Assessment of the Rules on Heater De-Rating

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INTRODUCTION

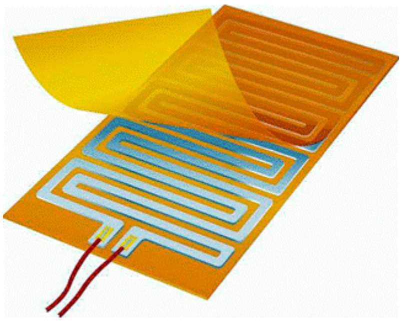


Fig. 1: Flexible Kapton® foil heater
Source: MINCO product catalogue

For many temperature control tasks in today's spacecraft flexible foil heaters of the type shown in Fig. 1 are used. These components consist of resistance wire networks embedded between two insulation layers (for flight hardware in most cases Kapton®) bonded together by an internal adhesive, usually FEP. The operational temperature of a heater is mostly feedback-controlled by temperature sensors or by thermostats, which are placed close to the heater foil. The active control of heaters limits their operational temperature band from typically about -25°C to prevent undesired low equipment temperatures to about +10°C for propellant systems. In general heaters are switched on at low ambient temperatures and not used at higher temperatures.
Heater are typically attached to substrates of different materials and shapes:

- Metallic (Al-, Ti-alloys, Invar, stainless steel, etc.),
- Composites (CFRP, polymers, etc.),
- Flat structures, cylindrical or spherical objects (tubes, tanks).

Typical heater applications in a spacecraft are shown in Fig. 2.

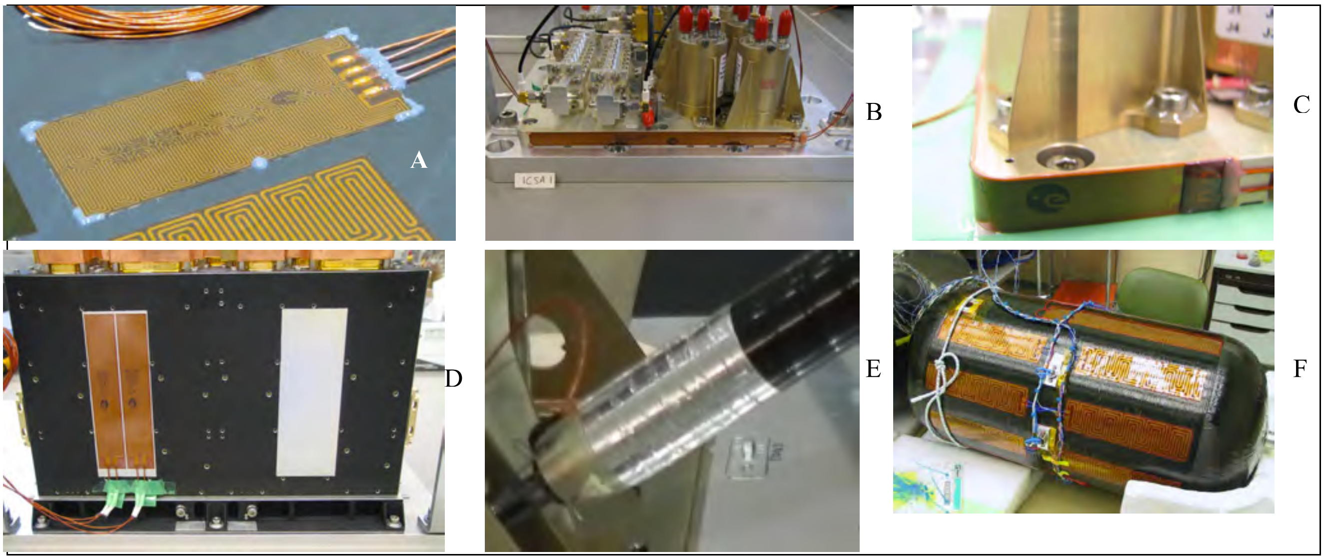


Fig. 2: Typical Heater Application in a Spacecraft (A: flat structure surface; B: mounting baseplate; C: curved application; D: black plated aluminium structure plate; E: cylindrical CFRP strut; F: Fibre-Wrapped Gas Tank)

Presently requirements for maximum heat flux density and power de-rating are not fully defined and are therefore controversially discussed in different spacecraft projects.
A work programme was therefore executed to determine allowable maximum heat flux density (W/cm^2) during operation, i.e. after the heater has been attached to its substrate and to assess the presently specified power de-rating rules.
In particular the following tasks have been performed:

- Elaboration of an evaluation test program that shall characterise the influence of bonding methods for different substrates on the maximum allowable heat power which is related to a criteria on the temperature reached by the heater,

- Perform the tests and evaluate the test results, propose a way forward for the definition of maximum heat power density of heaters,
- Use the study outcome for further discussions about clarification and revision of the ECSS heaters derating requirements.

