CRYOGENIC QUAD-REDUNDANT THERMAL SWITCH

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ABSTRACT

A Quad-Redundant Thermal Switch (QRTS) for the James Webb Space Telescope has been successfully designed, fabricated, and tested at the Space Dynamics Laboratory (SDL). A flight-like prototype successfully passed thermal and structural qualification tests in a representative space environment and achieved Technology Readiness Level 6. The QRTS serves as a high thermal conductance, high reliability thermal connect / disconnect between heat sources and sinks. The switch design is passively closed over the entire operational range of 32 – 300 K. The construction is an all metallic core packaged in a cross-strapped quad-redundant configuration. Actuation of the switch is based on differential thermal expansion and is opened by applying heat to the mechanism. Key qualification tests included: robust characterization of thermal closed and open performance from 32 to 313 K; and a full suite of vibration testing (sine, random, and sine burst). This paper presents an overview of the QRTS functionality, thermal and structural qualification tests, and resulting switch performance.

KEYWORDS: cryogenic, thermal switch, thermal, JWST

INTRODUCTION

The James Webb Space Telescope (JWST) Thermal Switch Phase II development program funded by Goddard Space Flight Center (GSFC) supported the design, fabrication, and thermal and vibration testing of a single flight-like prototype cryogenic Quad-

FIGURE 1. Assembled quad-redundant thermal switch.

redundant Thermal Switch (QRTS) by Space Dynamics Laboratory (SDL). The overriding objective of the work was to fabricate a flight-like QRTS and measure switch performance against specified requirements in a flight relevant environment.

During this developmental phase, a single flight-like prototype of the full QRTS was fabricated and assembled (see FIGURE 1). A full suite of vibration and cryogenic thermal characterization was performed.

The fabrication and testing of the thermal switch were successful. TABLE 1 shows the switch key performance results. The formal testing sequence consisted of a series of pre-vibration thermal tests, full qualification level vibration tests, and a full suite of post-vibration thermal tests. Pre-vibration thermal tests showed excellent performance. A full suite of vibration tests were successfully conducted. Post-vibration thermal test also showed excellent results with closed conductance values greater than 190% of required values. The tests also confirmed that the switch remained closed, providing an excellent thermal path, from room temperature to 32 K which was a design driver. Thermal and structural models were correlated with the test results.

At completion, the tests confirmed that the SDL QRTS shows excellent thermal and structural performance in a flight relevant environment. The QRTS work culminated at a Technology Readiness Level assessment at GSFC in November, 2006 where the switch was given Technology Readiness Level 6 status. The QRTS is now qualified and ready for flight fabrication.

TABLE 1. Measured QRTS performance.

Specification	**Performance**
Closed Thermal Conductance	2.14 W/K @ 40 K (2.95 W/K all contacts closed)
Open Time/Close Time	47 min / 110 min (average)
Power to Open	2.0 W vacuum / 12.0 W atmosphere
Mass	2.83 kg
Volume	133.9 x 170.3 x 196.1 mm
Fixed Base Frequency	161 Hz
Structural Load	Qualified to 37.5 G

SWITCH DESIGN OVERVIEW

The QRTS acts as a thermal connect/disconnect between a cooling source and an instrument. In normal operation, the switch is closed and acts as a continuous thermal strap. When desired, this thermal path may be broken by applying electrical power to the QRTS which opens the thermal path using a straight forward differential thermal expansion approach. The quad redundant design allows the switch to remain closed with the failure of one leg open, and conversely will remain open with one leg failed closed. The switch consists of four individual thermal connect/disconnect actuators packaged in a quad-redundant configuration. FIGURE 2 illustrates the switch quad-redundant configuration.

