Reliability and Fault Tolerance in ISS Thermofoil Spaceflight Heaters

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Abstract

Extra-vehicular avionics systems and mechanisms used on the International Space Station (ISS) typically require redundant survival heaters due to cold thermal extremes. Two such survival heater systems have completely failed to date. These designs were not truly fault tolerant because a failure within the heater patch would bring down both the prime and redundant systems. This report is intended to make designers and operators of mechanisms requiring survival or operational heaters for spaceflight applications aware of common issues that contributed to in-flight failures.

Introduction

A dual element thermofoil heater is in essence set of two resistive elements laminated together. Failures in either element can easily propagate to the other by damaging other element or the laminate structure. Figure 1 illustrates a layered, dual element design.

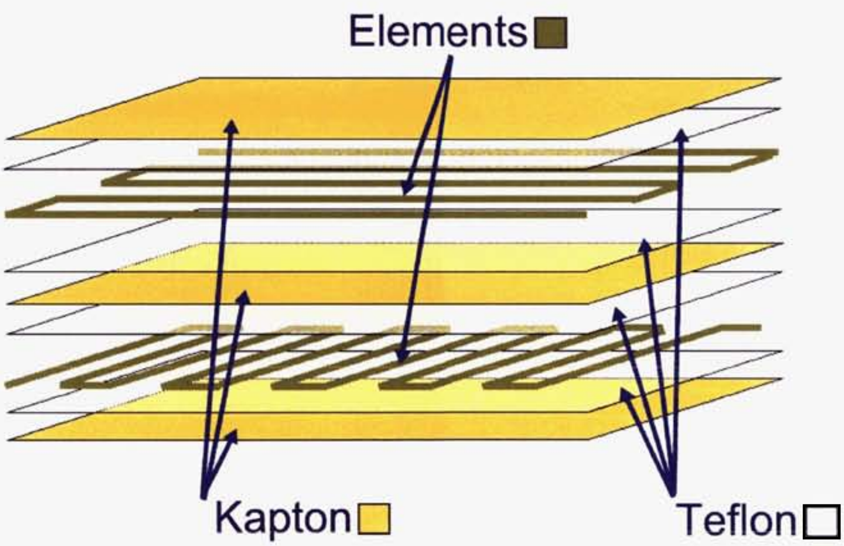

Figure 1. Layered Design Flexible Heater Exploded View

Heaters are often treated exclusively as electronic components; however, standard electronics qualification and acceptance testing is insufficient to certify a heater design. Flight history lessons learned lead directly to design and testing recommendations for mechanism heaters. Survivability in particular was not thoroughly examined in the design and testing process.

Failures are presented with a short description to provide data points that suggest areas to pursue alternative designs. Recommendations are meant as solutions to these known problems and other sensitivities of heater patch design and installation. History and descriptions presented here were developed through in depth analysis of failure telemetry, and by direct interview of hardware designers, manufacturers, and operators.

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By reviewing the lessons learned from these failures we can create more robust designs that significantly reduce risk and are tolerant of severe conditions: high watt density, over-voltage, complex installation and unknown stress. These lessons are consolidated in the design and testing recommendations section.

Failure History

Requirements for survival or operating heaters were determined after much of the hardware design process, leaving this critical system as an afterthought. Flexible heaters have a long flight heritage within the US space program. In the ISS program to date we have seen at least three failures of flexible heater systems on-orbit: Auxiliary Power Converter Unit discharge resistor (not used for heating purposes), Nitrogen Tank Assembly (NTA) survival heaters, and the Segment-to-Segment Attach System (SSAS) Capture Latch Assembly survival heaters. We have also seen one failure in on ground testing, the Flex Hose Rotary Coupler Flight Support Equipment survival heaters. The Nitrogen Tank Assembly and Segment-to-Segment Attach System Capture Latch Assembly cases are presented in this paper.

Nitrogen Tank Assembly (NTA)

The NTA uses two separate heater patches with layered elements. Each layer within the patches was wired in series to form two circuits that spanned both patches (Figure 2). As a result, failing both layers in a single patch would completely fail both strings of heaters.

