Technological challenges and roadmap for flexible heaters

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INTRODUCTION

The flexible heating element consists of an etched foil resistive element laminated between two insulation layers. Flexible heating foils produced by IRCA S.p.a. - ZIHET (Zoppas Industries Heating Element Technologies) are ESCC-qualified in accordance with [1], [2], [3], and are duly included in ESA QPL ([5]). They provide fast heat-up and cool-down rates, ensuring uniform heat distribution at various watt densities. This product has gained widespread popularity due to its versatility and is extensively used for thermal control in various parts of satellites or inhabited modules, including piping, electronics, batteries, structures, optics, detectors, and more (see Fig.1).
Flexible heaters are the cornerstone of ZIHET's product portfolio for the space market, around which the company is developing a technical roadmap to expand the range of capabilities offered by these heating products, in order to keep pace with the rapidly evolving space economy.
In this paper, we will provide an overview of ZIHET's current and future portfolio of products for the space industry. We will also discuss the various technical challenges that the company has encountered during the development of these space-qualified solutions, and how they have been addressed.
In particular, we will address the support provided by the new tools for correct applicability of derating rules and preliminary design of the thermal system.

TECHNOLOGY DESCRIPTION

The key components of an etched foil flexible heater include:

- Resistive Foil Element:
    - Made from a thin metallic foil of flexible nickel/chromium/iron alloy (Inconel) in accordance to ESCC applicable detailed specifications [2] and [3]
    - The foil is etched to create the desired resistance and heating profile
    - The etching process allows for precise control of the heating element geometry and resistivity

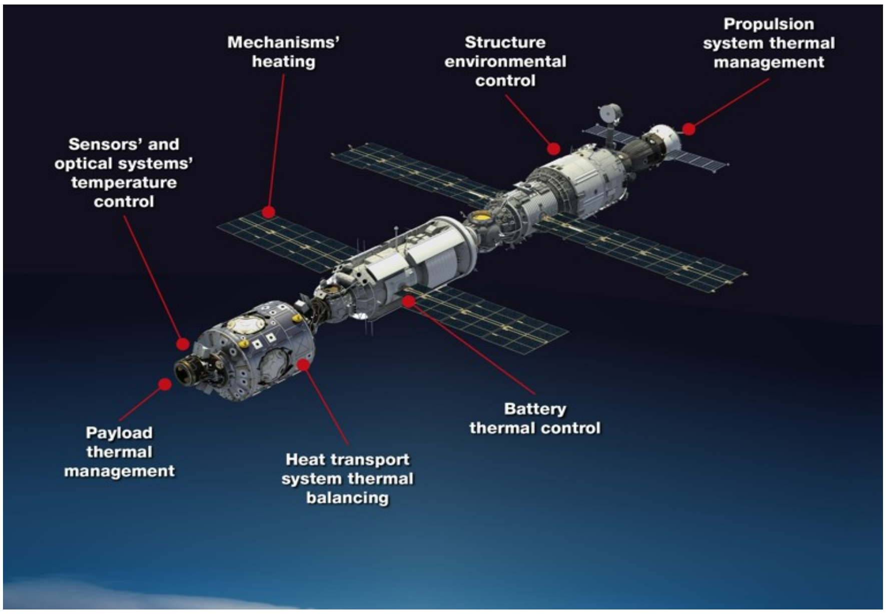


Fig. 1. Typical applications of ZIHET flexible heaters on board of a spacecraft.

- Insulation Layers:
  - The resistive foil element and the terminal leads connections are laminated between two layers of thin, flexible insulation material
  - The insulation material can be Polyimide Polymer/FEP in accordance with ASTM-D5213 ([2]) or Polyimide Film/Acrylic Adhesive in accordance with IPC4203/1 ([3]).
  - These insulation layers provide electrical isolation, thermal insulation, and mechanical protection for the heating element and the terminal leads connections.
- Lamination:
  - The resistive foil and insulation layers are laminated together under heat and pressure to create a robust, flexible heating assembly
  - Specialised adhesives or bonding techniques are used to ensure a strong, durable lamination, depending on the heater's variant.
- Electrical Terminations:
  - Terminal leads and connecting wires are electrically welded to the heater resistive element.
  - Terminal leads and connecting wires are made of multi-strand silver-plated copper in accordance with [6]
  - The wire gauge is defined by the applicable specification [2] or [3].
  - The connection is then sealed to increase strength and electrical insulation
- Optional layers are described in the next sections.

The flexible heaters are manufactured in accordance with the Customer needs in terms of dimensions, shape, resistance and number of circuits.

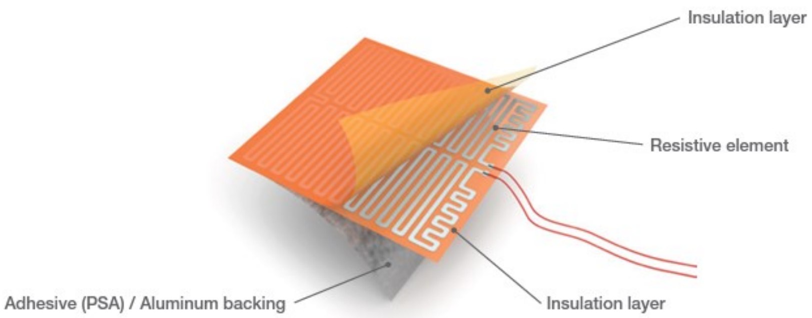


Fig. 2. Exploded vision of an ESCC-qualified flexible heater.

