2.5. Development and Validation of the New IRCA S.p.A.'s Pure-Polyimide Flexible Heater for High-Reliability and High-Performance Markets

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ABSTRACT

Standard FEP or Acrylic polyimide flexible heaters, which have a long history in IRCA S.p.A.'s portfolio for high performance applications such as medical, aeronautics, automotive and space flight, are limited in output power by the maximum operating temperature of the materials used as an adhesive and insulator between the layers.

This paper presents the first European development and validation of the pure-polyimide heater (PPH), a technology which eliminates all internal adhesive layers of a flexible heater, allowing for higher maximum power density and operating temperatures up to 260°C. The PPH offers significant advantages such as very low thermal mass and thickness (minimum 50 microns overall), enhanced thermal transmission, and superior radiation resistance compared to traditional flexible heaters. Key benefits also include minimal outgassing and resistance to a wide range of chemicals. Furthermore, its construction is in line with incoming REACH regulations.

The paper also discusses the direct lamination process validated by IRCA to facilitate bonding of the heater on the heatsink, allowing operations at higher temperatures than common adhesives used for integrating flex heaters allow. Customers who require heaters already integrated with the heatsink now use this process.

THE FLEXIBLE HEATERS' TECHNOLOGY

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.- Zoppas Industries - are widely used in the medical, aeronautics, automotive, industrial and space markets (for the latter, they are ESCC-qualified and are duly included in ESA QPL). They are a flexible and lightweight solution to 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 high-tech applications.

The key components of an etched foil flexible heater include:

- Resistive Foil Element etched to create the desired resistance and heating profile
- Polyimide Insulation (PI) Layers: for medical and aerospace applications, it can be Polyimide Polymer/FEP (Fluorinated ethylene propylene), Polyimide Film /Acrylic Adhesive, or Polyimide Film / Epoxy Resin.
- Terminal leads and connecting wires, which are tinned or electrically welded to the heater resistive element, and then covered with a patch to increase strength and electrical insulation.

The resistive foil and insulation layers are laminated together under heat and pressure to create a robust, flexible heating assembly, resistant to humidity and EMI interference. Specialized adhesives or bonding techniques are used to ensure a strong, durable lamination, depending on the heater's variant.

Different options are also available in terms of redundancy, to fully cover all the possible system design FMEA choices: single circuit heaters, double circuit heaters, double-layer heaters (see Figure 1). Furthermore, the double-sided heater can also be designed in order to provide electro-magnetic compensation between the two tracks.

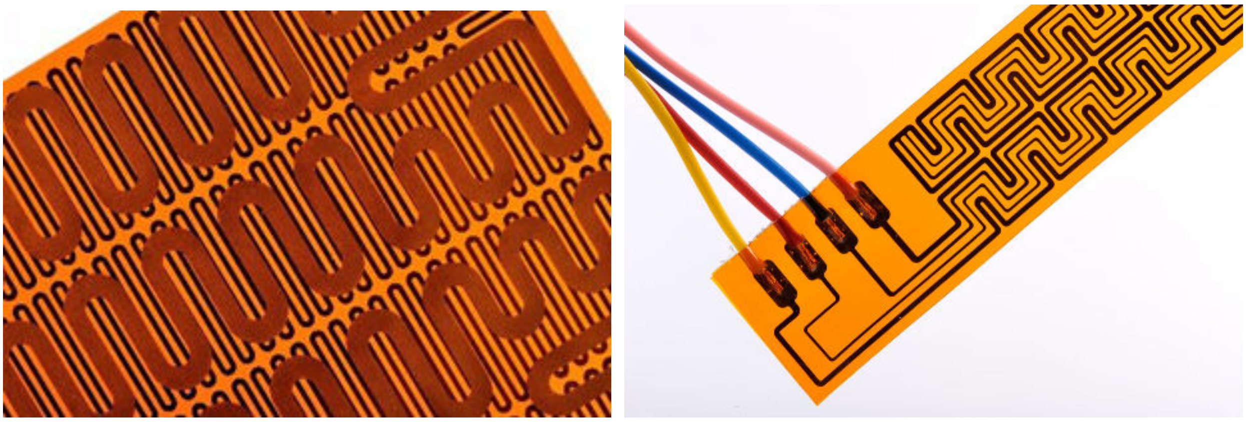


Figure 1: Some examples of double layer and double circuit flexible heaters.