SITUATION IN EUROPEAN SPACE PROJECTS

In most European space projects maximum power densities for foil heaters are based on a rated power of 0,54 W/cm^2, as specified in ESCC 4009/002 [1]. Furthermore, it is required to de-rate the heater power with 50% as specified in ECSS-Q-ST-30-11C [2].
For example, in large space projects, which are currently running at OHB System AG, the following has been agreed with the customer:

- SGEO: 0,54 W/cm^2 as maximum value for FM hardware. Qualification is performed with 0,54 x 2 = 1,08 W/cm^2 in order to meet the 50% derating requirement,
- EXOMARS: 0,27 W/cm^2. Application of the 50% derating requirement on the 0,54-W/cm^2 value as specified in [1] and [2],
- MTG: 0,27 W/cm^2. Application of the EXOMARS approach, which in this case has been agreed with the prime contractor TAS (F). Application of the 50% derating requirement on the 0,54-W/cm^2 value as specified in [1] and [2].

It can be noted that the mentioned projects refer to ESCC and ECSS requirements, but the interpretation of its applicability is quite different.

REQUIREMENTS FOR HEATER POWER AND DE-RATING IN EUROPEAN AND US STANDARDS

European Standards

Definition Of Heater As EEE Part

A heater is correctly defined as component, which is synonymous for part. The term "component" is preferred for EEE devices.
However, the classification of a flexible foil heater as EEE part seems questionable. In general, EEE parts are located internal to electronic equipment and de-rating requirements are specified since these parts are normally not redundant. The intention of EEE parts as being components internal to equipment is expressed in [2], which states:

- “Derating is a means of … enhancing the end-of-life performance of equipment” and
- “The aim is to obtain reliable and high performance equipment without over-sizing of the components”.

In contrast, foil heaters are located always outside of an equipment and fall therefore not under the general definition of EEE parts. Critical heaters are either internally redundant or a cold redundant item is placed close to the normally operated heater.
There are therefore some arguments to classify foil heaters as a general thermal control item, which need to be verified at qualification levels and applied after verification at acceptance level (similar to other thermal control items).

Maximum Allowable Power Density

The maximum rated power for a foil heater is specified in [1] with 0,54 W/cm^2, at ambient temperature of 25°C, but operating “suspended in still air”.
The ESCC and ECSS system does presently not define the maximum heater power, when attached to a substrate within a spacecraft. The only remark in this respect is contained in [2], Chapter 6.26.2.8:
“Actual rated power shall be specified in the applicable heater design drawing and be determined by taking into account the thermal properties of the mounted heater in the application.”
There is no advice how the thermal properties of the mounted heater shall be taken into account. As a consequence it can be stated that a generic power density specification for attached heater does presently not exist. The property should, instead, be related to specific applications and must be determined for each of these applications.
Due to the missing specification for maximum power density, projects have taken the specified value used for heater qualification at the supplier, i.e. 0,54 Watt/cm^2 [1]. However, this power rating is defined for a not-attached heater, i.e. suspended in air and the 0,54 W/cm^2 are specified in order not to overheat the unit in this condition.

Heater Derating

As mentioned above, EEE parts, which are located internal to equipment, are specified to be de-rated in order to increase the reliability of the entire equipment.

The de-rating requirements, specified in [1] are for heater suspended in still air and thus not applicable for heater attached to a substrate.

Reference [2] specifies for foil heaters, when classified as EEE part, a derating of 50%.

Several projects use erroneously the above mentioned 0.54 W/cm^2, which are specified for heater suspended in still air, and apply in addition the 50% derating requirement. The approach finally leads to the very low power density of 0.27 W/cm^2.

US Standards

The heater power and de-rating requirements in US standards seems to be simpler. The governing Standard is the EEE-INST-002 [3], which calls up the NASA heater specification [4].

Relevance of these two documents:

- EEE-INST-002 [3]:
  - Contains requirements for heater qualification (Section H1 of this document) and the purpose is similar to ESCC 4009 series in Europe,
  - The document calls up [4] for detailed heater qualification requirements,
  - The document does not require heater power de-rating by a %-value, but specifies to use the heater within the manufacturer's recommended current, voltage and temperature range.
- S-311-P-079 [4]:
  - Contains detailed requirements for heater qualification,
  - For heater application as attached to a substrate within a spacecraft maximum allowable "Watt densities" are given in diagram form (Watts/cm^2 over Heat Sink Temperature in °C),
  - The mentioned diagram specifies for Kapton® foil heaters [pressure sensitive tape (equivalent to 3M type 986)] a maximum heat density of 3 Watt/ cm^2 up to 50°C. the value decreases linearly above 50°C to 0,0 Watt/cm^2 at 100°C.

Conclusion With Respect To Spacecraft Projects

Spacecraft designers are interested to use high heater power densities in order to minimize heater dimensions. Especially in spacecraft payloads available area to place heaters are scarce, especially when redundant heaters are required.