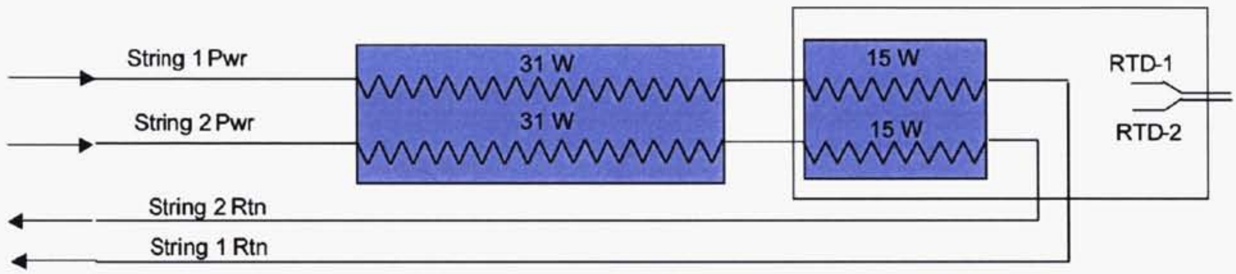

Figure 2. NTA Heater Strings

On January 17, 2003 (GMT 2003_017:16:00) both heater strings failed. The NTA heater assembly cannot be inspected until it is replaced with a spare and returned for analysis. After the failure of the NTA heaters, all similar ISS heaters were identified for further analysis.

Suspect Condition Action Notice (SCAN) 044

After the failure of the NTA heaters, a Suspect Condition Action Notice (SCAN) was issued across the entire ISS program to check for similar issues. Many heaters were identified by the search criteria:

1. Multiple elements in a single patch.
2. Greater than 0.46 W/cm^2 (3.0 W/in^2) watt density.

Once identified, the true redundancy of the elements, software control, and possible impacts were evaluated. The majority of station heaters have watt densities under 0.46 W/cm^2 (3.0 W/in^2); unfortunately, several systems contained multiple elements in a single patch.

The critical impact of the suspect condition to ISS operations was mitigating the hazard presented by activating both elements in a layered patch simultaneously. Simultaneous activation effectively doubles the watt density of a heater, greatly increasing the risk of failure. Suspect software controlled heater activation set-points were offset to reduce the possibility of this type of failure. Set-point adjustment was not possible for thermostatically controlled heaters on orbit, and operational procedures were modified to minimize this risk during power up.

<u>P1-P3 Segment-to-Segment Attach System (SSAS) Capture Latch</u>

On May 25, 2004 (GMT 2004_146:20:01), both heaters on the Port side, segment 1-3 SSAS capture latch failed. This heater was a single patch with dual element, layered design. Figure 3 gives a general view of the capture latch mechanism. The heater patch wraps around the gearbox at the base and would not be readily visible in this view. Telemetry was available at the time of failure and automated warning alarms were activated when cold limits were approached.