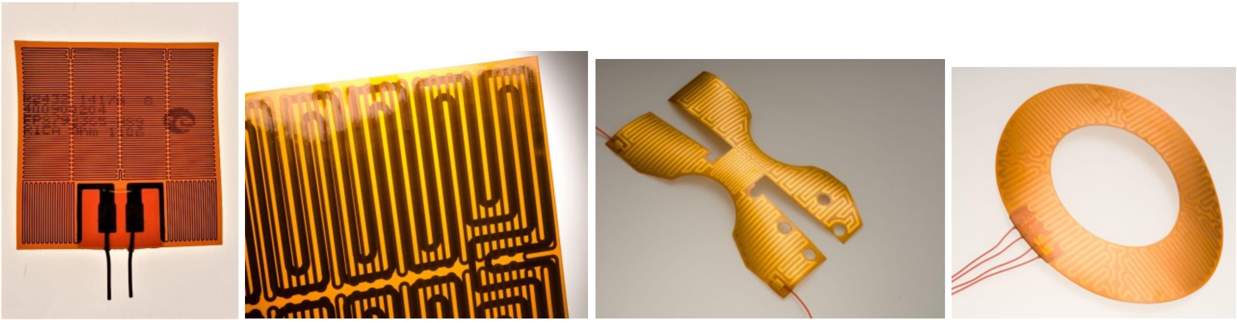


Fig. 3. ZIHET space-qualified flexible heaters in various shapes and variants.

Table 1. Summary of technical characteristics and features of the flexible heaters

voltage range	≤400 AC/DC (1 or 3-phase)
ohmic density	up to 200 Ω/cm² (FEP), up to 330 (Acrylic) Ω/cm²
resistance tolerance (± %)	2, 3, 5, 10% according to ESCC spec
length	8 - 600 mm
width	6 - 590 mm
min thickness	0.15 mm (depending on product configuration)
max continuous operating temperature	200°C (FEP), 150°C (Acrylic)
min operating temperature	-65°C
RoHS	YES
optional additional layers	adhesive (3M 966) / Aluminum backing / second heating layer with redundant circuit
approval	ESCC 4009/002 - ESCC 4009/004

TECHNOLOGICAL CHALLENGES

The technological challenges for space-qualified flexible heaters are diverse and primarily involve thermal efficiency, reliability, safety, and resistance to extreme space environments. Here are some of the main technological challenges faced in the development of these heaters, and a description of how ZIHET is involved in actively supporting and solving such challenges.

Size and weight reduction

In the context of space missions, optimising the size and weight of components is crucial. Flexible heating technologies are designed to be lightweight and compact, enabling efficient use of space within space platforms. ZIHET flexible heaters start with a minimum thickness of just 0.15 mm and can reach an electrical resistance of 330 Ω/cm².

Reliability and derating

Space heaters need to be extremely reliable and able to function without failures for long periods. ZIHET is a global supplier of heaters and systems for space satellites, spacecrafts, pressurised modules and ground-based antennas, ESA/ESCC-qualified (ESCC 4009/002 [2] - ESCC 4009/004 [3]) since 1992. This certification, which has been renewed this year, ensures full flight compatibility of all the products provided by ZIHET.
Moreover, ZIHET offers different options in terms of redundancy, to fully cover all the possible system design FMEA choices: single circuit heaters, double circuit heaters, double-layer heaters (see Fig.4).
To further increase the reliability of the heaters, a commonly required strategy is the application of derating rules. Specifically, the applicable derating rule for heaters is reported in the ECSS-Q-ST-30-11C standard ([7]). ZIHET has been involved in several discussions with the users regarding the correct interpretation and application of this rule. In the next subsection, the approach used by ZIHET to support this process is described.

ECSS derating rules application

The mentioned ECSS document ([7]) has been recently updated from rev.1 (4 Oct.2011) to rev.2 (23 June 2021) in particular for the section dedicated to heaters (6.26.2.8).

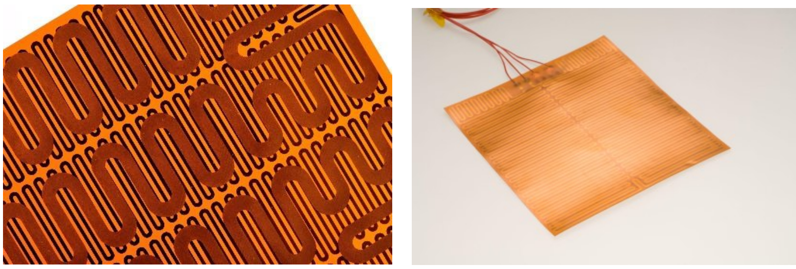


Fig. 4. Some examples of double layer and double circuit flexible heaters.