Several European projects use erroneously the above mentioned very low heater power density of 0.54 W/cm^2 as maximum heater power allowance, which however is specified only for heater suspended in still air, i.e. for qualification of the component at the manufacturer. In addition the 50% derating requirement is being applied. The approach finally leads to the very low power density of 0.27 W/cm^2 and consequently large heater dimensions.

Present ESCC and ECSS documents do not include requirements for validation of the heater bonding process. The results of the present study indicate, however, that heater failure is in most cases due to imperfect attachment of the heater to the substrate.

FOIL HEATER TEST PROGRAMME

Objective of the Test Programme

Based on the described typical heater applications in a spacecraft, we tested Kapton® foil heater, which are attached to commonly used spacecraft structure substrates, with various power densities. In order to investigate possible failure mechanisms, we increased the heater power step-wise until failure. During testing the substrate temperature was controlled to constant values, in order to achieve high power densities without premature burnout.

Definition of Test Configuration

We selected the most used substrate for heater in a spacecraft, i.e. flat aluminium alloy and flat CFRP surfaces.

The selected configurations are seen in Fig. 3. The dimensions of the aluminium alloy plate are 500 x 230 mm and of the CFRP plate 180 x 190 mm. The CFRP material was bonded by an adhesive to the aluminium plate.

The aluminium plate is bolted to a cold plate, the temperature of which can be regulated and stabilized to a desired level. The entire test object is placed in a climatic chamber in order to control the test environment. Due to budget restrictions tests under vacuum could not be performed in this study.
The characteristics of the test items are summarized in Table 1.

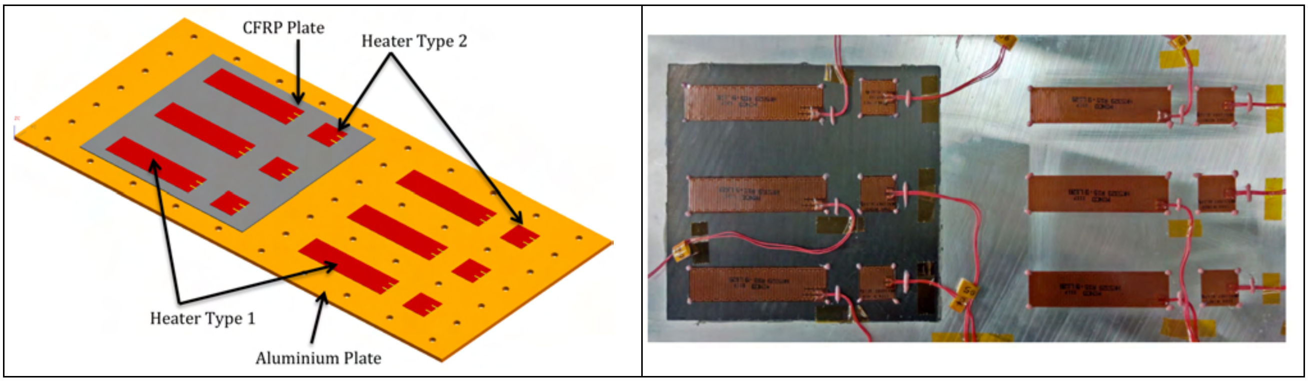


Fig. 3: Test configuration

Table 1: Characteristics of Test Items

Item	Characteristics
Heater Type 1 (one layer)	• Minco order and identification number: HK5329R15.9L12B, • 3 pieces attached to CFRP, • 3 pieces attached to aluminium plate, • PSA backing (3M 966), • Resistance: 15,9 Ohm, • Dimensions: 97 x 25,4 mm = 24,6 cm^2.
Heater Type 2 (one layer)	• Minco order and identification number: HK5318R7.6L12B, • 3 pieces attached to CFRP, • 3 pieces attached to aluminium plate, • PSA backing (3M 966), • Resistance: 7,6 Ohm, • Dimensions: 25,4 x 25,4 mm = 6,45 cm^2.
Heater attachment process	• Pressure Sensitive Adhesive provided attached to the heater, • Application procedure according to: EXM-OM-PRD-OHB-0045, Issue 02, 18.09.2013: "Work Instruction: Integration of heaters with PSA on Aluminium and CFRP". • Adhesive dots for heater peel protection were applied (seen in photo of Fig. 3).
CFRP Plate	• Seize 0,65 x 180 x 190 mm, • Unidirectional fibre K13D2U, parallel to the 180 mm edge, i.e. perpendicular to the long side of Heater Type 1, • Matrix MTM46, • Local evenness 0,1mm/100mm; surface roughness Ra=3.2, • Glued on Aluminium plate.
Aluminium Plate	• Seize 4 x 230 x 500 mm, • AlMg3, • Local evenness 0,1mm/100mm; surface roughness Ra=3.2, • Threaded (M6) hole pattern 50 x 33 mm (except area occupied by CFRP plate).

