Failure Analysis after in orbit anomaly on COMEPA bimetallic thermostat TH47

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ABSTRACT

Bimetallic thermostats are widely used on spacecrafts in combination with heating and/or cooling units to control temperatures of critical sections and subsystems.
This paper will give a detailed description of an in-flight anomaly reproduction on-ground and will provide the failure analysis results obtained on the thermostats used to reproduce such anomaly.
After several months of nominal operation, in-flight telemetry data showed anomalous and unexpected temperature variations on the pressure reduction unit of the propulsion subsystem. Preliminary investigations identified TH47 bimetallic thermostats from a specific lot mounted on board as a possible cause of the anomaly.
Two parts, from the same manufacturing lot, were submitted to tightly controlled thermal cycles mimicking the in-flight telemetry data in the attempt of reproducing on-ground the observed anomaly.
The thermostat temperature cycle gradients and the electrical contact bias/load conditions were accurately reproduced. A computer-controlled monitor system measuring the case temperature, the contact resistance as well as the mechanical vibration of the switching thermostats by means of piezoelectric transducers, was implemented.
After several temperature-controlled switch on/off cycles, evidence of contact wear-out was observed as the closed-contact resistance increased significantly. After few additional thermal cycles from the first evidence of contact degradation, the contact resistance increased outside of specification value. The increased contact resistance led to a higher power dissipation at the thermostat contacts producing a self-heating temperature increase inside the component ultimately causing a significant shift in the switch-on and switch-off temperatures. Permanent degradation of the thermostat contact resistance was observed before reaching 10% of its nominal lifetime.
The detailed reproduction and understanding of the in-flight failure-mode could be used to implement different strategies in the subsystem thermal management circumventing the thermostat function. The different thermal management approach resolved the anomaly caused by the defective components and prevented the failure of a critical unit, ensuring the safe continuation of the mission.
Further techniques so as Thermal Imaging, Internal Vapor Analysis, X-ray imaging while heating and scanning electron microscopy were performed to further investigate the root cause of this failure and identify the underlying failure mechanism responsible for the thermostat failures.

Figure 1: Thermostat TH47 [1]

INTRODUCTION

The thermostat TH47 was used on a heater subsystem. Here the objective of the thermostat is to keep an electromechanical installation in a certain temperature range.
The used thermostat had the part number 370200101B0**39**0**34**BY.
The numbers code 39 and 34 in that part number refer to a nominal functioning temperature of 39°C and to a nominal restoring temperature of 34°C. This is according to the standard ESCC3702/001[2]. At restoring temperature, the thermostat contact closes to enable the heater, and at functioning temperature the contact opens again and stops the current flow to the heater unit. With this simple principle it is very easy to achieve a regulated temperature at certain locations.

IN ORBIT ANOMALY

Figure 2 shows a plot of the temperature measured on a subsystem in flight. The temperature log was obtained by an additional temperature sensor placed on the heater unit close to the thermostat under investigation.
During normal operations this telemetry value would oscillate between around 34°C and 39°C. Small deviations from those limits can come from the initial tolerance of the thermostat (maximum ±2°C according to the relevant detail specification) and due to the fact that the temperature measurement is not performed at the exact location as thermostat. In addition to that, temperature under/overshoot might happen due to the effect of thermal inertia of the mechanical assembly introducing a delay between the heat generation by the heater and the temperature variation seen by the thermostat.
The first few hundreds of cycles of the thermostat were nominal. Out of no apparent reason nor possible external factors however, the temperature oscillating profile started showing anomalous drops in the upper temperature as it can be seen on Figure 2 at around 20 and 30 hours of shown telemetry timeline.