The applicable derating rule for heaters passed from a control approach based on the maximum applicable input power (Rev.1) to the maximum qualified temperature (Rev.2).
With the application of the former requirement based on power density, some users encountered difficulties because there is no generic rule on the maximum heater power. Indeed, the maximum applicable input power level is mentioned in [2] and [3] but it is only referred to heaters suspended in still air, as it is intended for heaters' manufacturers, giving an indication on how to perform the internal qualification tests. On the other hand, the rule reported in [7] refers to the heater attached to a substrate within a spacecraft, under mission thermal conditions. This value is heavily affected by the environmental and material properties of the surrounding of the heater, which are very variable, platform- and mission-dependent. It is straightforward that the evaluation of this parameter is a complex task that is not accessible at component level, because it needs to be accomplished at system level, taking into account all the involved parameters listed here above. To provide support to Customers with a first estimation of this parameter, ZIHET has developed *EFsim*, a numerical tool that is described in the next section.
The update of [7] to Rev.2 requires powering the heaters while ensuring a 50°C margin on the maximum qualification temperature. This new rule overcomes the above issues, defining a clearer and safer rule based (when possible) on temperature, simply posing a margin between the maximum reachable temperature and the materials' (i.e. heater itself, or adhesive if present) qualification higher limit. The heater's manufacturer provides the operative temperature range of each unit, related to the used materials and configuration (this is already always provided, in line with ESCC rules). The user shall then guarantee, through direct or indirect temperature control of the heater itself during usage, that these limits are respected.
This new rule for heaters is simpler to apply for thermal systems and heaters' designers, it is more in line with available information, and allows designing the heater less conservatively but still guaranteeing the requested quality and reliability standards. In this view, the user has the need to know the operative heater temperature at least during the ground test and correlation phase.
ZIHET can support this process by providing flexible heaters equipped with an integrated temperature sensor (PT100/PT1000/NTC) - a solution commonly offered for other high reliability markets such as the medical industry - to be used during ground testing phases (see Fig.5).
Through a precise temperature measurement of the heating track, the user will be able to accurately model and calibrate the heater input power in accordance with the ECSS regulation. This calibration can then directly be applied in flight, being (TBC by ESA Programs) its applicability guaranteed by the fact that the heaters used for Ground testing and on flight are exactly the same (ESCC qualified), with the sole difference that the one on Ground has the embedded sensor. The extracted thermal data can be used to validate the heater performance and ensure reliable operations.
Within the available types of RTD sensors, PT100, PT1000, and NTC options are available, as well as thermocouples - all of which are also used in the space market and that can be procured from ESCC-qualified manufacturers. The qualification within ESCC QPL of the above embedded solution is ongoing and will be accomplished by 2025.

Operations in extreme environments

Space-qualified flexible heaters are designed to withstand extreme temperatures, both high and very low. They are qualified to operate in a wide temperature range that can vary from -65°C to +200°C.
Recently, we have had confirmation that the ZIHET heaters can support even more extreme missions and conditions. In fact, they have been used to restore the functionality of the primary mirror of the Euclid telescope. Water molecules released from the multi-layer insulation (MLI) after launch had deposited on the mirror behind the primary optics, reducing its visibility by approximately 15%. The heaters were successfully powered on to warm the mirror from -147°C to -113°C in around 100 minutes, reaching a sufficiently high temperature to cause the ice to sublimate, and fully restoring the instrument's functionality.

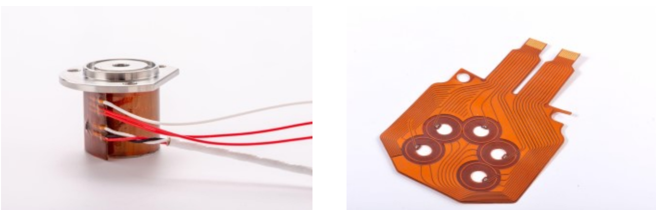


Fig. 5. Some examples of ZIHET flexible heaters with embedded temperature sensors.

ZIHET is currently also ESCC-qualifying the "Pure polyimide heater" (PPH), a new product which will be able to reach even higher temperatures (i.e. +260°C). This kind of heater has been recently developed (and already UL certified) by ZIHET for the medical market, as the most performing product from a thermal point of view. It represents the best solution when highly specific power is required, combined with the lowest thickness and the better thermal transmission. It can be provided with single or double insulation and single or double layer (primary and redundant, or heater + sensor).
Its main advantages and features are (see Table 2):

- Very low thermal mass and thickness (minimum 50 microns overall)
- Solution without any additional glue to bond the heater itself or on a heatsink plate (1)
- Full free design and optimised power density
- Max temperature up to 260°C and high specific power, up to 15W/cm2
- Higher ohm density (up to 330Ω/cm2)
- Any possible shape or possibility to combine more heaters for extra length
- Very low outgassing compared with epoxy/acrylic technology
- Absence of fluoropolymers (which is advantageous in consideration for potential future REACH-related restrictions)
- Resistance to many chemicals
- Higher radiation hardness with respect to the current technologies (which makes the PPH more attractive for long-duration and interplanetary missions)

Heat management and Design optimization

An optimal design of the thermal subsystem involves, besides the correct definition of the heater itself (shape, dimensions, resistance and redundancy), also the selection of materials and fastening methodologies for mounting the heater to the heatsink, as well as the sizing of the power budget based on the operating temperature requirements.
ZIHET qualified flexible heaters can be provided with an optional additional layer of qualified PSA (3M 966), ready to be applied on the satellite components to ensure an optimal bonding. Additionally, each heater can be equipped with an additional Aluminium substrate, which distributes heat more evenly and can be also used for grounding purposes.
Concerning the optimization of the power budget, ZIHET has recently developed an internal project of thermal characterization of the flexible heater products, for several options of insulating material, adhesive and mounting. The outcome of this activity is a model, *EFsim* (for Etched Foil Simulation), described here below. This tool is also very useful in support of the application of the above-mentioned ECSS derating rule ([7]), for the projects where Rev.1 is still applicable.

Thermal Profile: "EFsim" Numerical Model

ZIHET has conducted an internal campaign of study, and experimental validation, to develop a numerical model to estimate the maximum power density a flexible multilayer heater could withstand, as a function of the needed interface temperature. This model, called *EFsim,* is designed to be used in a preliminary sizing phase.
EFsim is a 1D model, it calculates the average temperature at the interface between two layers on a Z-axis, considering the bottom layer is a heat sink and the top layer is in a vacuum. As it is a thermal model, only the thermal aspect of the vacuum is addressed. This numerical model provides instant results for a critical scenario, excluding convection and radiation losses.

Table 2. Product Identity Card of the Pure Polyimide heater, which will be ESCC-qualified by 2025. Notes: (1) custom options will be available (2) To be validated in the specific product configuration.