Test Program

The temperature plan for the test specimen is shown in Fig. 4. Three temperature sensors are associated to each heater, in order to measure the temperature of the substrate near to the heater pad (2 sensors) and of the heater pad itself (1 sensor).

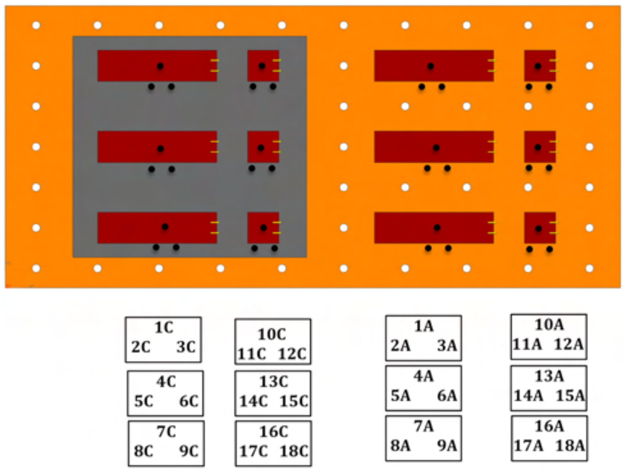


Fig. 4: Temperature sensor location and designation

Testing was performed according to the following procedure:

- One of the heaters was tested, while the other heater remained unpowered
- Each heater was powered by increasing the heater power in steps.
- After each step operation continued until temperature equilibrium was reached
- At temperature equilibrium the health of the heater was controlled by an IR-camera.
- Power steps are increased until heater burnout condition is observed.
- During the entire test campaign the cold plate temperature is controlled in a way that the heater temperature will remain at nearly 50°C, whatever heater power is used.

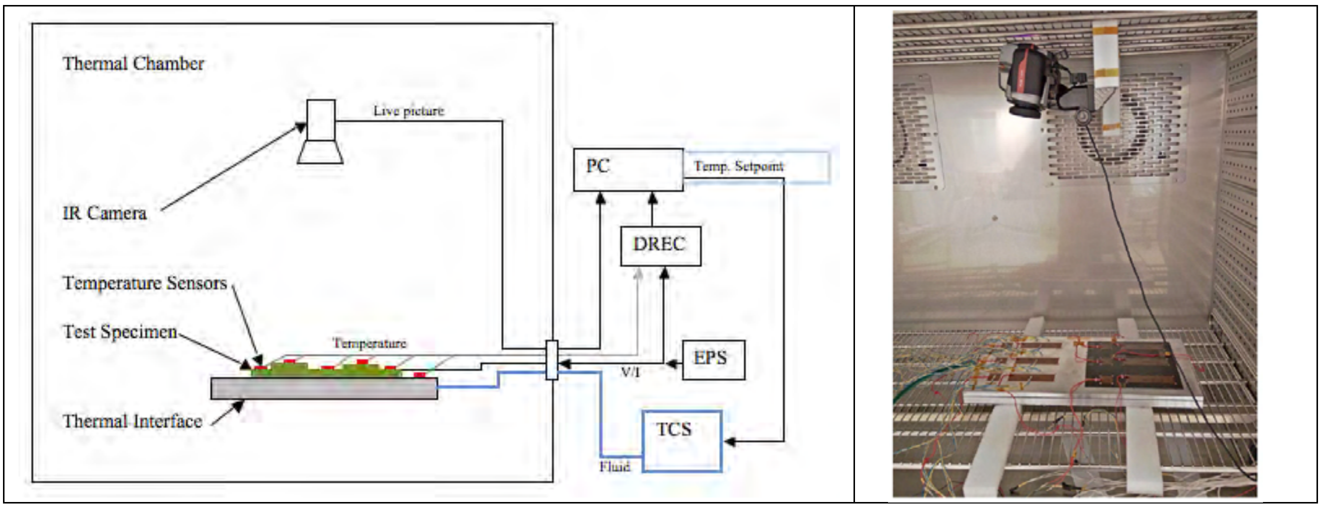
In order to provide an order of magnitude of electrical power needed to obtain a heater power density of 5 Watt/cm^2, the following figures have been calculated:

- Type 1 Heater: 123 Watt
- Type 2 Heater: 32 watt

Test Set-Up Description

Test Set-Up Overview

Testing was performed in a thermal chamber under atmospheric pressure. The test specimens are mounted on a thermal interface plate, which is thermally controlled with a suitable fluid. The schematic test setup is shown in Fig. 5.



DREC = Data Recorder; EPS = Electrical Power Supply; TCS = Thermal Control system

Fig. 5: Test setup overview

The temperature is controlled in a closed loop. All temperatures are continuously measured. The thermal interface is cooled or heated in a way that a defined temperature at the test specimen is maintained. In addition, the thermal chamber is set to a constant temperature to reduce radiation losses of the specimen during test.
The data recorder measures continuously temperatures, voltage and current. The information of the Infrared Camera is continuously stored. All data are collected and managed by a PC.