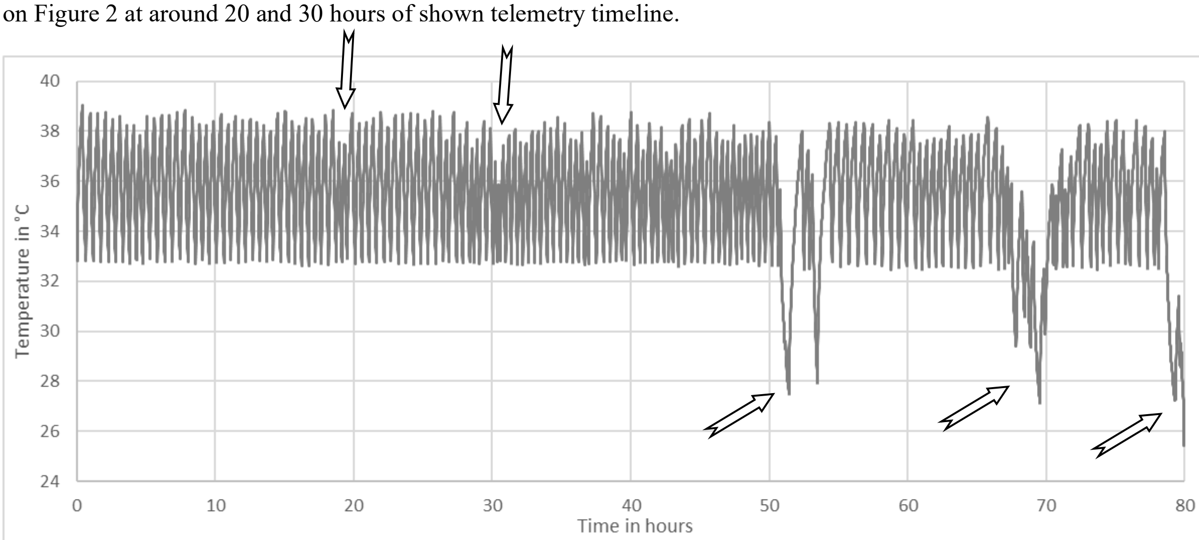

Figure 2: Partial Section of Telemetry data of heater temperature controlled by Thermostat TH47

The drop in temperature occurred stochastically and initially affecting only the functioning temperature (temperature at which the switch opens). Few cycles later, the restoring temperature started to be affected as well, as it can be seen from hour 50 onward. The temperature drop became so significant that the specific subsystem could not be operated reliably anymore and the switch to a redundant unit was deemed necessary.

THERMOCYCLING TESTING

A failure analysis investigation was started to identify the root cause of the anomaly and to estimate its likelihood to eventually affect also the redundant unit. A setup aiming to reproduce the anomaly on ground was designed at the ESA Materials and Electrical Components Laboratory and four samples, two thermostats from the same lot as in flight and two thermostats of more recent production, were submitted to thermocycles. The core of the setup, seen in Figure 3, consists out of Peltier elements mounted on a quite massive metal plate. On top of the Peltier elements, a second smaller metal plate was mounted, and all four thermostats were glued on the surface of the smaller metal plate. Each thermostat switch was connected between an external resistive load and a power supply. The body temperature of each thermostat was monitored via a PT100 temperature sensor, directly attached to the side of the thermostat itself. To minimize the interference of the external environmental conditions, the whole setup assembly was placed in a non-ventilated oven which was set at a constant temperature of 30°C. The resistive load was dimensioned to achieve electrical conditions closer to the actual in-flight conditions: $28V_{DC}$ in open circuit and 0.34A through a resistive load with closed switch contacts. The switch contacts were also connected to an oscilloscope and to a data acquisition unit allowing the real-time capture of the voltages at the contacts and the live calculation of the actual contact resistance. The Peltier elements cooling/heating was controlled by a ©Lab-view based automation software to achieve the thermostat desired temperatures, with a defined thermal gradient. In a few words, the test set-up was designed to verify the behaviour of the thermostat during the temperature ramps-up and ramps-down, as close as possible to the actual temperature ramps and load conditions seen in the application, however, maintaining the control of the temperature ramps completely independent from the thermostats and the loads. This strategy allowed a clearer understanding of the sequence of events leading to the failure.

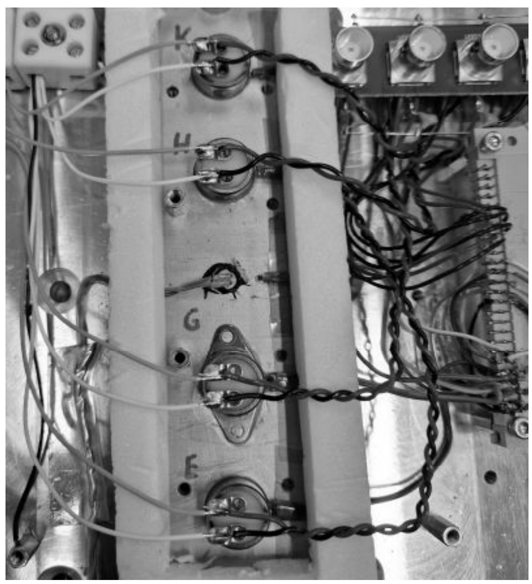

Figure 3: Test Setup – Thermostats on Metal Plate heated/cooled by Peltier Elements