Overall Thickness	from 50 to 200 microns (typ.) (1)
Maximum Dimension	430x280 mm - higher on request Possibility to combine different heaters in case of extra size heaters (1)
Dielectric Strength	Typ. from 500V to 5.000V
Insulation	Typ. > 500 MΩ @500VDC
Watt Density	Up to 15W/cm² (2)
Max Ohm Density	Up 330Ω/cm², higher on request

The following description outlines the working conditions and variables considered in the creation of the numerical model, as well as its implications.
Every layer is considered infinite on the Y-axis and the X-axis, so that the only heat transfer taken into account is from top to bottom. The heat sink temperature is fixed. The other temperatures are calculated relatively to the heat sink with the thermal resistance in between, using Fourier's law.
The thermal resistance (R_{th}) depends on three properties of the layer: the thickness (D), the thermal conductivity (λ) and the area of its surface (S).

$$R_{th} = D/(\lambda S) \tag{1}$$

In the case of a heater, we must also take into account additional coefficients:

- possible thickness variation of the polymeric layers during the production process (percentage, V_D)
- a coverage factor defined as the ratio between the area of the track and the heating area (percentage, C) of the track
- a track section reduction (from now on referred to as TSR) coefficient (K_{TSR}) which considers the possibility of the presence of track defects
- electrical tolerances to be considered in order to anticipate a lack of precision of the electrical devices (percentage, voltage tolerance τ_V and electrical resistance tolerance τ_R)

as shown by equation (2):

$$R_{th} = \frac{D+V_D}{\lambda SC}\frac{(1+\tau_V)^2}{1-\tau_R}K_{TSR} \tag{2}$$

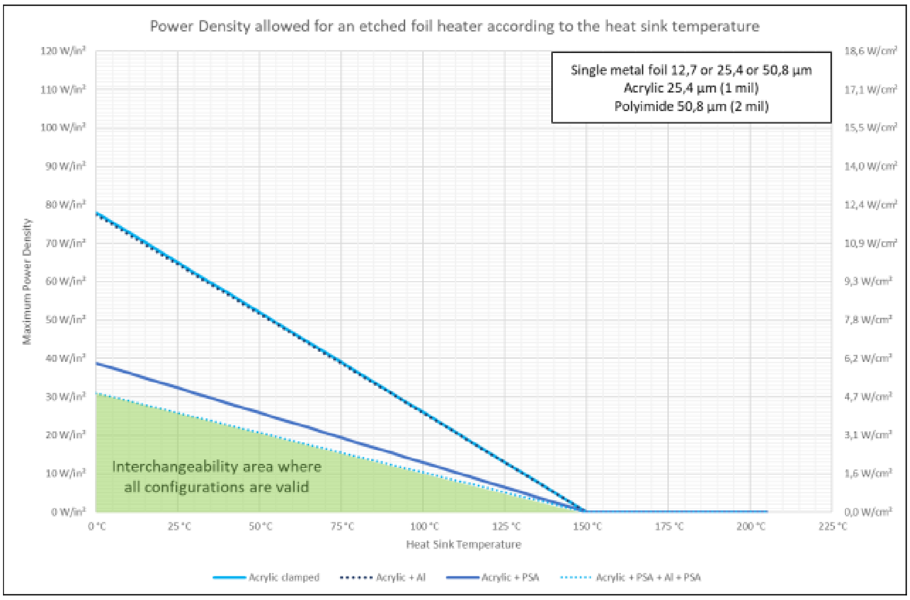
By using Fourier's Law and the electrical analogy, the power flowing through an insulant layer from the heating track to the heat sink is:

$$P = \frac{T_i - T_{HS}}{R_{TH}} \tag{3}$$

with P the power in Watts, T_i the average temperature on a generic point i of the heating track in °C, and T_{HS} the average temperature of the heat sink in °C. Thus, the temperature T_i is calculated as follows, considering a safety margin M(%):

$$T_i = T_{HS} + R_{th}P(1 + M) \tag{4}$$

The tool instantly gives the temperatures inside a multilayer heater and automatically draws a plot showing the maximum power density of this configuration according to the heat sink temperature.
The range of use for different materials can be easily compared using straightforward visual aids.



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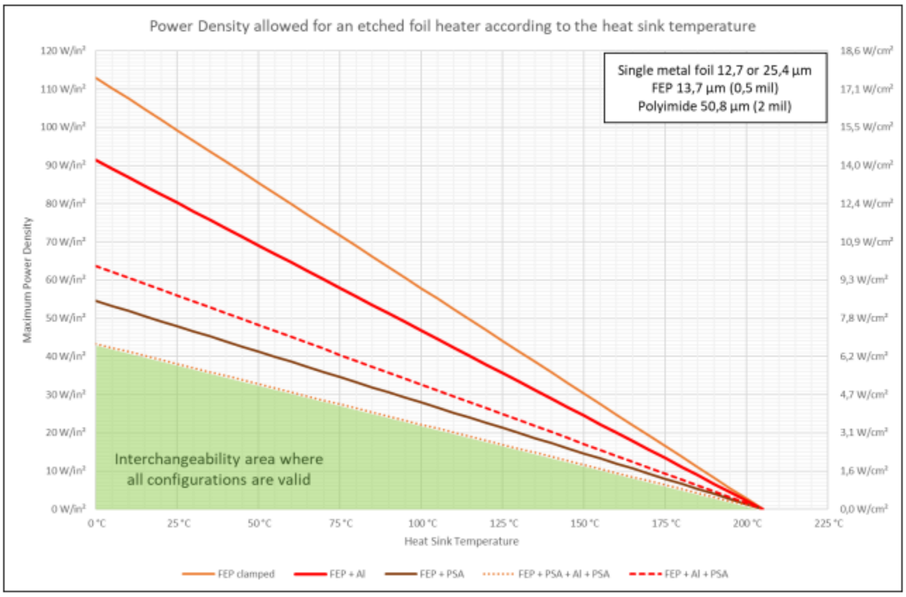

EFsim_2.0.xlsm

Fig.6. Typical results from EFsim for the most common flexible heater configurations used in space applications.