Test Instrumentation

The equipment and sensors as defined in Table 2 has been used during the test.

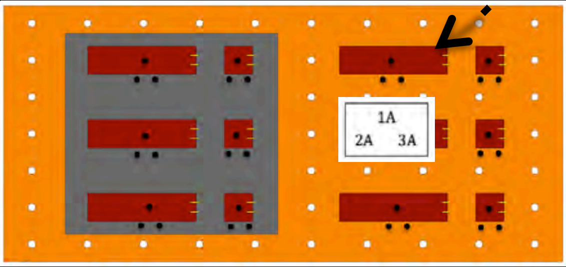
Table 2: Test equipment and sensors

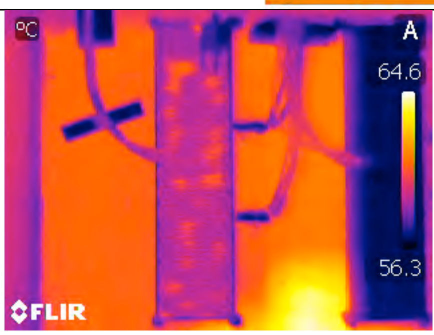
Equipment	**Manufacturer**	**Type**
Thermal Chamber	Binder	MTK 720
TCS	Lauda	RC6
Data Recorder	Yokogawa	MW100
EPS	Sorensen	DLM300-2
Infrared Camera	Flir	T350

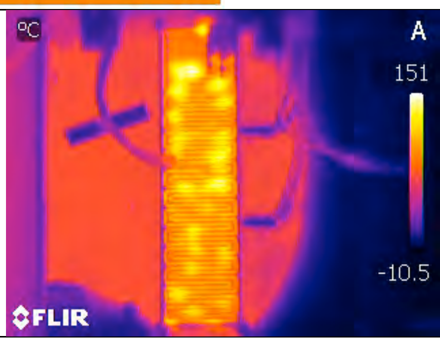
Sensor type	**Manufacturer**	**Type**
PT100	LABFACILITY	2.0x10mm

Test results

Fig. 6 to Fig. 10 show infrared pictures of some heater during operation. The figures include also operational parameter, as well as observations with respect to heater bonding quality and power limit / heater failure.



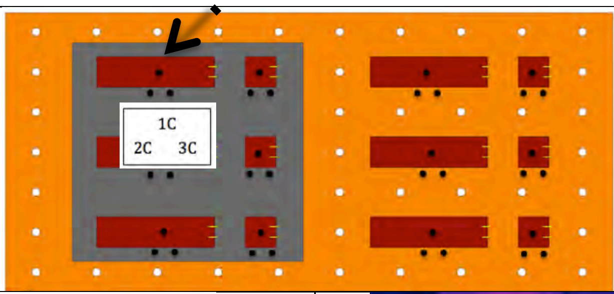


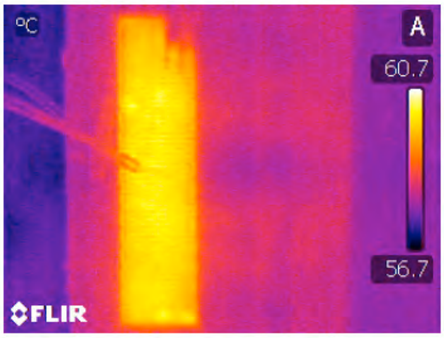


Power Density: 0,26 W/cm^2 Heater Temperature (1A): 50°C Substrate Temperature (2A, 3A): 48°C	Power Density: 7,73 W/cm^2 (or 190 Watt) Heater Temperature (1A): 68°C Substrate Temperature (2A, 3A): -4,0°C
Temperature Difference Heater – Substrate: 2°C	Temperature Difference Heater – Substrate: 72°C

Imperfect bonding is seen at low power and temperature (light yellow spots on left side). These develop to hot spots at high power / temperatures (bright yellow spots on left side). Temperatures of the hot-spot areas are about 50°C higher than the temperature of the remaining heater foil. Testing was terminated due to cooling capacity and power supply limits.