Degradation of contact resistance

The TH47 manufacturer datasheet [3] specifies a limit of 50mΩ for the contact resistance of closed contacts. The data plot in Figure 4, shows the calculated average closed contact resistance of the tested device up to 50 000 cycles. The tested thermostat S/N-007 started exceeding this value after about 400 cycles. The contact resistance showed a slight recovery before increasing significantly after 600cycles and showing a permanent open contact after approximately 5000 cycles, well below the 100 000 cycles expected lifetime for this thermostat, according to the relevant datasheet [3].

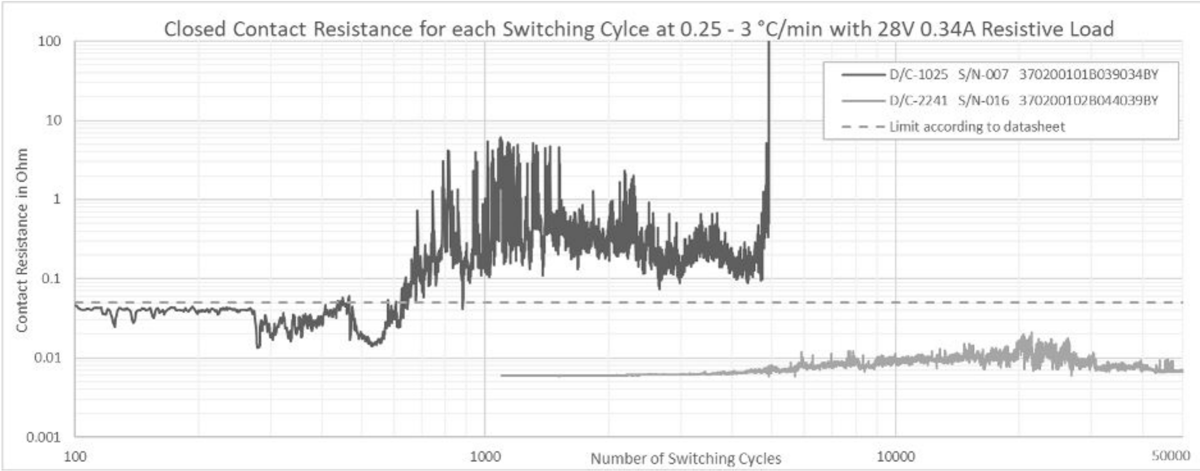

Figure 4: Contact Resistance Increase over Number of Switching Cycles

Thermostat S/N16, from a more recent production lot, was tested until 50 000 cycles (half of the rated lifetime according to manufacturer datasheet [3]), still exhibiting no significant anomalies.

EFFECTS OF CONTACT RESISTANCE DEGRADATION: SELF-HEATING

With the increase of closed contact resistance, the dissipated power at the contact increases following the well-known Joule heating relation $P=I^2 \cdot R$. Before the wear-out, on thermostat S/N 007 a contact resistance of up to 6Ω was measured during the thermocycling. This resistance values at 0.34A led up to 600mW power dissipated at the thermostat contacts. In the temperature plots of Figure 5, showing the measured temperature of the supporting metal plate and the body temperature of the thermostat s/n 7, the effect of this 600mW power dissipated at contact level, caused the increase up to 4 Kelvin of the thermostat body with respect to the metal plate temperature, independently heated. This, so called self-heating effect, by reaching the bimetallic disc inside the thermostat, disrupt its nominal behaviour, leading to an opening of the contact well before the functioning temperature of 39°C is reached on the metal plate. The central cycles shown in Figure 5 for example, show the thermostat switching on at about 34°C and soon after, its body temperature increases sharply due to the joule heating at the internal contacts. The body temperature reached about 40°C while the plate temperature was still at about 36°C. With 40°C body temperature, the thermostat switched off and no more joule heating was produced at the contact, therefore the body temperature could quickly equalise to the plate temperature at 36°C.