Flexible heaters can be equipped with optional layers as:

- Aluminium substrate, which distributes heat more evenly and can be also used for grounding purposes,
- Pressure-sensitive adhesive, for easy integration,
- Coverage thermal insulation foam, to avoid unwanted thermal dissipation towards the external environment.

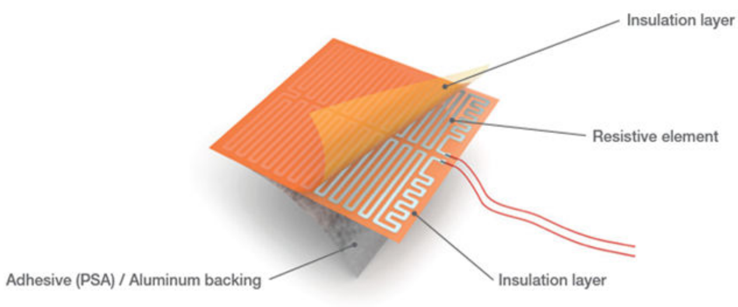


Figure 2: Exploded vision of a flexible heater.

In addition to the performance and limitations of the aforementioned products, IRCA has established a technological roadmap to enhance and extend the performance of incumbent flexible heater technology, addressing more demanding scenarios and broader customer requirements that traditional solutions alone may not fully meet. This initiative has culminated in the development of a new type of heater, termed the "Pure Polyimide Heater" (PPH). This heater represents the optimal solution for applications demanding e.g. high specific power, minimal thickness, and superior thermal conductivity. Below, we describe the case studies that contributed to the development of the PPH.

CASE STUDIES

The following case studies illustrate the scenarios where the PPH provided significant advantages.

- Real-time PCR system (Medical)
  - Product:
    - A Real-Time PCR (or qPCR) system is a biology instrument that finds and measures specific bits of DNA or RNA, monitoring the amplification process in real-time. It does this by watching the DNA copying process happen live. Unlike traditional PCR, where the amplified product is detected only at the end of the reaction, qPCR measures the accumulation of fluorescent signals as DNA is amplified in each cycle.
    - The core functionality of a Real-Time PCR system relies heavily on its heating technology, which precisely controls the temperature cycles essential for the PCR process. This thermal

cycling is what drives the denaturation (separation), annealing (primers attach), and extension (DNA grown) steps of DNA amplification.

- Challenges:
  - The heaters produced with traditional materials like FEP or acrylic fail to meet the client's strict low-outgassing requirements. This discrepancy in performance represents a significant deviation from the client's expectations, even risking the project's success. Therefore, an in-depth investigation became essential to identify alternative materials, capable of effectively reducing the unacceptable release of volatile organic compounds.
  - Traditional material-based heaters also have limited capability in minimizing unwanted reflections, a critical factor in applications where stray light or reflected energy can lead to inaccuracies.
  - The design for this application demands a defined through-hole pattern (see Figure 3), forcing the heaters to feature particularly compact and precisely routed heating tracks around the holes and edges.

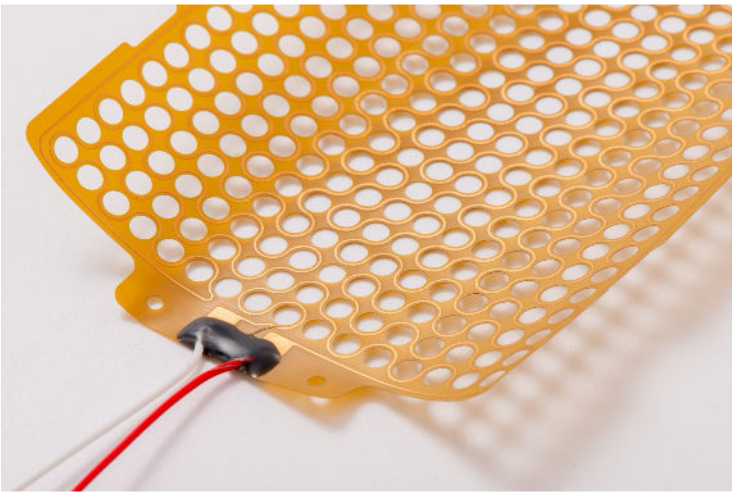


Figure 3: PPH for qPCR application where the through-hole pattern is evident.