The actuation of the individual switches is based on application of heat to the actuators and the resulting differential thermal expansion. The redundant heaters on the

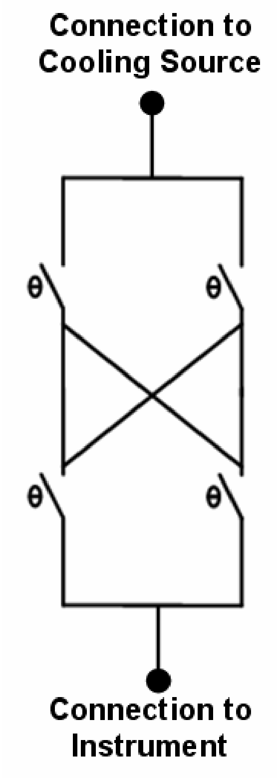

FIGURE 2. Illustration of quad-redundant configuration.

individual actuators are wired in a parallel fashion resulting in simultaneous actuation of all four switches. Upon removal of heater power the switches return to the closed state. The overall actuation configuration is ideal for providing high conductance cooling to an instrument at cryogenic temperatures with low levels of parasitic heat loads.

Power requirements to actuate the switch are 2.0 W total in vacuum and 12.0 W total in atmospheric conditions at 293 K. Upon actuation to the open state the switch acts as a thermal stop preventing heat from flowing along the conduction path. Typically the 2.0 W of applied heat flows back into the two thermal interfaces. The distribution of this heat flow is dependent upon the temperatures of the thermal interfaces.

The switch is packaged in an aluminum case, which houses the switch assembly. The case is also designed to mount directly to a support structure. OFHC (C10100) copper was carefully selected as the material for the conduction path. Copper was selected for its high thermal conductivity-to-weight ratio over the entire switch operating temperature range and its availability.

Integration of the switch to an assembly is accomplished via thermal, mechanical, and electrical interfaces. The thermal interfaces are located on the sides of the switch and consist of a lapped bolted interface. Structural mounting of the switch is accomplished by bolting the switch to on the bottom surface via four fasteners. Four electrical connections are provided (two flight and two ground connectors) to provide control and monitoring of the internal switch heaters, temperature sensors, and strain gauges.

In addition to the development of the switch technology, the switch design also incorporates several other SDL developed technologies. Thermal connections from the thermal interface to the switch actuators are accomplished via solderless flexible thermal links. Thermal isolation and structural support of the thermal interfaces are provided by Fiber Support Technology (FiST).