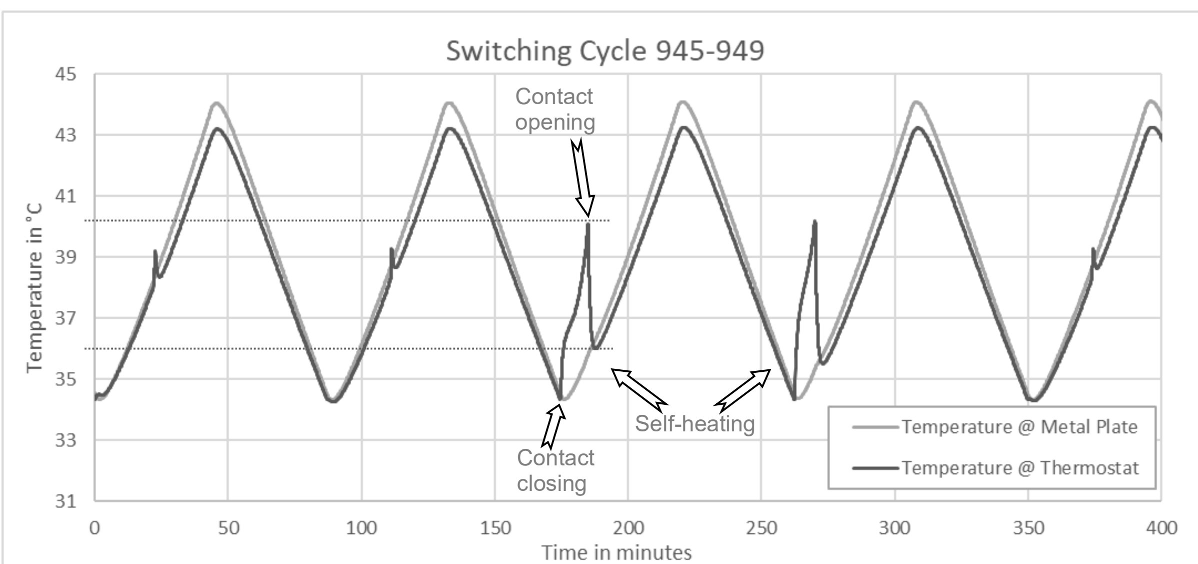

Figure 5: Self-Heating local Temperature increase on Thermostat

The on-ground observed behaviour in Figure 5, mirrors the telemetry data in Figure 2 where first the functioning temperature starts to fluctuate before the restoring temperature drops as well.

SWITCHING VOLTAGE BEHAVIOUR AT THE CONTACT

Complementary observations on the anomalous behaviour and on the degradation of the contacts were possible by analysing the voltage at the contacts during the switching, sampled by the oscilloscope.

Figure 6 shows the voltage curves during the opening of the contact (on the left) and closing of the contact (on the right) switching's of the thermostat. The shown plots were recorded at the very beginning of the thermocycling, with no significant degradation of the contact yet observed. At the contact opening the voltage transferred very sharp from 0 volt to 28 volt. The small overshoot visible, is due to parasitic inductances in the loop. At the contact closing event, similar sharp transitions, with a significant bouncing's of the contact, can be seen. This bouncing back effect happens two times in total and can be considered normal for this kind of thermomechanical switches.

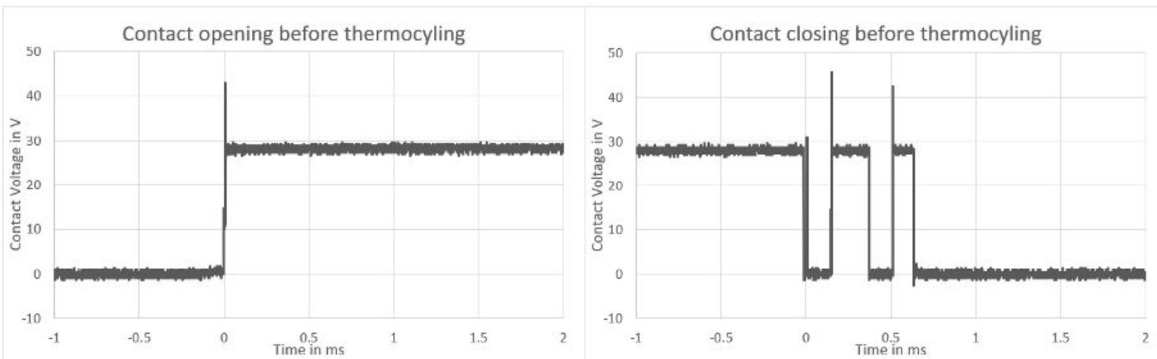

Figure 6: Switching Voltage Oscilloscope Plot at the beginning of Thermocycling

Similar curves, taken after a significant amount of thermocycles, are shown in Figure 7. The voltage change from 0V to 28V at the contact opening, is not sharp anymore. Instead, the voltage sets to an intermediate potential level in the range of about 12V, showing random noise behaviour. This can be considered an indicator of electrical arcing between the switching contacts. This arcing event lasts over a duration of about 1ms. At the contact closing, similar arcing evidence can be observed with shorter duration.