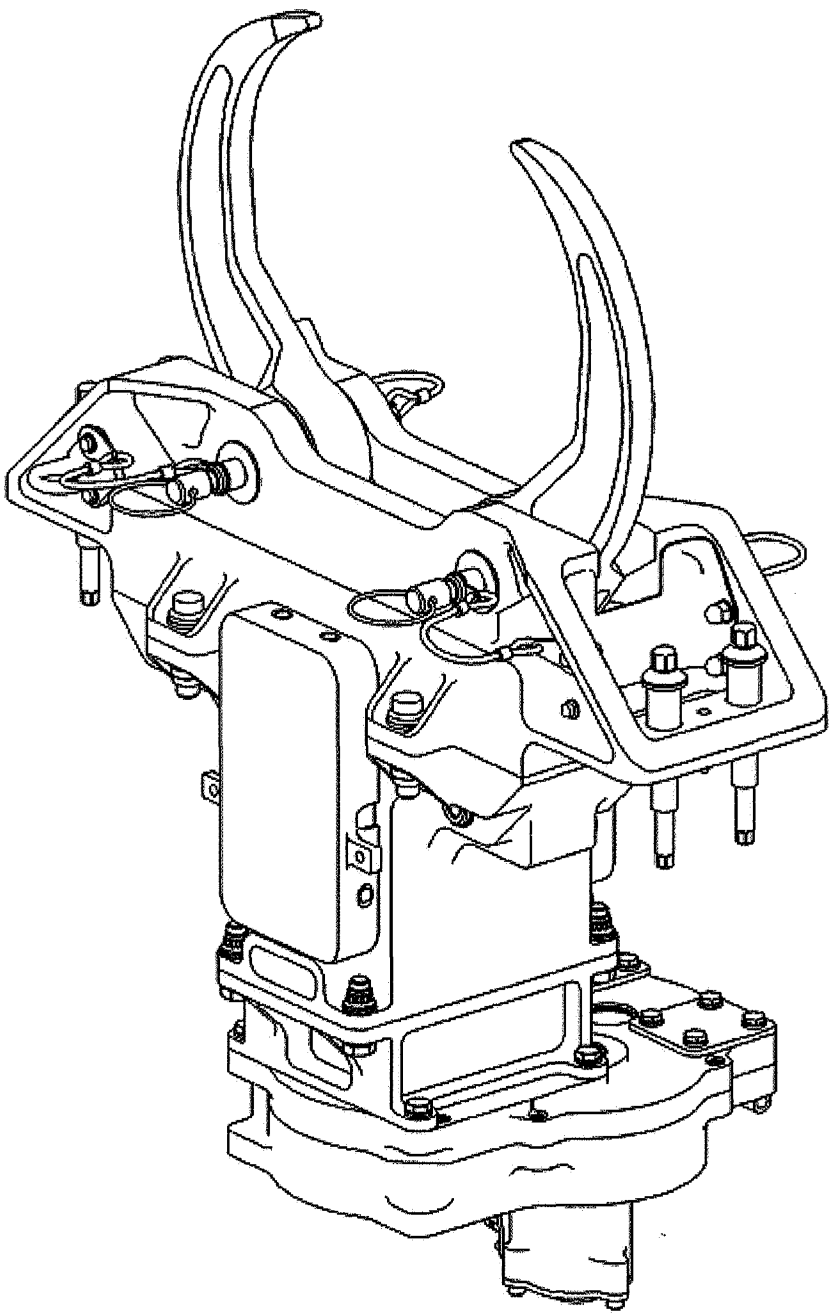

Figure 3. ISS P1 Truss SSAS Capture Latch

Failure of both elements was simultaneous. The last short peak in both traces in Figure 4 represents the failure point. The temperature of the system began to decay, and system temperatures did not begin recovery until the Integrated Motor Controller Assemblies (IMCAs) were activated to provide self heating. The IMCAs are rectangular motor assemblies that bolt to the gearbox at the base of Figure 3. They will actuate the capture latch to berth the P3/P4 truss. Until the P3/P4 truss arrives on flight 12A, the IMCAs will run continuously to mitigate this failure.

At the time of failure only one of the two layers was powered; however, software changes to avoid simultaneous activation of both strings may have helped to prevent this failure. The most likely cause of the failure is heater patch burn-through. This heater assembly is permanently installed to structure and cannot be returned for failure investigation.