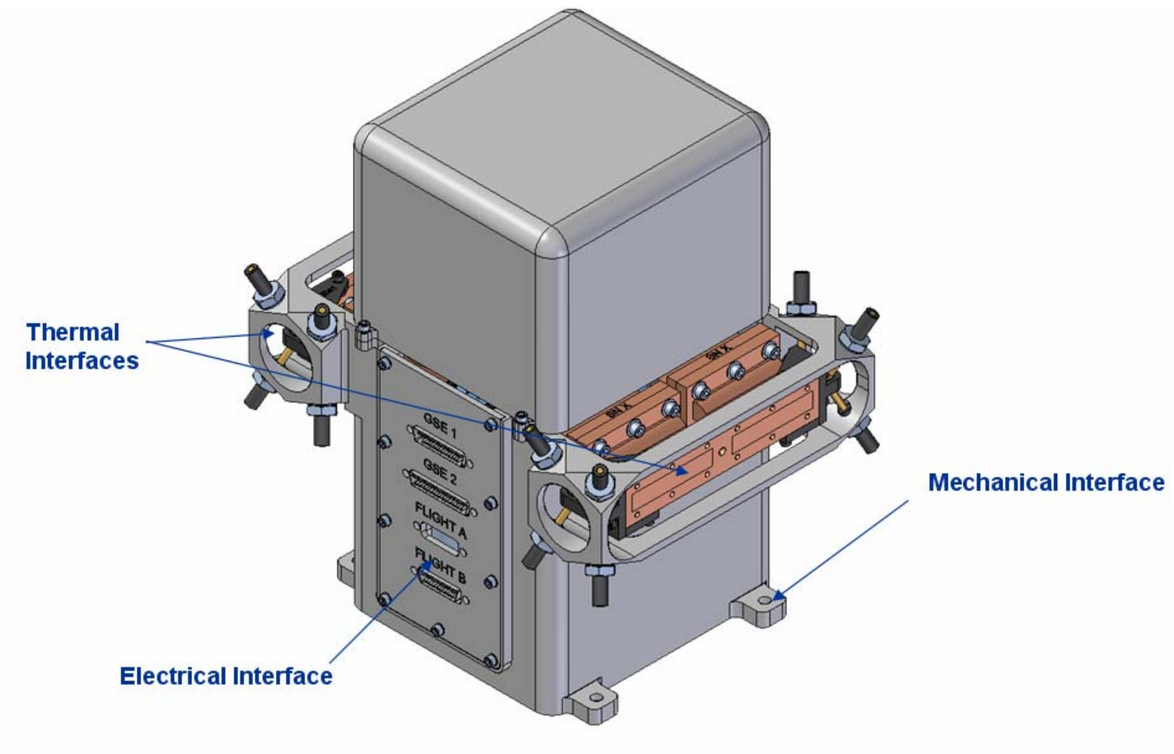

FIGURE 3. Switch thermal, mechanical, and electrical interfaces.

THERMAL AND STRUCTURAL MODELING

Extensive thermal and structural analyses guided the QRTS design and allowed correlation of test results to provide predicted switch performance at non-test points.

The thermal analysis models consisted of both finite element and finite difference nodal network analysis at the assembly and part levels. The thermal models included temperature dependent material properties. A simplified assembly level thermal model that included open and closed actuation was used for correlation to the test results. FEMAP 9.1 was used for finite element meshing and SINDA/G as the thermal analysis engine.

Finite element structural analysis models were developed using FEMAP 9.1 for meshing and pre/post processing. The structural analysis solvers were NX NASTRAN for quasi-static loads and IDEAS-12 for response analyses. The structural models were correlated to the vibration test results.

TEST PROGRAM

FIGURE 4 shows the suite of testing thermal and structural testing performed on the QRTS. The testing consisted of a preliminary phase to verify the switch functioned as expected. Following the preliminary testing phase the formal testing phase consisted of ambient temperature open tests, thermal cycles, and closed conductance characterization. Vibration testing was then performed at ambient temperature and pressure. Following the vibration tests the closed conductance characterization was repeated and the open performance tested. The vibration testing consisted of sine survey, random vibration, and sine burst testing in all three orthogonal axes.