3D numerical simulations have been made in ANSYS Fluent in order to estimate the track section reduction (TSR) coefficient and the validity of the thermal model (see Fig.7). The mathematical model allows for an estimation even when considering minor defects related to the manufacturing process of metallic traces. A defect that reduces the track section, creates a hot spot.

For sizing purposes, it's useful to consider that such a defect will happen by applying a coefficient, because the important temperature is the highest one. The TSR is impact is normalized with a coefficient being the ratio between the thermal resistance of a layer calculated at the TSR (R_{th}^{TSR}) and the nominal resistance ($R_{th}^{nominal}$):

$$K_{TSR} = \frac{R_{th}^{TSR}}{R_{th}^{nominal}} \tag{5}$$

The model is a small area of 1,3 cm² from a heater composed of a 12,7 µm thick heating track made of a Ni-Cr-Fe alloy and a 101,6 µm thick layer of acrylic based adhesive. The heater has not been modelled in its entirety in order to have a fine mesh (10 µm, vertical sweep with 5 divisions for the Inconel and 10 divisions for the adhesive). The TSR has the shape of an arc of a circle with a width of 50% of the track width and a length that is twice the track width.

Calculations have been made with different voltage values up to 12 W/cm². The TSR coefficient found with every simulation is $K_{TSR}(50\%) = 1{,}7$. Considering that the 1D model overestimates the track temperature by ignoring the convection and radiation losses, the proposed value in order to make a compromise between margins and competitiveness is $K_{TSR}(50\%) = 1{,}5$.

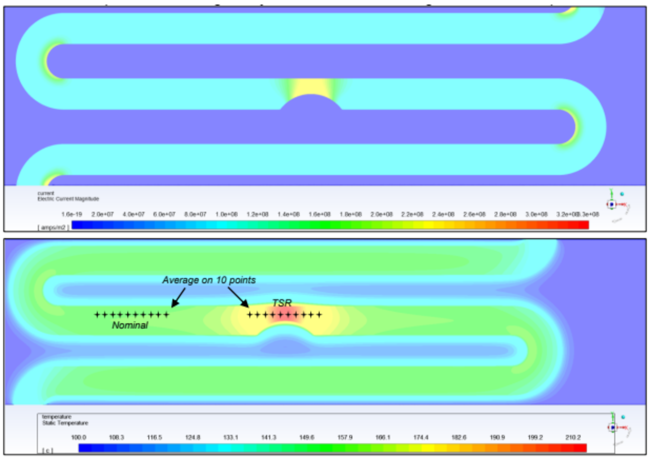

Fig.7. Example of the visuals given by Fluent for the current magnitude and the temperature

The same simulation was employed to evaluate the precision of *EFsim*. The results provided valuable insights into its performance, This thorough assessment helps in validating the effectiveness and reliability of *EFsim* in various applications.
The heating power on the 3D model is obtained by simulating the Joule Effect with an electrical tension fixed at 1,8 V. The electrical resistance of the track is 4 Ω. The materials on the sides of the heating track have a really small thermal conductivity (1E-6 W/mK) in order to compare the results with a 1D model, only the part directly under the track has the thermal conductivity of a Polyimide – acrylic adhesive ensemble (0,22 W/mK). The track temperature given by the 3D simulation can be viewed in Fig. 8.
The nominal temperature is approximately 161°C. With the 12,5% thickness variation of the adhesive, the temperature goes up to 169°C.
If the materials have all their true conductivity, the nominal temperature is only 145°C. With *EFsim*, as seen on the screenshot in Fig.9, the track temperature (without the thickness variation) is also 161°C.
Two conclusions can be derived from this:

- *EFsim* correctly models the heat transfer when we consider that heat only goes through one dimension;
- Making calculations with the theoretical conductivity will give a conservative result, so it can be enough for most sizing purposes. In reality, heat spreads also in the other dimensions, so a 1D model seems to overestimate the track temperature. The solution is to measure the conductivity of every material in an experiment with heaters used as sensors around a powered heater: the heat coming from the powered heater will go towards the sensing track with a small propagation but the conductivity will only be calculated by taking into account the temperature of the area facing the heating track. This will compensate the error that the 1D model makes by ignoring the propagation. In order for this design to work, the tracks have to be identical and aligned.

Experimental tests have also been conducted in order to evaluate whether the model is conservative enough with respect to a real situation.
The experimental setup used for the characterization of the thermal profile of the polymeric insulators was built to be as similar as possible to the *EFsim* model.
The idea behind this setup is to have a heating source and a sensor separated by the insulator sheet: at thermal equilibrium conditions, a temperature difference ΔT is formed between the heating and sensing elements and it is possible to determine the thermal conductivity of the sheet.