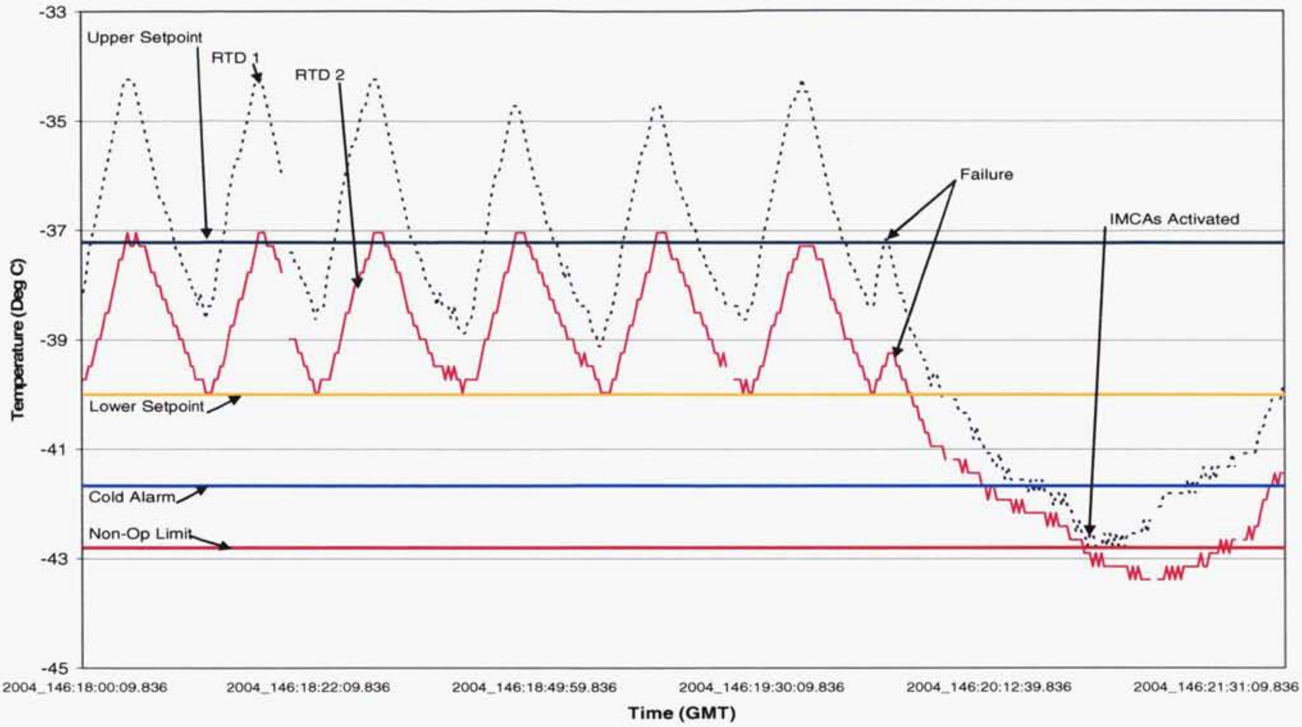

Figure 4. Failure Temperature Traces

Progressive Failure in a Thermofoil Heater

Progressive failure or burn-through is the result of overheating within an element. Many things cause overheating: over-voltage, necking in the element trace, bubbles under the element, incomplete or improper installation, or delamination within the patch. Once the overheating begins, the stages of failure typically follow these steps:

- Temperatures increase within the element, increasing resistance.
- Melting temperature for the Teflon is reached and the patch delaminates. In this process the Kapton film may char.
- Once delamination occurs, there is no direct conductive path for heat transfer and radiation becomes the dominant mode of heat transfer.
- Unable to release the heat, the heater element foil continues to increase in temperature until it melts or fractures and loses electrical continuity. At this point the heater has failed irrecoverably.

- In dual element heater patches the local delamination will likely cause failure to propagate between both elements, in both side-by-side and layered conditions.

A heater is typically considered failed when it delaminates. The remaining steps lead to failure of the element and an open circuit. There is no data available to determine a critical flaw size. As a result, any visible delamination would be considered unacceptable.

Design and Testing Recommendations

<u>Design Recommendations</u>
Due to their physical proximity, elements in a dual element heater patch are highly likely to fail simultaneously, even if they are not layered directly on top of one another. They do provide system redundancy for other failures that occur in the power system leading up to the heater patch, but any failure within the patch itself will fail all elements. Multiple element heater patches do NOT provide fully redundant thermal conditioning. Dual element heaters are inappropriate for situations that require true redundancy and fault tolerance unless survivability is addressed.

Individually, high watt density, layered design, and installation difficulty would not necessarily be a significant driver towards failure for a flexible heater; however, the combination of multiple higher risk design elements into an individual heater patch creates sensitivity to conditions that increase the risk of failure. Because layered design has been common across all discovered failures to date it should be approached with a high level of caution. Each individual issue further erodes the margin for error.

Heater systems should be integrated as early in the design process as is possible. Earlier inclusion in the design process would allow for specifications of system components that would permit a large, flat area for heater installation.

Heater patch effective area should be maximized and watt density should be minimized within the bounds of required heat generation: An ideal heater system will be as large, simple, flat and low-watt density as possible. As watt density increases, the importance of effective heat transfer from the element to the heat sink increases. Installation conditions must be carefully examined and fully understood to mitigate overheating.

<u>Testing Recommendations</u>
Acceptance and qualification testing of thermofoil heaters is specified similarly to standard electronic components; however, this approach is not sufficient to determine all three crucial criteria: Suitability of the design for the intended use, Capability of the design to maintain the desired temperature under minimum power conditions, or Survivability of the design under extended use and maximum power conditions. Survivability verification under worst-case use conditions must be part of acceptance testing.

Survivability in particular has not been part of heater acceptance and qualification testing programs. ISS voltages historically have been running near the upper end of the acceptable range of 113-126 volts. Heaters were typically tested with the minimum voltage (or ambient equivalent) to verify they would produce sufficient heating in a worst-case environment, but never tested to verify they could survive the highest available voltages indefinitely. A 25% increase in heater power can lead to failures not found in qualification testing at 113 V.