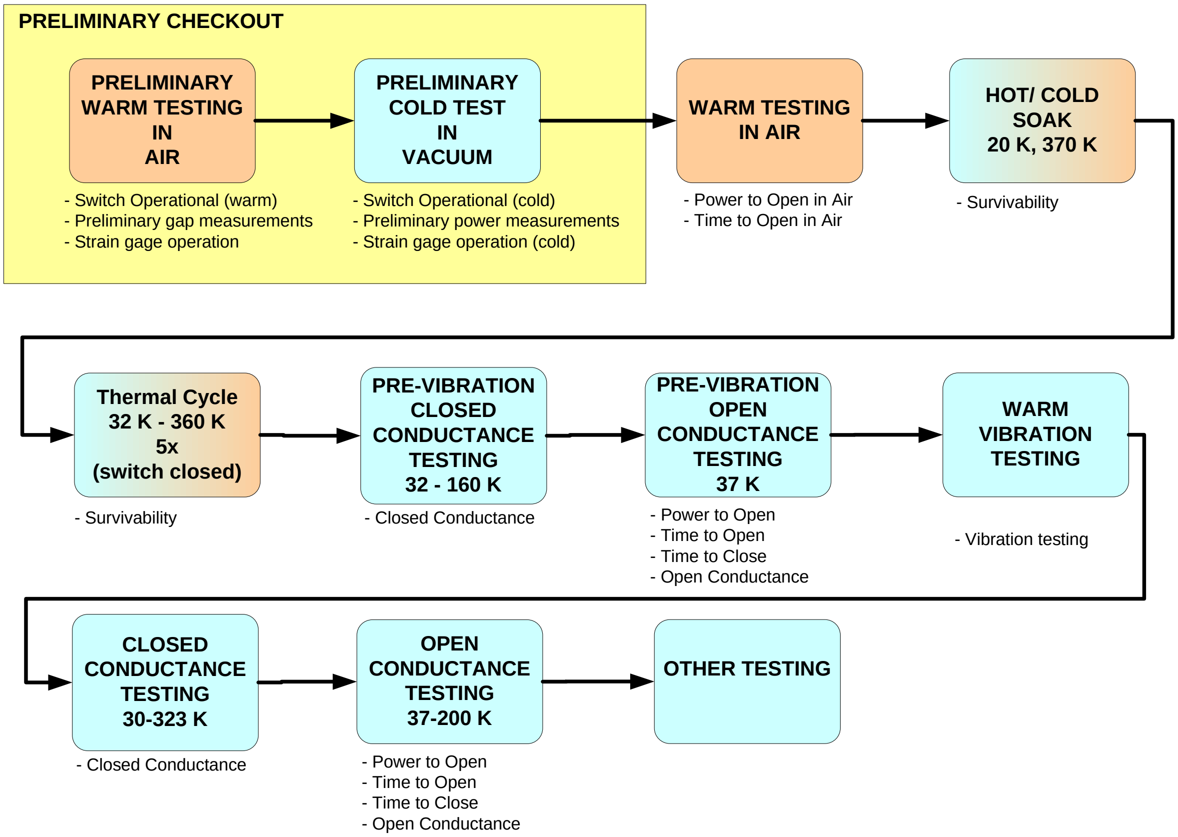

FIGURE 4. Switch test flow

The methodology for testing the closed conductance of the switch is a simple application of Fourier's Law. Steady state heat was applied to one thermal interface of the switch at various levels and the corresponding steady state temperature gradient across the switch was measured. Applied heat versus temperature gradient was then plotted and a linear regression performed to determine the switch thermal resistance.

TEST RESULTS

The thermal and vibration testing was performed in approximately a three month period of time and consisted of 54 closed conductance tests and seven open performance tests. In addition, ambient temperature checkout tests were performed. The following paragraphs present snap-shots of typical testing results.

FIGURE 5 shows a typical closed conductance test measurement. The total switch temperature difference is plotted against applied heat and a linear regression performed to calculate the switch resistance at the test temperature. In addition, the distribution of thermal resistance within the switch was determined by examining temperature differences between internal components in the conduction path.

FIGURE 6 shows the resulting measured switch closed conductance versus temperature and performance predictions with one switch failed open. The increase of switch closed conductance below 100 K is due to increased thermal conductivity of the copper conduction path. The closed conductance results showed excellent performance, especially at temperature from 32 to 40 K with the peak conductance being 3.6 W/K at 32 K.

