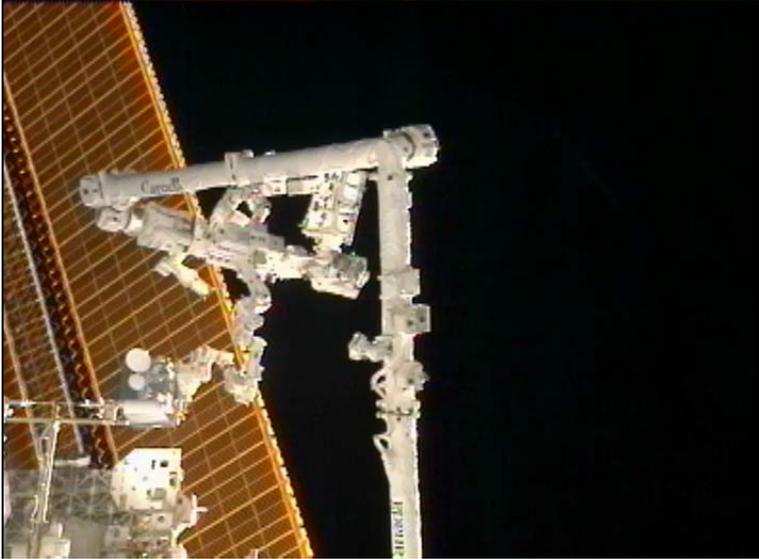
- 1) 1:30 am: SSRMS with DEXTER takes hold of SCaN FRAM



- 2) 1:37 am: JEM-EF heater power to SCaN is confirmed OFF, Thermal Clock ON! SSRMS lifts SCaN FRAM from JEM-EF



3) 2:00 am, 3:00 am, 4:00 am....All is well on the way to P3 ELC



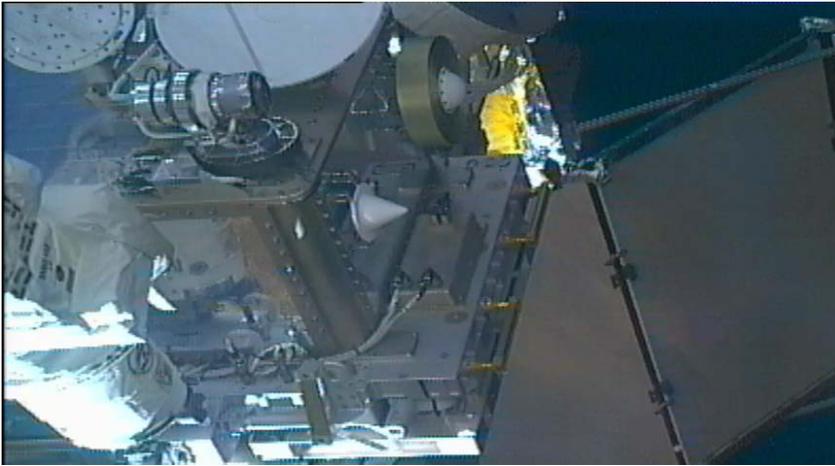
4) 5:30 am... All is well, SCaN arrives near P3 ELC, almost Home!



5) 5:30 am to 6:00 am, the EVR crew is trying to engage the connectors and secure SCaN on P3 ELC and provide heater power. Tries #1 and #2



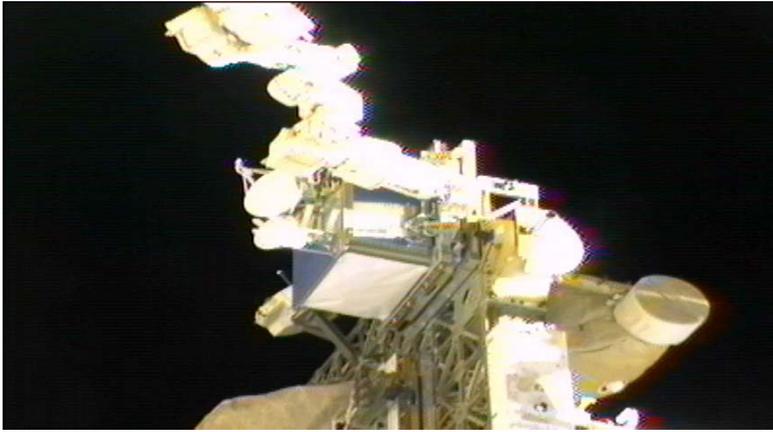
- 6) 6:00 am to 6:30 am, the EVR crew is trying to engage the connectors and secure SCaN on P3 ELC and provide heater power. Tries #3 and #4



- 7) 6:30 am to 7:00 am, the EVR crew is trying to engage the connectors and secure SCaN on P3 ELC and provide heater power. Tries #5 and #6



- 8) 7:00 am to 7:25, the EVR crew is trying to engage the connectors and secure SCaN on P3 ELC and provide heater power. Tries #6 and #7 and.....



- 9) 7:25 am. The SCaN Payload is successfully installed and heater power from the P3 ELC to SCaN Payload is confirmed via telemetry received at GRC Control Room.

6.0 SCAN ON-ORBIT THERMAL MODEL VALIDATION

After the successful installation of the SCaN payload on the ISS P3 ELC, and for the following four months (August – November 2012) the SCaN Operations Team went through their detailed on orbit check out of the payload.

During this time, there were several combinations of radios operating with different Beta angles, and other parameters such as ISS altitude, attitude, etc.

The SCaN thermal team reviewed the on-orbit telemetry data and worked with the SCAN operations team and gathered several on-orbit data “points” for several power configurations and Beta angles, to start the thermal model validation.

Six cases were chosen to be used for the on-orbit TD thermal model validation because they covered a wide range of parameter variation and SCaN total power dissipations.

The detailed SCAN Thermal Desktop thermal model was then used to predict temperatures for the six on-orbit cases.

Predicted component temperatures were in excellent agreement (within 3 to 4°C) with the on-orbit temperatures.

NO further (after TVAC testing validation) TD thermal model modifications were necessary.

The TD thermal model is therefore available to provide SCAN scientists a set of predicted temperatures that can be used in the future to estimate when a specific “mode” of operations can be performed and what the expected temperatures will be. Since there were no modifications to the TD thermal model, the Analysis Report and all the accompanying information that has been delivered to the team in the past is still adequate and there is no need for an update.

ACRONYMS AND ABBREVIATIONS

BOL	Beginning-Of-Life
SCaN	Space Communications and Navigation
ELC	ExPRESS Logistics Carrier
EP	Exposed Pallet
GRC	Glenn Research Center
HTV	H-II Transfer Vehicle
ISS	International Space Station Program
JAXA	Japanese Aerospace Exploration Agency
JEM	Japanese Experiment Module
JSC	Johnson Space Center
MLI	Multi-Layer Insulation
NASA	National Aeronautics and Space Administration
ORU	Orbital Replacement Unit
SDR	Software Defined Radios
SSP	Space Station Program
SSRMS	Space Station Remote Manipulator System
STRS	Space Telecommunications Radio System