Fig. 6: Temperatures of Type 1 Heater with Low and High Power Density (Substrate Aluminium Plate)

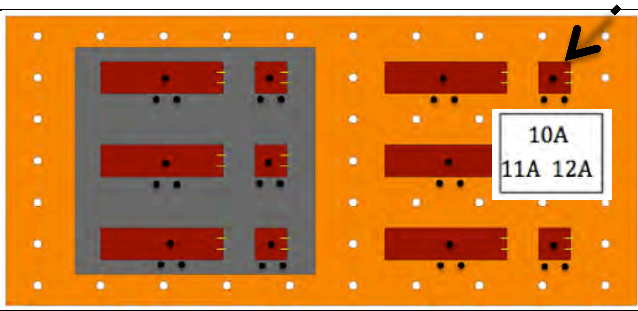


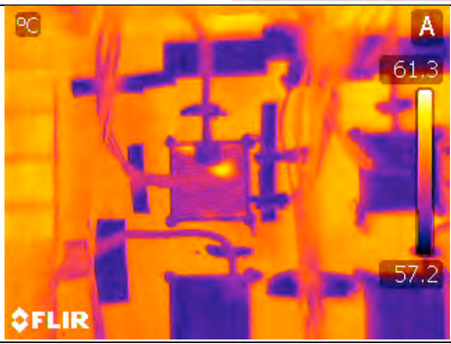


Power Density: 0,06 W/cm^2 Heater Temperature (1C): 50°C Substrate Temperature (2C, 3C): 44,5°C	Power Density: 4 W/cm^2 Heater Temperature (1C): 123°C Substrate Temperature (2C, 3C): -11,0°C
Temperature Difference Heater – Substrate: 5,5°C	Temperature Difference Heater – Substrate: 134°C

Imperfect bonding spots at low power / temperature are almost not visible (left side). These develop to marginal hot spots at high power / temperature (right side). Testing was continued beyond cooling capacity limit (heater temperature considerably higher than 50°C), but terminated during the next power step (5,18 W/cm^2) due to heater destruction.

Fig. 7: Temperatures of Type 1 Heater with Low and High Power Density (Substrate CFRP Plate)

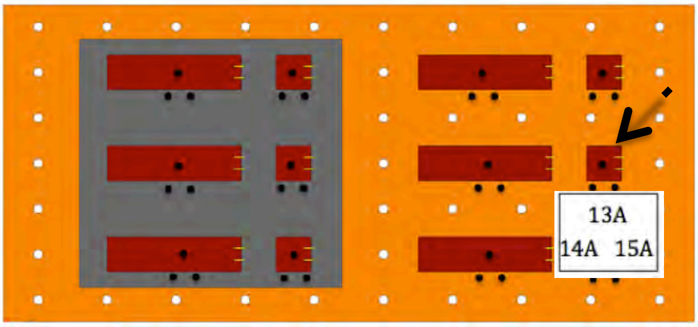


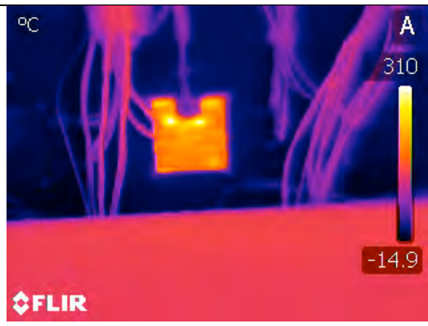


Power Density: 0,08 W/cm^2 Heater Temperature (10A): 50,2°C Substrate Temperature (11A, 12A): 49,7°C	Power Density: 6,61 W/cm^2 Heater Temperature (10A): 70°C Substrate Temperature (11A, 12A): -2,8°C
Temperature Difference Heater – Substrate: 0,5°C	Temperature Difference Heater – Substrate: 72,8°C

Imperfect bonding is seen at low power and temperature (yellow spots on left side). These develop to hot spots at high power / temperatures. The temperatures of the hot-spot areas are about 50°C higher than the temperature of the remaining heater foil. Testing was terminated, due to cooling capacity limit.

Fig. 8: Temperatures of Type 2 Heater with Low and High Power Density (Substrate Aluminium Plate)

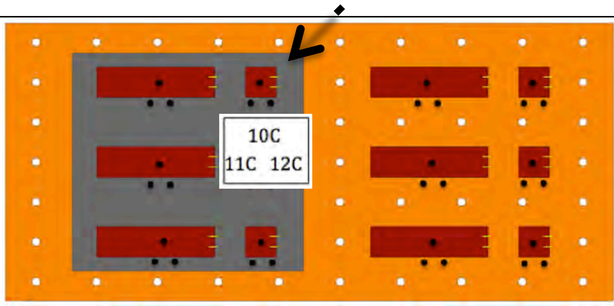


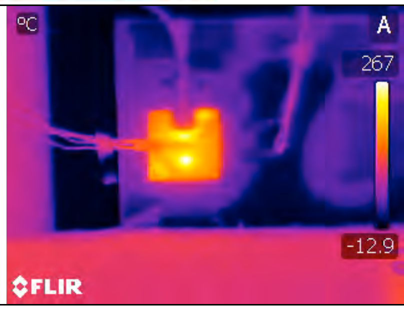


Power Density: 0,73 W/cm^2 Heater Temperature (13A): 50,4°C Substrate Temperature (14A, 15A): 42°C	Power Density: 11,75 W/cm^2 Heater Temperature (13A): 121,5°C Substrate Temperature (14A, 15A): -12,5°C
Temperature Difference Heater – Substrate: 8,5°C	Temperature Difference Heater – Substrate: 134,0°C

Imperfect bonding is seen at low power and temperature (yellow spots on left side). These develop to hot spots at high power / temperatures. The temperatures of the hot-spot areas are about 50°C higher than the temperature of the remaining heater foil. Testing was continued beyond cooling capacity limit (heater temperature considerably higher than 50°C), but terminated during the next power step (16,57 W/cm^2) due to heater destruction (power supply interruption due to burn-through).