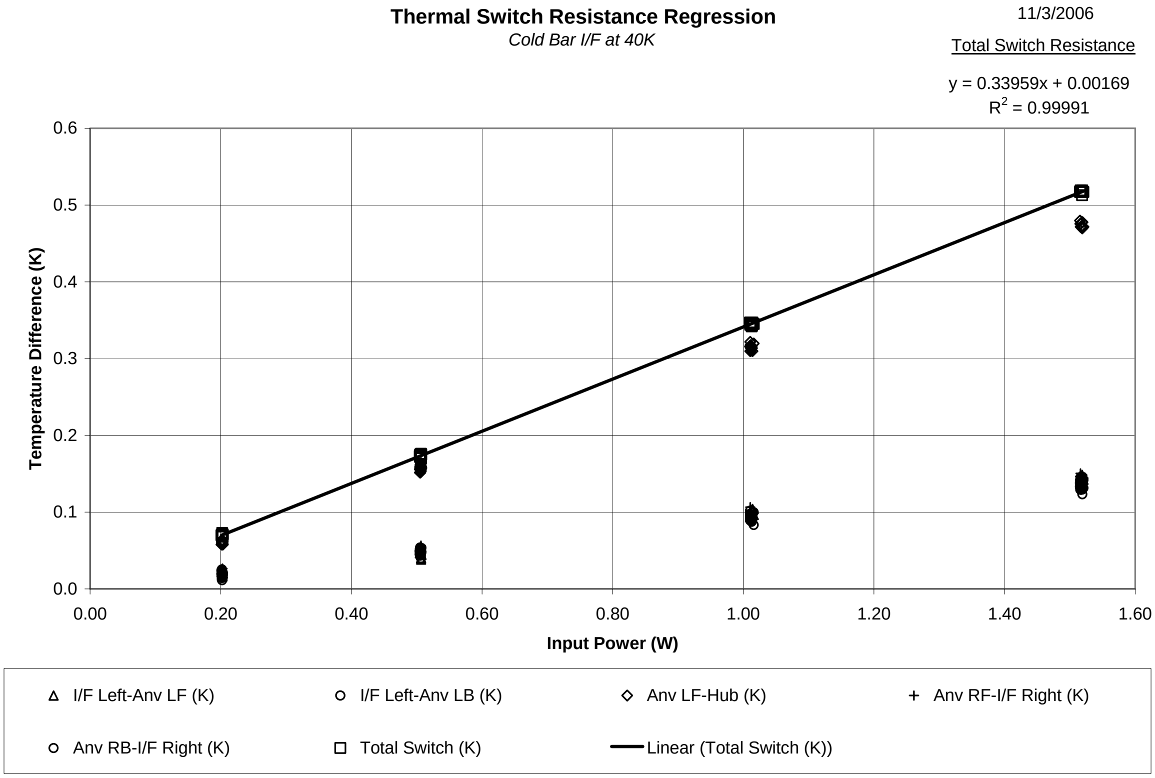

FIGURE 5. Typical closed conductance resistance determination

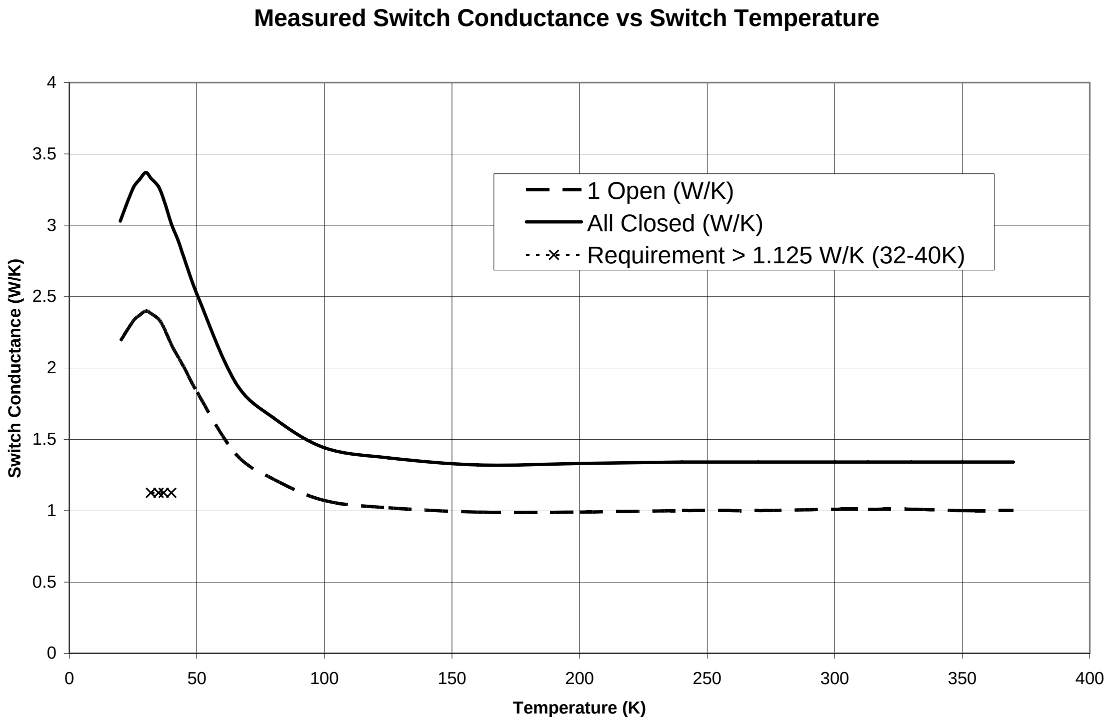

FIGURE 6. Measured switch closed conductance versus temperature

Examination of the open performance test results showed that the switch was actuating as designed. Switch actuation times were determined (from both temperature sensor and strain gauge readings) to be 47 minutes to open and 110 minutes to close (at worst case warm temperatures).

COLD JOINING OF SWITCH CONTACTS STUDY

Early in the development of the QRTS the concern of potential cold joining of the switch thermal contacts was raised. To mitigate this risk a study to assess the potential for joining of the switch contact surfaces was initiated. While a detailed account of this effort is not possible in this report, an overview of the approach, testing, and conclusions is briefly presented. The cold joining study was performed by Dr. Leijun Li at Utah State University.

The cold joining study consisted of an initial literature search and identification of potential cold joining mechanisms. Two categories of joining mechanisms were identified 1) short term joint interaction due deformation of the faying surfaces, and 2) long term diffusion bonding of the surfaces. An initial theoretical model was to predict the extent of joining as a function of temperature and loading conditions. The modeling predicted that joining was more favorable at higher temperatures and the extent of joining was expected to be less than 1% of the thermal contact area.

Following the literature search and modeling, testing of the two joining mechanisms was performed. Representative samples of the switch contacts were fabricated and subjected to joining tests. The areal extent of the potential joining area was evaluated by optically examining the morphology of the sample surfaces. In addition, scanning electron micrographs were taken of the surfaces to examine the morphology of the faying surfaces.