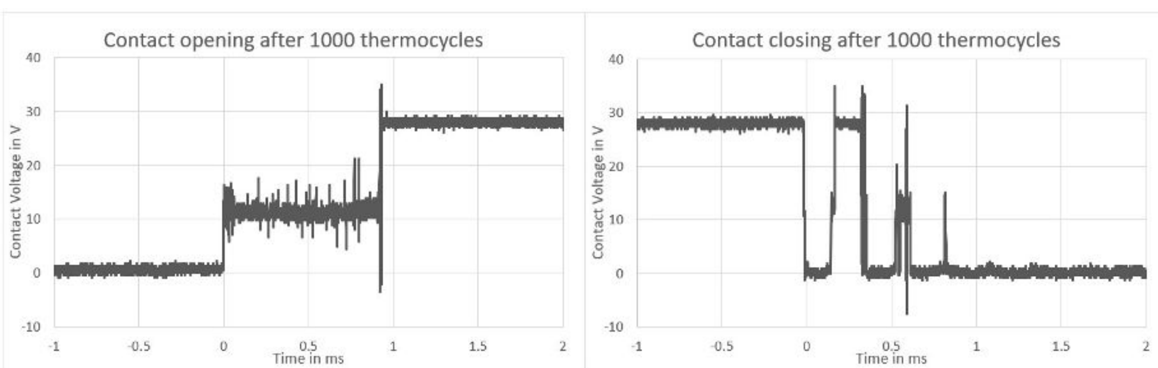

Figure 7: Switching Voltage Oscilloscope Plot after 1000 Thermocycles

After the successful reproduction of the in-flight anomaly, a destructive physical investigation was conducted to determine the cause of the malfunction of the thermostats.

RESIDUAL GAS ANALYSIS

Thermostats for high reliability application, are manufactured in metal/ceramic packages hermetically sealed.
The investigation started by performing hermeticity tests followed by residual gas analysis (RGA) on thermostat S/N 7, failed after about 5000 cycles, in order to identify the composition of the inert gas filling the internal component cavities.
The RGA test was performed by Oneida Research Services Inc. using Mass Spectrometry according to MIL-STD-1018 standard.

Table 1 shows the composition of the gas filling thermostat S/N/ 7. In addition to the expected nitrogen gas, some contaminants were found: carbon compounds, moisture, oxygen and a small amount of silicon compounds.

Table 1: Residual Gas Analysis results of S/N 007

Nitrogen	ppmv	984 728
Hydrogen	ppmv	11 698
Carbon Dioxide	ppmv	1 467
Moisture	ppmv	888
Methane	ppmv	805
Oxygen	ppmv	171
Argon	ppmv	141
Hydrocarbon	ppmv	94
Si Compound(s)	ppmv	8

CONTACT ANALYSIS

Thermostat S/N 7 was opened to inspect the contact surfaces at the internal switching mechanism. A black spot in the middle of the contact surface is visible in Figure 8. This is most likely due to contaminants burnt-out during the electrical arcing between the contact surfaces.

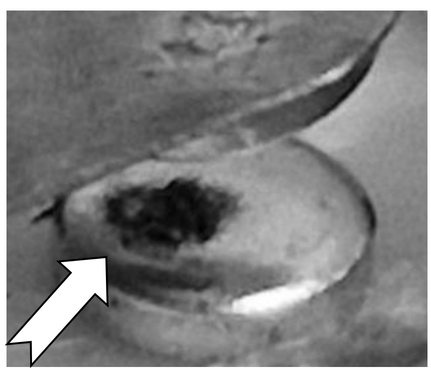

Figure 8: Thermostat S/N 007 with contaminated switching contact surface

A more detailed investigation on the contact surface was performed to determine the nature of the contamination. Figure 9 shows a scanning electron microscope image of the bottom contact in Figure 8. Evidence of solid material deposited around the spot where the two contacts touch each other it is clearly visible. Due to the distribution and the morphology of the residual fragments, it is likely that the electrical arcing played a significant role in the formation and deposition of the foreign material at the contact interfaces.