Testing under vacuum conditions in particular will create a more realistic environment for verifying survivability of a heater system design. Ideally, all hardware would be fully tested in a thermal vacuum environment, but cost and schedule constraints can prohibit this level of testing. When planning the testing regime, additional planning and analysis should be spent to ensure that the heater has seen an equivalent duty cycle. Because vacuum conditions drastically change the thermal environment, testing of a heater design under vacuum attached to an appropriate heat sink would be a reasonable compromise.

Conclusions

Flexible thermofoil heaters have failed several times in the ISS program. We must look at and seriously consider the processes going into design, testing, and installation of heater patches on spacecraft. Suitability and capability of the designs to fulfill their functions have generally been understood and analyzed in depth; however, survivability has not always been treated with sufficient rigor. Qualification and acceptance testing must include steps to verify heater survival.

Overestimation of the ability of the system to survive high voltages, extended use, or inadequate installation undermines all design effort spent on the system. If the heater itself does not survive, failure of the thermal system jeopardizes mission objectives. If no resolution can be found, the system could be a total loss. Mitigating the impacts of these failures consumed substantial time and resources within the ISS program. The most critical lesson learned is to do everything possible to maintain the survivability of the mechanism via heater patch design by incorporating knowledge from previous failures during initial design.

References

1. Bolton, Victor J "SCAN 044 Response for Structures and Mechanisms," Boeing memo A92-J383-STN-M-VJB-04-032, February 2004.
2. Bares, Geoffrey "PRACA 3661: P1 Nitrogen Tank Assy (NTA) Heater Failure," Boeing presentation, February, 2003.

Development, Pre-qualification and Application of an Active Bearing Preload System

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Abstract

This paper describes the development to pre-qualification status of a novel and widely applicable technology development known as a Bearing Active Preload System (BAPS). The BAPS can be thought of as a "smart bearing housing" which replaces a conventional bearing or mechanism housing and whose function is to permit ball bearing preload variation on command. An overview of typical BAPS requirements, its design, the range of actuation options and some performance data are provided. A number of historical and recent bearing applications are reviewed and the benefits realizable by a capability to vary preload are highlighted. These can include order of magnitude improvements in lubricant lifetime, reductions in bearing torque, mechanism mass, cost and complexity.

Introduction

Ball bearings are preloaded to provide adequate rotor location and bearing stiffness, as well as to protect the bearings themselves from damage due to "hammering" during launch. However, increased preload also has some undesirable effects discussed below.

Grease- or oil-lubricated bearings have essentially two main torque components, namely a speed and temperature dependent "Viscous" component and a load dependent "Coulombic" torque component. At low- to moderate-speeds, the Coulombic component can be dominant, such that mean bearing torque is approximately proportional to preload$^{4/3}$. This relationship is also true at all speeds for solid- and self-lubricated bearings. Furthermore, peak Hertzian ball-raceway contact stress is proportional to preload$^{1/3}$ [1].

In ESTL much work has been done in the past concerned with characterization of bearing torque and lifetime, particularly for self-lubricating (e.g., Duroid or PGM-HT) and solid-lubricated (e.g., thin films of MoS_2 or lead) bearings. A review of some of the highlights of this experimental work [2-5] demonstrates that preload (or peak Hertzian contact stress) has a very significant effect, both on film lifetime for solid lubricated bearings, and on separator (cage) wear for self-lubricating bearings as shown in Figure 1. For liquid lubricated bearings too (especially PFPE-based oils and greases), though the lifetime may be often be longer, ultimately lubricant degradation due to shear or chemical reaction at ball/raceway asperities and separator stability/wear issues are aggravated by high bearing preload.

In summary, the use of a high preload throughout life not only increases the Coulombic torque and therefore motor mass/power requirements for the bearing, but also decreases the potential operational lifetime significantly. Furthermore, since in most applications the high bearing stiffness required for launch is no-longer essential once in-flight, the capability to operate in-flight at relatively low preload is highly desirable, particularly in long-lifetime applications and those with challenging thermal requirements (e.g., those having a particularly wide operational temperature range, large or adverse thermal gradients).

Historically bearing "off-load devices" or "launch-locks" have been used to protect bearings during launch by providing an alternative load path in those relatively few applications where the launch loads necessarily exceed the capacity of the bearings, or more often where the low-torque or long-life requirement dictated a moderate to low preload should be selected (e.g., Giotto de-spin bearings [6]). However, bearing off-load devices are relatively mass inefficient and need to be tailored to the application.

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