Fig. 9: Temperatures of Type 2 Heater with Low and High Power Density (Substrate Aluminium Plate)





Power Density: 0,08 W/cm^2 Heater Temperature (10C): 50,1°C Substrate Temperature (11C, 12C): 47,7°C	Power Density: 4,0 W/cm^2 Heater Temperature (10C): 105,1°C Substrate Temperature (11C, 12C): -10,5°C
Temperature Difference Heater – Substrate: 2,4°C	Temperature Difference Heater – Substrate: 115,6°C

Bonding with good quality. Light imperfect bonding area in lower left corner and close to cable connection at low power and temperature (yellow spot on left picture). Hot spots develop there and elsewhere at high power / temperatures (right picture). Testing was continued beyond cooling capacity limit (heater temperature considerably higher than 50°C) and terminated during the next power step (5,22 W/cm^2) due to heater destruction.

Fig. 10: Temperatures of Type 2 Heater with Low and High Power Density (Substrate CFRP Plate)

All heater were operated by adjusting the sink temperature in such a way that the heater temperature (sensor mounted on top the heater foil) maintained at or near 50°C. At high heater power either the power supply limit or / and the cooling capacity limit was reached. In order to power the heater up to heater destruction, the heater temperature requirement of 50°C could not be met. All observed heater destruction took place with heater temperatures well above 100°C, while the substrate temperature was below zero degrees.

The heater test results may be summarized as follows:

- If the substrate temperature can be controlled to sufficient low temperatures, heaters are able to operate flawlessly at high power and temperatures. Temperature differences between heater and substrate are rather high and can reach easily >100°C.
- The quality of heater bonding to the substrate may be decisive for maximum allowable heater power density. All heaters which were operated until destruction showed an imperfect bonding, which was reason for hot spots at high power / temperatures. Destruction was due to burnout of one of the observed hot spots.
- Not perfect bonding, which may lead to early hot spots, can be detected with an IR camera at already very low power densities (see for example Fig. 6 left photo). IR-camera monitoring should therefore be introduced for flight heater hardware to verify the quality of heater bonding.
- Aluminium substrate
    - The maximum power supplied was 190 Watt or 7,7 W/cm^2 for heater Type 1 with 97 x 25,4 mm = 24,6 cm^2. Under these conditions the power supply limit was reached, but the heater was still operating nominally.
    - The tested foil heaters can sustain very high temperatures. The highest measured temperature with nominal heater operation was measured for aluminium substrate and heater Type 1: about 121°C with a temperature difference to the substrate of 134°C (power density 11,7 W/cm^2).
    - Destruction of the Type 2 heater (with 25,4 x 25,4 mm = 6,45 cm^2) occurred at power density of 16,5 W/cm^2 at a heater temperature >120°C and a temperature difference to the substrate (aluminium) of >130°C.
- CFRP substrate
    - Due to the lower heat conductivity of the CFRP substrate the heater temperature raised more quickly, compared to the aluminium substrate.
    - Destruction for Type 1 heater (97 x 25,4 mm = 24,6 cm^2) occurred at about 5,0 W/cm^2, at 130°C heater temperature and a temperature difference to the substrate of about 140°C.
    - Destruction for Type 2 heater (25,4 x 25,4 mm = 6,45 cm^2) occurred again at about 5,0 W/cm^2, at 110°C heater temperature and a temperature difference to the substrate of about 120°C.
- Dominating factor, which determine heater destruction, is the heater temperature, which was about 120°C in our tests with a temperature difference to the substrate of >130°C. Heater destruction is initiated at hot spots, due to imperfect heater bonding.
- The heater power or heater power density, which is necessary to reach this threshold temperature, depends on the thermal conductivity and temperature of the substrate. For a substrate temperature of about -10°C the critical heater temperature of about 120 °C is reached:
    - At a power density of about 16 W/cm^2 for aluminium substrate,
    - At a power density of only about 5,0 W/cm2 for CFRP substrate.
- The low critical power density for the CFRP substrate was surprising, because the substrate consists of high-conductive fibres with an in-plane thermal conductivity, which is much higher than the aluminium substrate. We suspect that the test results are due to the low out-of-plane conductivity of the CFRP material, i.e. the high thermal resistance between heater foil and carbon fibre.
- Heater mats with the measured high temperatures may radiate a considerable amount of heat into the environment (especially for large surface heaters), which has not been evaluated during this activity. The high heater mat temperatures (and subsequent radiation heat losses) should be introduced into the spacecraft thermal analysis process.