- Solutions which the new PPH technology offers:
  - Across all rigorous evaluations conducted at external laboratories, PPH heaters have unequivocally demonstrated a notably lower outgassing characteristic, reducing the overall outgassing value of the assembly by a factor of 4, with respect to the previous (epoxy) solution. This huge advantage is possible both thanks to the properties of the insulation material itself, but also to the fact that an assembly with a PPH presents a noticeably lower thickness and related mass. This observed trend signifies a substantial step towards mitigating the expulsion of volatile compounds, thereby enhancing the suitability of these heaters for the qPCR application, which demands stringent contamination control.
  - Our materials facilitate direct lamination with black polyimide films. This seamless integration eliminates unwanted reflections, which is crucial for applications requiring optical clarity or preventing interference with sensitive components. This direct lamination process also simplifies manufacturing and enhances the overall robustness of the final assembly.
  - The PPH offers high dimensional stability in demanding thermal environments. This precise control includes minimal shrinkage, a critical factor in achieving tight tolerances and consistent part dimensions throughout production.
  - Linked to the point above, and thanks to a new laser machinery (Galvo 40W - 355nm wavelength), now we possess the unique capability to manufacture parts with significantly reduced clearance between heating tracks (internal gap) and between the tracks and the outer

edges. This allows for greater circuit density and miniaturization, optimizing space utilization without compromising performance or reliability.
    - The new material exhibits excellent heat transfer properties.
    - Beside all the advantages below, PPH also has undergone rigorous testing and are certified by Underwriters Laboratories (UL), providing assurance of their safety and performance according to recognized industry standards.

- Aseptic Tube Sealer for Pharmaceutical-grade Tubes (Medical)
  - Product:
    - An Aseptic Tube Sealer is an essential technology in the pharmaceutical and biotechnology industries, designed to hermetically seal plastic or TPE (Thermoplastic Elastomer) tubing in a controlled, sterile environment without compromising the integrity of the fluid within.
  - Challenge:
    - The actual materials' heaters experience delamination when subjected to elevated operating temperatures. This failure mode directly affects the reliability and longevity of the sealing device, potentially compromising the sterility of the pharmaceutical products being processed.
  - Solutions which the new PPH technology offers:
    - The new material demonstrates excellent thermal transmission properties, efficiently transferring heat, which is crucial for the reliable operation of the aseptic tube sealer at elevated temperatures, enhancing the durability and longevity of the sealing device and ensuring the sterility of pharmaceutical products.

- Synchrotron (Scientific)
  - Product:
    - A synchrotron is a large-scale research facility that uses powerful particle accelerators to produce extremely bright beams of electromagnetic radiation, ranging from infrared to hard X-rays. Scientists use these intense light sources across various disciplines—including physics, chemistry, biology, materials science, and medicine—to study the structure and properties of matter at atomic and molecular levels. Key components of a synchrotron include an electron gun, linear accelerator (linac), booster synchrotron, and a large storage ring where electrons circulate at nearly the speed of light, emitting synchrotron radiation as they are bent by magnetic fields.
    - Polyimide heaters play a vital and often indispensable role within synchrotron facilities, particularly in ultra-high vacuum (UHV) environments. Their primary function is to enable bake-out processes, which are essential for achieving and maintaining the extreme vacuum conditions required for accelerator operation and beamline experiments.
  - Challenge:
    - The existing FEP material was inadequate for applications within an high-radiation environment, due to its susceptibility to degradation and failure under such conditions. This limitation necessitates the development of alternative materials with enhanced radiation resistance to ensure the reliable and safe operation of devices in these demanding environments.
  - Solutions which the new PPH technology offers:
    - The material exhibits excellent high-radiation resistance, effectively withstanding hard conditions, such as those found in synchrotron facilities.

- Semiconductor Testing Equipment (Scientific)
  - Product:
    - Semiconductor testing is a critical phase in the manufacturing process, ensuring the reliability, performance, and longevity of integrated circuits (ICs).