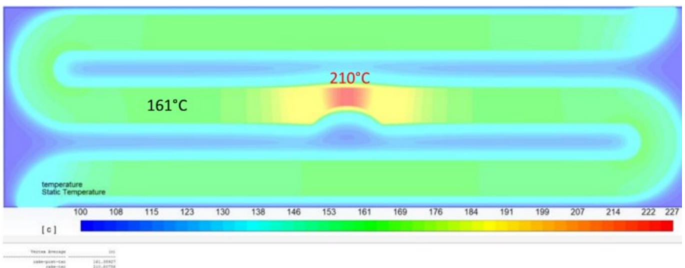

Fig.8. Simulation obtained with Fluent used to evaluate the precision of *EFsim*

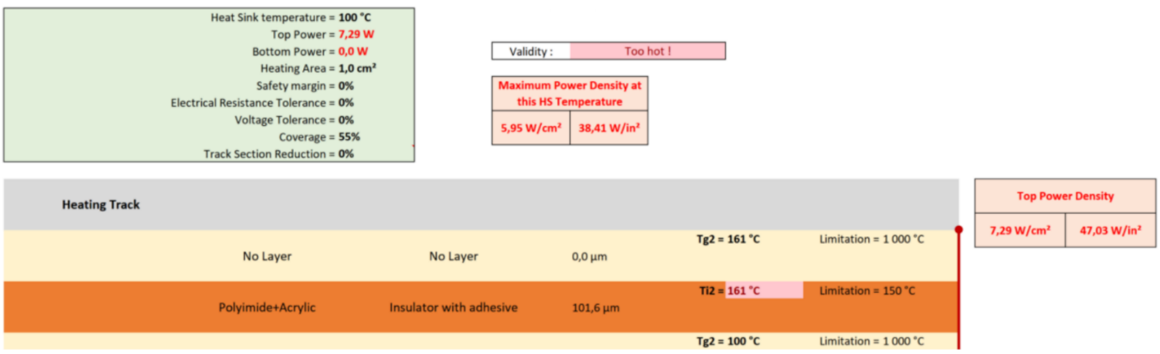

Fig.9. Screenshot of a simulation obtained with *EFsim*

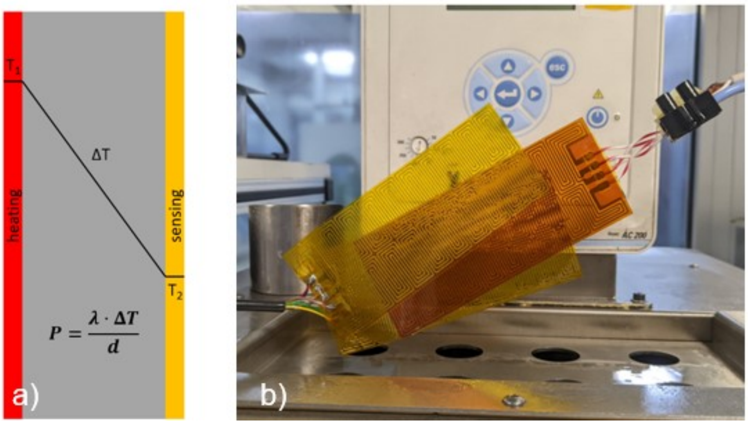

Fig.10. a) schematic of Fourier's Law of thermal conduction; b) an EF sandwich (two sensing elements + one heating element)

Measurements were conducted by means of EF sandwiches consisting of two heating elements used as RTDs (Resistance Temperature Detectors) and a central element used for heating connected to a power supply and to a voltmeter/ammeter. The material selected for the tracks of these elements is nickel, since it has a positive temperature coefficient (PTC) property: as the temperature increases, the electrical resistance of the track also increases. This property directly links the ohmic value of the track with the temperature of the system: by measuring voltage and current on the track, it is possible to monitor the temperature of the track itself. The stack was placed in silicon oil (PDMS) at 25 °C. A calibration was needed in order to define the temperature coefficient of resistance (TCR) of every sensing and heating element and calculate in real time the track temperatures from the registered ohmic values. The two nickel tracks in each sensing element were designed with a resistance of 18 **Ω** (at 25 °C) and were connected in series, while the tracks of the heating element were designed with an ohmic value of 13 **Ω** (at 25 °C) and were connected in parallel.
The sensing elements were set in passive (sensing) mode through a Seneca Z4RTD2 module, and the heating element was powered by a power supply. The sensing tracks were connected in series in order to ensure that the ohmic value would be high enough for the Seneca module to have a reading.
All measurements were conducted by means of the 4 wires method.
Data on the conductivity of the insulating materials were acquired on sandwiches consisting of two sensing elements and a central heating element, between which a few sheets of insulating material were placed (see the following schematics). In order to measure a satisfactory ΔT, a few sheets of insulator were stacked so that the thickness would be 250 µm or more (excluding the coverlays of the heating elements, which would add 64 µm). The two temperatures obtained from the sensing elements were used to calculate an average, which was then used to obtain the ΔT. Layer thickness of the elements and insulating sheets was confirmed by means of a micrometer. Power was fed in a range between 5 and 20 W, by steps of 2,5 W. Thermal equilibrium was ensured by leaving the system at every power-step for 5 minutes.
Silicone conformal pads were implemented on the external faces of the sensing foils, in order to ensure the maximum contact at the interface between the layers. The whole system was kept in place by two 3 mm thick brass slabs held together by four M4 screws, and the elements were centered together with 2 mm pins. The tracks were designed so that the heating and the sensing tracks would be overlapping (the heating track is wider than the sensing tracks), and the sensing tracks were left without coverlay on one side, reducing the experimental error.