Energy Dispersive X-Ray Analysis (EDX) was performed to investigate the elemental composition of the contaminants. The main elements detected were: Silicon, Oxygen, and Carbon. Worth to remember is that hydrogen cannot be detected via EDX analysis but, most likely, is still one of the elements in the chemical composition of the contaminants.

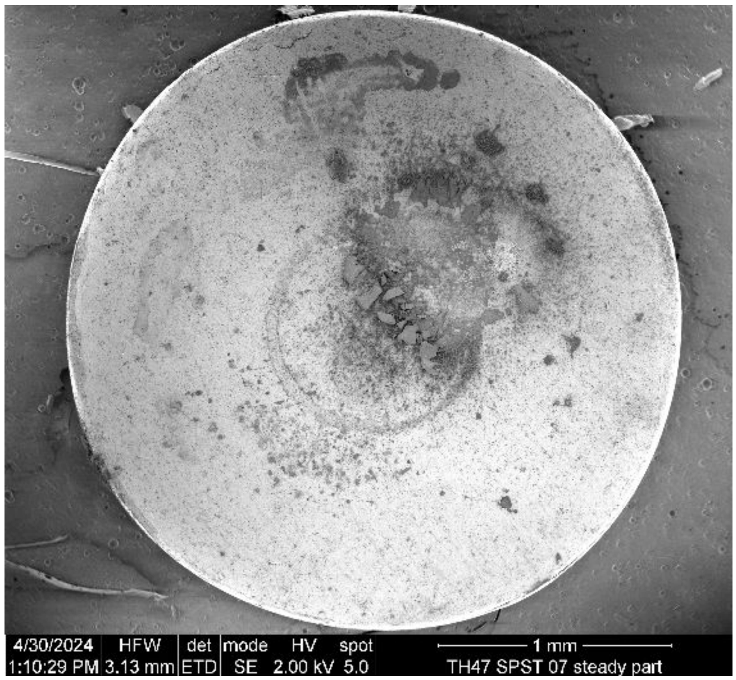

Figure 9: Scanning Electron Microscope Image of the contact surface

FAILURE MECHANISM

Based on all the measurements and analysis mentioned in the chapters above, the root cause of the in-orbit anomaly and the on-ground reproduced failure, is most likely the internal contamination of contacts by silicon compounds present inside the thermostat. In literature [4][5][6] the presence of silicon in close proximity to electrical contacts has been reported to cause the degradation of the contact resistance up to persistent opens. With the contact operations and arcing's, silicon compounds contaminating the contact area, break down [6] forming an insulating SiO_2 film [4]. The mechanical action of the contacts on this insulating film may disrupt its integrity, restoring the electrical contact to a certain extent. However, the stochastic nature of such "cleaning action" and the cumulation of non-conductive debris at the contact interface, eventually leads to a permanent open-circuit condition. Several factors play a role in the degradation of the contact resistance such as the voltage across the contacts, this should be high enough to create an arc but still with a current below a certain level so that the arc is not strong enough to clean the contact surface from contaminations; other significant factors could be: the force exerted on the insulating film during the mechanical switch and last but not least the amount of contaminant material in the proximity of the contacts.

Usually, the degradation of the closed contact resistance occurs slowly over many hundreds of switching cycles and may be not strictly steady due to the several stochastically occurring variations from one cycle to the next one.

In the case under scrutiny, the increase in contact resistance causes the dissipation of electrical power across the contacts with an associated increase of temperature inside the thermostat. From the functional point of view, the internal self-heating is seen as a drop in the nominal functioning temperature. In other words, the worsening of the contact resistance will also alter the switching temperature of the thermostat before its complete failure, the permanent electrically open contact seen even at low temperature with the contacts mechanically closed.