        - The thermal one, in particular, is a key testing because semiconductors generate heat during operation, and excessive temperatures can lead to performance degradation, premature failure, and reduced lifespan. Therefore, semiconductor testing equipment incorporates sophisticated heating and cooling mechanisms to simulate a wide range of operating conditions.
    - Challenge:
        - The semiconductor testing equipment sector demands materials with high specific power capabilities to ensure efficient and reliable operation under rigorous testing conditions. Existing materials often fall short of these requirements, limiting the performance and accuracy of testing procedures.
    - Solutions which the new PPH technology offers:
        - The new material is engineered to deliver significantly enhanced specific power capabilities, directly addressing the critical demands of the semiconductor testing equipment sector for efficient and reliable operation under rigorous testing conditions, where existing materials often fall short.

PPH TECHNICAL FEATURES AND ADVANTAGES

As seen in the above study cases, the PPH represents the best solution when highly specific power is required, combined with the lowest thickness and the better thermal transmission and low outgassing.

Here below a recap of its main technical features is reported, while in the next section we will detail the tests performed during the internal validation campaign.

The PPH can be provided in different configurations:

- single or double circuit within the same layer;
- single or double layer (in the latter case: primary and redundant circuits are overlapped);
- with an embedded temperature sensor, that can be integrated both over the hot area or outside the heating track;
- capacitive sensor: with a dedicated design and the addition of a proper detector for touch or contact sensing;
- with an Aluminum or Copper layer, on one or both sides, to improve and uniform the thermal transmission;
- with a co-laminated PSA layer (to be noted, however, that in this case the adhesive might not support the heater's maximum temperature);
- directly laminated on the Customer's heatsink (for this feature, see sec. "PPH Direct Lamination Service") without any additional glue;
- typically with PTFE/FEP wires according to UL, MIL or ESCC standards;
- in the black variant (see Figure 4) for aesthetic or low reflectivity needs.

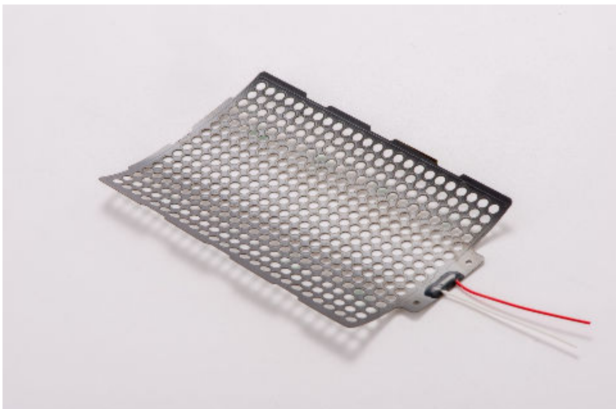


Figure 4: Black Polyimide Heater

In the Table below, a recap and comparison of the technical features of the three main types of heaters mostly used in the aerospace sector: Acrylic heaters, FEP heaters, and PPH (under ESA qualification), is reported.

Characteristic	PI ACRYLIC HEATERS	PI FEP HEATERS	PPH HEATERS
Substrate	Polyimide insulated heaters glued with acrylic film. Different thickness of PI and adhesive available.	Polyimide insulated heaters glued with FEP film. Different thickness of PI and FEP adhesive available.	Polyimide insulated heaters w/o any internal layer of adhesive (adhesiveless solution). Different thickness of PI available.
Min heater thickness	0,15 mm	0,15 mm	0,05 mm
Thermal Stability	High	Very High	Very Very High
Rated temperature	-65°C / +150°C	-65°C / +200°C	-65°C / +260°C (@ 0 power)
Typical maximum dimensions [mm]	600(*)x590 (*: special products also up to 3000x590)	600x590	430x280
Typ. power density [W/cm^2] (example: depending on temperature and substrate)	5	6.5	15
Insulation material's thermal conductivity [W/mK]	0.220	0.190	0.230
Ohmic Density, Maximum [Ω/cm²]	330 or higher	200	330 or higher
Typ. Insulation [MΩ @500VDC]	> 1000	> 1000	> 500
ESA qualification	ESCC 4009/004	ESCC 4009/002	… coming soon
Outgassing (*)	Low: %TML = 0.93 %RML = 0.21 %CVCM = 0.03	Low: %TML = 0.68 %RML = 0 %CVCM = 0	Very low (from literature and currently under measurement @ESA): %TML = 0.49; %CVCM < 0.01
Chemical resistance	High	Very High	High
Radiation resistance	High	Medium (we tested it at 1 Mrad)	Very High (typ. 1000 Mrad)
Mechanical Strength	High	High	Medium