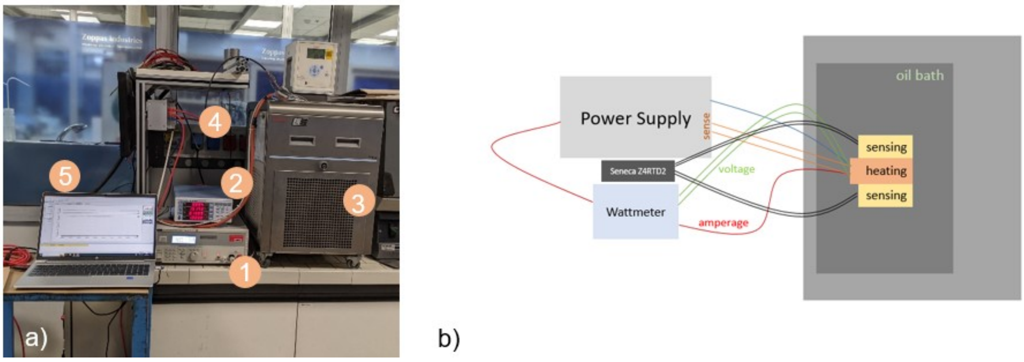

Fig.11. a) the measuring setup: 1) power supply, 2) wattmeter, 3) oil bath, 4) Seneca modules and 5) data acquisition terminal; b) schematic of the measuring setup

The values of thermal conductivity of the whole system (64,5 µm heating element coverlay + n µm insulating sheet) were calculated from the linear regression of the P vs ΔT data using Fourier's Law (equation (1)). In order to evaluate the conductivity of the insulator alone, the thermal resistance (R) of the coverlay was taken into account:

$$R_{tot} = R_{coverlay} + R_{insulator} \tag{6}$$

$$R_{insulator} = R_{tot} - R_{coverlay} \tag{7}$$

As the heat exchange area is the same for every element of the system, it follows that the ratio between the thickness D and the thermal conductivity λ of the insulator can be written as:

$$\frac{D_{insulator}}{\lambda_{insulator}} = \frac{D_{tot}}{\lambda_{measured}} - \frac{D_{coverlay}}{\lambda_{coverlay}} \tag{9}$$

Thus,

$$\lambda_{insulator} = \lambda_{calculator} = \frac{\lambda_{measured} \cdot \lambda_{coverlay}}{(D_{tot} \cdot \lambda_{coverlay}) - (D_{coverlay} \cdot \lambda_{measured})} \cdot D_{insulator} \tag{10}$$

The obtained experimental results are shown in the leftmost column of Table 3 and in Fig.12.

The measured conductivity values are similar to the values reported on the data sheets. As expected, the measured values are usually higher than the theoretical values since the model contains many approximations (1D heat flux, no convection and no radiation). The simulations made by *EFsim*, which is a model based on Fourier's Law and implements various safety factors, used as a preliminary designing tool, will not deviate that much from the true working conditions (assuming that the majority of the heat is dissipated by conduction) if the data sheet value for thermal conductivity is considered. Since the calculated conductivity values are higher than the ones reported on the data sheets, it is reasonable to consider the latter for the simulations, as a lower conductivity means worse working conditions for the overall system.

The simulations and the tests have demonstrated that the *EFsim* model can be used to give conservative results, which is a common strategy for a preliminary sizing phase. As needed, it is simple to use and gives a quick view of the operative range of an etched-foil multilayer heater's configuration.

EFsim is therefore a valuable tool, which can be helpful for thermal engineers as a support during the preliminary TCS design and sizing phases.

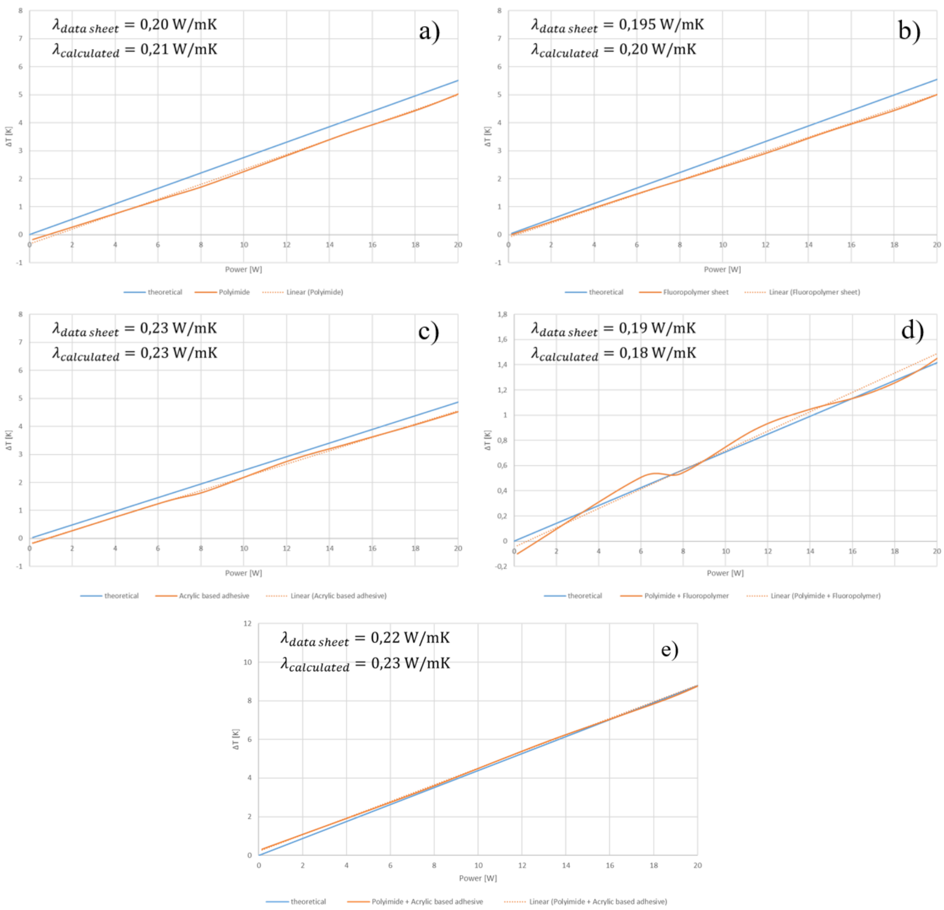

Fig.12. Experimental data obtained for the insulation materials listed in Table 3.