APPROACH TO MITIGATE THE IN-ORBIT ANOMALY

After identifying the thermostat as the reason for this in-orbit anomaly, a mitigation intervention was proposed to avoid the foreseen failing of the heater unit subsystem on the already flying spacecraft. There was no possibility to bypass the thermostat after failing with an open circuit, nevertheless, by understanding the degradation mechanism the decision taken was to use the thermostat with closed contacts only by operating the heating unit at a few degrees lower than the thermostat restoring temperature. By keeping the thermostat contacts permanently closed, no further degradation of the closed contact resistance is expected. The solution implementation was possible thanks to the flexible circuit design that allowed to control the temperature at the target via an additional external control loop. This control loop used: a programmable logic, the temperature sensor used for telemetry and a MOSFET from the power distribution board.
Figure 10 shows how the thermostat, root cause of the anomaly, could still be used even with a degraded contact resistance while the heater is now switched ON/OFF directly by the power distribution unit MOSFET. A relatively simple two-level control loop could be implemented in the code of the programmable control unit to keep the temperature at the target inside a 2 Kelvin window below the nominal functioning temperature of the thermostat, still meeting the requirements for this specific subsystem.

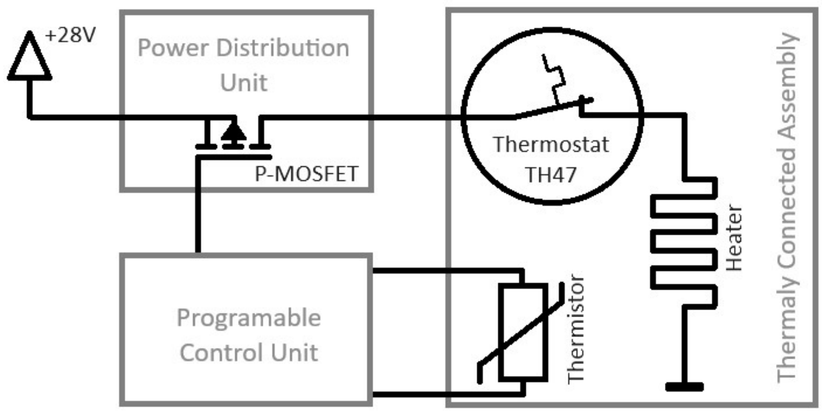

Figure 10 : External control loop to keep temperature stable without switching the thermostat

CONCLUSION

A critical in-orbit anomaly was successfully reproduced on ground. The on-ground tests confirmed causing the anomaly, the suspected thermostat from a specific manufacturing lot. On ground test excluded the occurrence of the malfunction on thermostats produced after a certain manufacturing date. The anomaly temperature response of the failing thermostat could be traced back to an internal self-heating of the thermostat. This heat was produced by dissipated losses across an increased closed switching contact resistance. The increase of resistance has been the result of wear out process at contact material in combination with the presence of silicon-based contaminants inside the hermetically sealed shell of the component. Under the effect of arcing during the switching cycles, the identified silicon compounds degraded producing the accumulation of non-conductive silicon debris between the two end contacts. This failure was only seen on a specific date code so far. The root cause could be found thanks to COMEPA's continual collaboration and contribution.
The detailed reproduction and understanding of the in-flight failure-mode could be used to implement a strategy in the subsystem thermal management circumventing the thermostat function. The different thermal management approach resolved the anomaly caused by the defective components and prevented the failure of a critical unit, ensuring the safe continuation of the mission.

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AUTHORS

Florian Krimmel received his Master Degree in Electrical Engineering focused on Power Electronics at the Vienna University of Technology in 2019. Since 2014 he worked as a Power Electronics Developer at EGSTON System Electronics, an YAGEO company in Austria. In 2020 he started working at ESTEC following the Young Graduate Trainee program and he continued in 2022 working at ESTEC as a Component Test Engineer in the Radiation and Component Reliability Section, together with Michele Muschitiello.

Michele Muschitiello, Senior Component Engineer, joined ESA-ESTEC TEC-QEC in 2007 to work on radiation effects on electronic components for space applications. In the previous twenty years, he provided his expertise on microelectronic technologies supporting EEE part procurement in the frame of several ESA missions and programs. He has also been active in the field of reliability of semiconductor devices, co-authoring various publications on failure analysis methodologies and techniques for microelectronics.

Joaquín Jiménez got a Master Degree in Telecommunications Engineering at the University of Seville (Spain). He started his career as EEE components test engineer at the Parts Laboratory department at ALTER TECHNOLOGY (Seville, Spain). He continued also as EEE component test engineer at the ESA Materials and Electrical Components Laboratory at ESTEC (Noordwijk, The Netherlands). Since November 2020 he works as Passive EEE component engineer at the ESA's Component Section, together with Léo Farhat.

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