Table 1: comparative technical datasheet of IRCA s.p.a. flexible heaters. (*) data from ESA outgassing database

The data presented in the table above demonstrate that the PPH, characterized by its minimal thermal mass and thickness, customizable design, enables a higher degree of miniaturization. This is evident in both width and length, thanks to the reduced clearance between the track and the outer edge, as well as in thickness, achieving a minimum overall thickness of 0.05 mm compared to 0.15 mm for other heaters. This allows for easy integration on curved surfaces, among other benefits. Furthermore, it has to be evidenced that the absence of fluoropolymers of the PPH solution is a significant advantage given potential future REACH-related restrictions.

The above-mentioned characteristics make the PPH particularly attractive e.g. for the following applications:

- Diagnostic analyzer in medical instruments,
- Electronic components,
- Semiconductor industry,
- Scientific industry,
- Aviation and space industry.

PPH Direct Lamination Service

Solutions have also been developed to allow us to directly laminate a PPH on heatsink. The direct lamination process enables the bonding of the heater directly onto the heatsink without the use of adhesives. Compared to conventional adhesive-based integration methods, this approach allows operation at significantly higher temperatures. Customers requiring heaters pre-integrated with heatsinks now adopt this process.

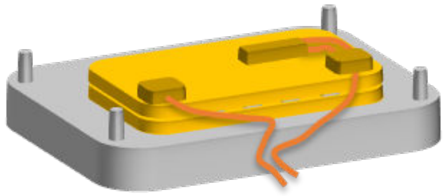


Figure 5: visual example of a Sensorized PPH sub-assembly laminated on a plate.

The main technical advantage is to provide:

- a totally adhesive-less assembly, therefore with reduced outgassing,
- a hot lamination process, at high pressure and temperature, with a vacuum phase that allows us to eliminate any air inclusion,
- a product where what typically represents the limit in terms of thermal resistance is eliminated (as PSA and resins typically have temperature limits lower than 150-200°C),
- a reduction in thickness, therefore further improving the heat transfer.

To date we have developed PPH heater/heatsink integration solutions on thin plates (1-2mm max), mainly linked to limits on the lamination processes. IRCA s.p.a. is also available to develop more complex solutions, to be designed and therefore validated together with the customer.

PPH VALIDATION CAMPAIGN

While developing the above solution, we have undergone a product validation campaign, which we summarize here below.

The following steps have composed the internal test campaign:

1. Cross-sectional analysis of laminated PP (Pure Polyimide) in different configurations (4 samples)
2. Cross-sectional analysis for the validation of the lamination process of etched foils with high temperature PP (12 samples)
3. Glow wire test on polyimide films (6 samples)
4. Cycled life testing of multiple PPH – PPH Cu etched foil (EF) products (19 samples)
5. Passive heating thermal aging test of PPH etched foil heating elements (9 samples)

A summary of the related results is reported in the next sub-sections.

Cross-sectional analysis

The scope of this test is to measure the effective thickness of the various layers of the PPH in different configurations, using a SEM (Scanning Electron Microscope, model Tescan Vega 3 SBH) at 200x magnification.
In particular, 4 samples have been tested, which refer to four different designs that were considered.

Table 2 shows the measurements compared with the theoretical layers' thickness in the first row:

PPH’s layer thickness SEM measurements						
Layer (theoretical thickness)	**Black PP (25 µm)**	**PP (25 µm)**	**PP (50 µm)**	**Cu track 1 (35 µm)**	**Cu track 2 (35 µm)**	**PP Cu (50 µm)**
sample #1	28,4 µm	---	43,2 µm	33,1 µm	---	39,5 µm
sample #2	25,2 µm	---	45,9 µm	35,2 µm	34,2 µm	50,2 µm
sample #3	---	16.1 µm	---	35,5 µm	36,5 µm	46,2 µm
sample #4	---	---	43,8 - 63 µm	35,8 µm	34,2 µm	50,2 µm

Table 2: test results of the first cross-sectional analysis campaign for PPH validation.