CONCLUSION AND RECOMMENDATIONS

Major Findings of the Test Programme

1. Heater failure mechanism seems to depend on a limiting heater temperature and not on a limiting heater power density. This is in contrast to existing ESCC or ECSS documents, where a maximum power density and power derating independent from heater temperature are specified.
2. The allowable heater power or heater power density, which will safely avoid heater destruction (burn-out), depends on the thermal conductivity of the substrate, i.e. on how efficient the heat will be transported away from the heater. For the described tests of this activity heater power densities of about 16 W/cm^2 could be allowed for aluminium substrates and only 5 W/cm^2 for CFRP substrates.
3. Due to the high thermal resistance of the Kapton® and adhesive layers foil heaters experience high temperature differences to the substrates. Heater temperatures of up to 130°C higher than the substrate temperature have been measured.
4. However, only the maximum heater temperature is decisive (about 120°C in the described tests) for safe operation and not the temperature difference to the substrate. In conclusion, if a heater is operated on an already warm substrate, a rather small heater power density will already lead to a critical heater temperature, compared to heater operation on cold substrates.
5. Radiation heat losses due to high nominal heater temperatures should be considered in the thermal design of spacecraft, in particular for large surface heaters.
6. Although bonded with a validated process, almost all heaters showed imperfect bonding results, which can be detected already at low heater powers with an IR camera.
7. The not perfect bonding areas develop to hot spots at higher heater powers. Temperatures of hot spots at nominal heater operation are about 50°C higher as compared to perfectly bonded areas. Heater destruction happens through burnout in one of the hot-spot areas.
8. It is therefore recommended to verify the bonding quality of space heater hardware with an IR camera. Reject criteria should be developed.

Recommendation for ESCC and ECSS Documents

Foil heaters are applied outside electronic equipment on space structures. In critical cases two cold redundant heaters are used. Operation is feedback controlled by redundant temperature sensors placed in the vicinity of the heater pad. These application characteristics are not typical for electrical / electronic components and it is questionable to classify foil heater therefore as EEE parts. The derating requirements specified in [1] and [2] seem in addition not logical for heaters, because derating has been solely introduced for internal parts of electronic equipment to enhance end-of-life performance of these units.

It is recommended to verify heaters in the attached state at qualification levels, which should be based on validated and reproducible bonding processes. Individual qualification campaigns shall be performed for different heater types (single / double layer pads, with aluminium backing, type of adhesive) and substrates (substrate material, curved and flat surfaces). An additional derating requirement is not necessary, if the thermal spacecraft design guarantees that heaters are operated during spacecraft life below maximum acceptance levels, which are by definition less severe than the qualification levels.

There is a general need to update heater related Standards, because other heater technologies, such as printed heater [5], cartridge heater and wire heater, are presently not covered.

Outlook

To guarantee operation of foil heaters with high reliability is difficult. The presented study shows that validated bonding processes are apparently not reproducible in all cases. Bonding imperfections, which may be caused by trapped air, cannot be totally excluded and may lead to unexpected heater failure at high temperatures. Furthermore, the qualification process of foil heaters needs to take into account a number of different available heater types and substrate conditions. Verification effort is therefore high and due to the involved application parameters the reliability of the heater attachment process remains critical.

In this situation the direct printing of heater tracks on flat and curved surfaces with an electrical conductive material may offer an interesting alternative (Fig. 11). The technology, developed for terrestrial applications, is presently being evaluated for space application under an ESA contract [5]. The heater printing

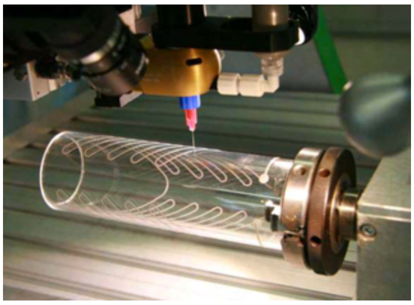


Fig. 11: Heater printing process
Source: Fraunhofer IFAM, Bremen

process is studied on Al- / Ti-alloy and CFRP, using flat and curved substrates as well as tubular configuration, i.e. propellant lines. Outgassing tests and radiation impact assessment are part of the study.
The evaluation is very promising and the following advantages could be identified for space application:

- Freedom of heater configurations and shapes,
- Reproducibility of heater tracks with predetermined electrical resistance,
- Very good adhesion of the heater track on the investigated substrates,
- Due to direct printing the temperature difference between heater element and substrate is low (at least an order of magnitude lower compared to Kapton® foil heater).

The application, i.e. printing, of heater outside the spacecraft is however precondition for using this technology. The “off-line” installation of heater is in most cases possible (panels, electronic equipment, heat pipes, etc.) and supports the need to pre-integrate complete sub-assemblies before submission to the central spacecraft integration site.

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