Table 3. Description of the insulator samples used for the experiments

Fig.12	Insulator description	λ, datasheet value	λ, calculated value
a)	Polyimide, 50 µm	0,20	0,21
b)	Fluoropolymer sheet, 250 µm	0,195	0,20
c)	Acrylic based adhesive, 102 µm	0,23	0,23
d)	Polyimide 50 µm + Fluoropolymer 12.5 µm	0,19	0,18
e)	Acrylic based adhesive 50 µm + Polyimide 50 µm	0,22	0,23

High-reliability materials

The materials used in space-qualified flexible heaters must be highly reliable and resistant to space conditions. They must be able to maintain their mechanical and electrical properties even in the presence of ionizing radiation, vacuum, vibrations, and thermal shocks.
Materials and processes for ZIHET flexible haters have been selected in full accordance with ESA regulations for outgassing and reliability. All used raw materials must respect high quality standards and comply with the ESA and EU regulations. With this respect, ZIHET Purchasing & Supplier departments closely work with the Quality managers in order to ensure the proper raw materials' quality.
This aspect has been particularly critical during the most recent periods, mostly because of the absence of a qualified European production chain for the Kapton-FEP insulation variant, while the non-European suppliers do not always guarantee space standards in line with the ESCC requirements. ZIHET has initiated several collaborative discussions with ASI, ESA and DEFIS in order to create synergies and the bases to grow a fully European supply chain for such important and critical materials.

Integration with other components

Flexible heaters need to be designed for easy integration with other components and systems present in space platforms. Thanks to their thickness and flexibility, they can be applied to the most complex shapes, geometries, curves and pipes conceivable without sacrificing efficiency or dependability.
Traditionally, the electrical integration of heaters on board of satellites has always been done through manual connection of the power cable to the on-board harness (through crimping or soldering). However, the integration on satellites of heaters with connectors, is increasingly becoming more common, especially for commercial constellations, where it facilitates the highly serialized production process, but also for satellites from both institutional and start-ups or growing companies in the New Space Economy, where new digitized and optimized approaches allow the cables' lengths to be defined more precisely at the initial design level, and to have agile and repeatable processes available.
Therefore, even if the current ESCC qualification only covers the assembly of heater plus wires, ZIHET also procures assemblies with space-graded connectors, to ease the electrical interface integration with the on-board power subsystem.
As part of the new projects of the space roadmap, finally, ZIHET will achieve by 2024 the ESA certification in compliance with the ECSS-ST-Q-70-26C "Crimping of high-reliability electrical connections" standard, and the QML ESCC qualification process of the above subassembly will take place in 2025.

Testing and qualification

ZIHET Flexible heaters undergo rigorous testing and qualification to ensure they meet the standards required for space use. These tests include visual inspection, electrical measurements, thermal shocks, life tests, etc. in full accordance with the ESCC specifications. Besides this, ZIHET also offers more commercial qualification levels, such as QM (Qualification Model) and PFM (Proto-Flight Model), which ensure compliance with the demanding space environment while addressing fast turnaround times and market competitiveness. These products are produced with the same materials and manufacturing processes as the ECSS ones, but with a more agile campaign for inspections and tests, in order to comply with all possible needs of the wide Space Market which goes from Institutional, Military or Commercial Programs, Cubesats, Nanosats or Constellations, to Ground testing facilities.

Table 4. Space Flexible Heaters qualification levels.

Qualification level	Description
Qualification Model (QM)	These heaters are provided in full compliance with the applicable ESCC specification's prescribed materials and manufacturing; a minimal set of verification steps (i.e. Functional visual inspection, Production Control tests and #ESCC-compliant Final Room Temperature Electrical Measurements) is performed, to ensure its suitability for functional and environmental qualification testing.
ProtoFlight Model (PFM)	These heaters are provided in full compliance with the applicable ESCC specification's prescribed materials and manufacturing; a partial verification campaign with respect to ESCC requirements is performed, mainly: - Visual inspection only focused on functional defects (according to internal ZIHET procedure available for review) - "Room Temperature Electrical Measurements" performed only once - Burn-in test performed on statistical sample, according to UNI ISO 2859-1 type G, AQL 0,40
ESCC Flight Model (FM)	Fully ESA-qualified Space Heater, covering all the inspections, controls and tests foreseen by the applicable ESCC specification.

CONCLUSIONS

Addressing these technological challenges requires in-depth knowledge of space requirements as well as advanced engineering skills in the design of flexible heaters and integration with complex space systems. Companies producing space-qualified flexible heaters need to invest in research and development to continuously improve the performance and reliability of their products. Simultaneously, ZIHET is actively investing in a technological development roadmap aimed at expanding the current qualification of their space product portfolio. This involves the inclusion of new solutions that leverage the company's expertise and high integration products in other high-tech markets such as medical, aerospace, and automotive. Some examples of new products currently undergoing qualification include a high-performance heater (utilising all-polyimide material with high-density and high-temperature capabilities), heaters with integrated connectors and temperature sensors, and the development of integrated control electronics. ZIHET has a dedicated R&D department specialising in material properties and engineering. This team continuously explores new techniques and solutions across all our markets, with a continuous focus on space-grade compatibility.

REFERENCES

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[4] EXTERNAL VISUAL INSPECTION OF FLEXIBLE HEATERS ESCC Basic Specification No. 2054009, Issue 5, January 2024

[5] ESCC QUALIFIED PARTS LIST (QPL) ESCC/RP/QPL005-250 (REP 005), May 2024

[6] WIRES AND CABLES, ELECTRICAL, 600V, LOW FREQUENCY - ESCC Generic Specification No. 3901

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