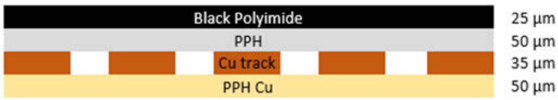
The test showed that the lamination process was successful, and the conformation of the layers looked optimal, as the SEM micrographies did not show any local defect on the track edges, voids or blistering between the layers. An example is visible in 

Figure *6* and Figure 7.

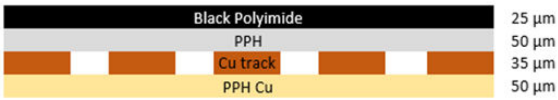


Figure 6: schematic of sample sheet n.1

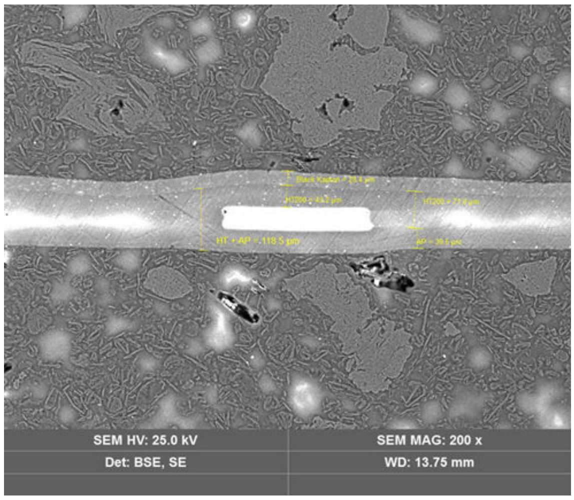


Figure 7*:* SEM image of sample 1's cross section

After this test, a second cross-sectional measurement has been conducted on other 12 samples, which provided different combinations of insulation and track layers’ thicknesses, track widths and track gaps (see Figure 8).

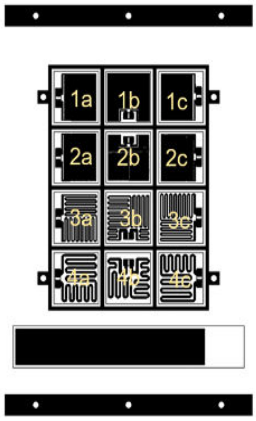


Figure 8: tested configurations of the second cross-sectional analysis campaign for PPH validation.

Again, the layers' thickness was measured using a SEM (model Tescan Vega 3 SBH) up to 933x magnification.

The resulting average deviation of the measured values from the theoretical ones was less than 6%, showing that the lamination process was successful. The images also showed that the conformation seems to be optimal, as the SEM micrographies do not show any local defect on the track edges, voids or blistering between the layers. Moreover, the Polyimide/Polyimide and Polyimide/metal track interfaces are almost irresolvable even at the higher magnifications.

Glow wire test

The aim of this test was to verify if the PI-based insulating materials are not prone to inflammability, according to regulation CEI EN IEC 60695-2-11_092022 at 750°C and at 850°C (30 seconds of contact, 30 seconds of observation). The test has been performed on two samples each for three different configurations. Each sample was subjected to the same test three times. The glow wire test was executed by means of an ATS-FAAR glow wire-testing machine.

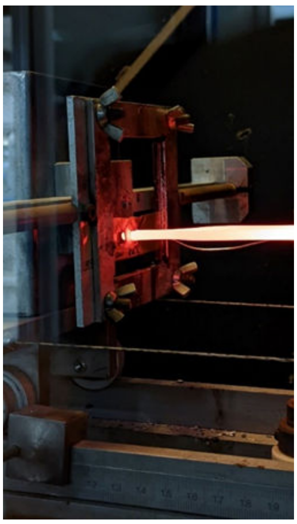


Figure 9: glow wire testing

No flame was observed at any point in time on any point of any sample. The tissue paper underneath the samples remained unaltered. Every sample passed the glow wire test, both at 750°C and at 850°C.