The results of the cold bonding testing showed that potential for cold joining was less than 0.8% of the switch contact area, and that the force required to pull the contacts apart should this small amount of joining occur is within the opening capability of the switch. Overall, the joining study showed that cold joining of the switch contact surface should not pose a problem for the switch.

CONCLUSION

The development of the QRTS switch was very valuable. The result was a successful quad redundant cryogenic thermal switch that is robust, shows excellent thermal performance, and is ready for flight production.

During this phase, a flight-like switch was successfully fabricated and assembled. Comprehensive thermal and structural testing of the QRTS was successfully completed showing that the switch meets or exceeds all performance requirements. The most critical performance requirement for the switch and largest technology advance, closed conductance from 32 to 40 K, showed excellent performance results. The resulting closed conductance of 2.14 W/K with one leg failed open at the worst case temperature of 40 K was close to double that required. The measured closed conductance with all switch contacts closed was 2.95 W/K.

In parallel, an experimental study on cold joining of the switch contacts was performed. The results of analysis and testing of all three mechanisms of cold joining show that less than 0.8% of the contact area has the potential for cold joining and that the measured break forces are well within the switch opening capacity. Furthermore no evidence of cold joining was observed during the testing. Overall, the results and conclusions of the cold welding study show that cold welding is not a problem for the switch.

The work culminated in November of 2006, where SDL presented the flight like development and performance results to GSFC for a TRL 6 assessment review. Feedback of the review board unanimously indicated that the SDL QRTS met the requirements for TRL 6 status.

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