Cycled life testing

19 samples of eight different types of PPH have undergone a cycled life testing, with maximum cumulative "ON" time of 2034 hours. Each cycle was set such that the heaters were powered on for 45 minutes, followed by 15 minutes of power off.
The samples experienced several successive cycles where the heater was powered on at a specific power density in order to reach increasing temperatures (steps from 135°C to 180°c with PSA, 270°C without PSA), in order to characterize the operational range of the PPH.
6 out of the 8 different configurations foresaw the presence of a plate, on which the PPH was applied (4 of 304 stainless steel and 4 of aluminum) with and without PSA. The remaining heaters were instead plate-less with an Aluminum sheet backing.
In order to monitor the temperature on the surface of aluminum and steel plates, a set of thermocouples were placed on top of the insulated tracks. The control boxes made use of these thermocouples only for safety purposes, to interrupt the power supply when the temperature became too high, protecting the elements from overheating.
The scope of the test was to compare initial and final measurements of the ohmic value, the insulation resistance at 500 VDC for 5 seconds, and the HighPot test (1600 VAC for 3 seconds) current values.
Measurements have been done by means of a GW-Instek model GPT-9903A Electrical Safety Tester.

Test results evidenced two failures among the different trials:
- HiPot test failed for 1 sample of the PPH on Al plate after cycling at 270°C
- HiPot test failed for 2 samples of the PPH on steel plate after cycling at 270°C

All the other measurements on all the other samples were compliant within the expected tolerances.

The test was useful to determine the PPH maximum rated temperature (260°C) but also to observe the visual impacts of the high temperatures on the materials. Indeed, after the cycled tests, the elements showed signs of embrittlement and increased overall rigidity. Moreover, the color of the insulant resulted to be darker compared to the situation before the tests. However, it has to be evidenced that, despite these characteristics, the heaters were still functional. This outcome is useful for us to support the Customers in the interpretation of the product's behavior and performance.

Passive heating thermal aging test

For this test, 9 PPH elements with different configurations were tested, keeping them in an oven at an uniform high temperature for 2000 hours continuatively:
- 3 at 230°C,
- 6 at 260°C and 280°C.

For each sample, after spending 2000 h in the testing oven (Gero Carbolite), the elements were subjected to a HighPot test (1600V_{AC} x 3s, GW-Instek model GPT-9903A Electrical Safety Tester) in order to evaluate their electrical properties.
All of the elements passed the HiPot tests at 230°C and 260°C, even if the ones subjected to higher temperatures showed signs of aging and embrittlement: the polymeric insulant looked shrunk around the metal tracks and the insulation material looked discolored.

At 280°C instead, the test failed on 2 out of the 6 samples.

This test was intended to determine the PPH maximum non-operative temperature (260°C), and to observe the visual impacts of the high temperatures on the materials, useful to support the Customers in the interpretation of the product's behavior and performance.

UL certification

From the early stages of the project, the definition of a UL approved product was considered as a target to best support our customers in the approval phases of the final system.
We have therefore followed the approval path in the configurations reported below:

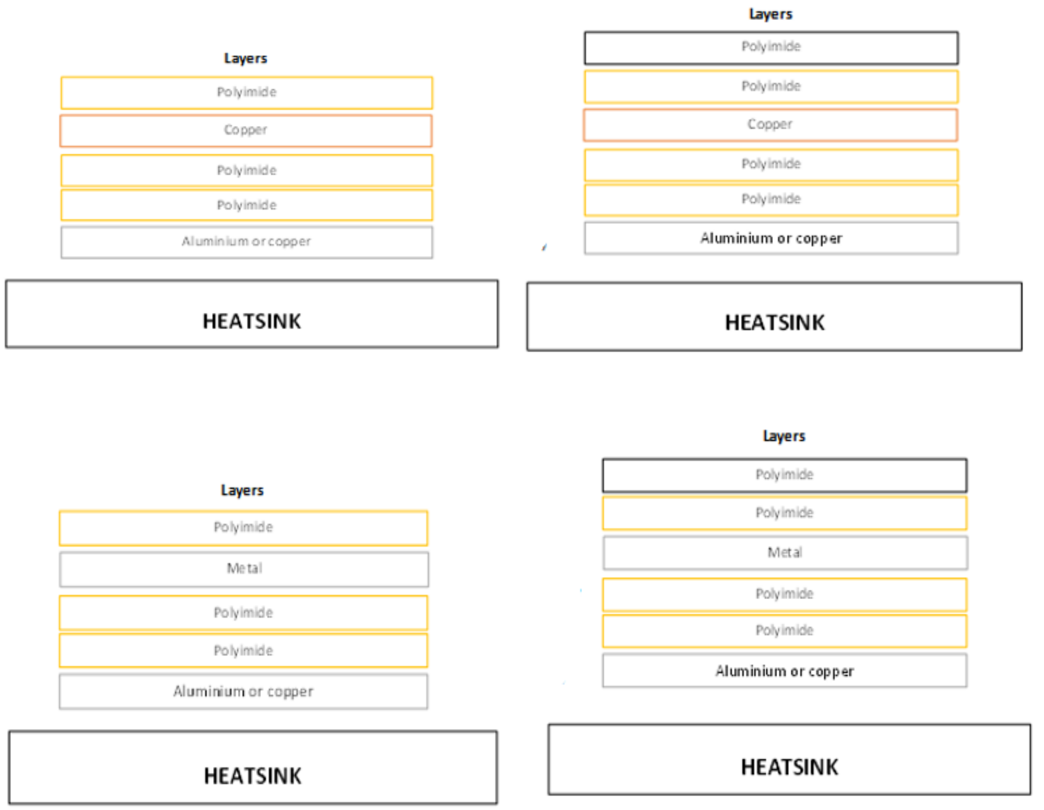


Figure 10: configurations tested for the UL certification

To achieve the objective, in addition to the tests already planned internally, it was necessary to consider additional tests, which we mention here below:

- Power input test rating (according to specific UL procedure)
- Normal temperature test (according to specific UL procedure)
- Dielectric voltage withstand test: dielectric strength test (according to specific UL procedure)
- Insulation resistance and leakage current as a result of moisture (according to specific UL procedure)
- Aging of special heater elements (according to specific UL procedure)
- Thermal aging test (according to specific UL procedure)

The objective has been fully achieved.
Moreover, the certification for the PPH has been rated also on flammability at level V0. A UL 94 V0 rating indicates that a material has demonstrated a high degree of flame retardancy, meaning it will self-extinguish quickly and will not drip flaming particles during a vertical flame test.

PPH SPACE APPLICATION SCENARIO AND NEW INCOMING QUALIFICATION

Once the PPH has been released for the medical market, the company has started proposing it also for other markets.

For example, the space market requires a product that is compatible with increasingly stringent requirements (high temperatures, radiation resistance, sustainability) that are fully satisfied by this new product.

In this field, the possible applications of the PPH are the same as those of current heaters (pipes, electronics, batteries, structures, optics, sensors, tanks, thrusters, and more). But in particular, given its particularly optimal properties with regard to high temperatures, high densities and resistance to radiation, a more marked use is expected for particular types of missions such as interplanetary and long-duration ones, or those involving miniaturized payloads or instruments or high performance and temperatures.

Of course, some parameters of the product were not already compliant with space requirements (e.g. in terms of materials vs. outgassing, verification performances, etc.). Therefore, we initially faced some trade-offs dealing with the design and process changes from the existing product to a variant which respects all the applicable ESA specifications.

In addition to the above-reported advantages, we have also been addressing some other aspects that evidenced the opportunity of space qualifying the PPH.

For example, the qualification of this product supports one of the target objectives by ESA and by the European commission, to develop a qualified European supply chain for this type of products (flexible heaters). Indeed, while there are currently no European qualified suppliers for the materials involved in the FEP heaters; the PPH relies entirely on European suppliers. Additionally, a similar PPH technology is present on the space market only by manufacturers from the United States (according to the NASA specification S-311-P-841), but has not yet obtained an ESA certification.

For all the above reasons, IRCA s.p.a. started last year the qualification activities in order to obtain an ESCC certification for the PPH. The new ESCC-PPH will then be available for the space market in accordance with the ESCC Generic Specification No. 4009 (including the screening, qualification and validation testing described in the related charts) and the Detailed Specification, which will be issued accordingly.

The evaluation activities to access the QPL are currently proceeding in accordance to a test plan which has been agreed with ESA and which involves the following tests:

1) Cycled life testing at additional temperature steps with respect to the internal test campaign, in order to better characterize the intrinsic PPH failure point and determine the future approach in terms of rated temperature qualification limits and related margins.

2) Flexibility test, after a passive heating thermal aging test of 5 days duration, in an oven at 250°C. This test was requested in order to capture a quantitative result concerning the visual effects that we observed on the PPH materials after the high temperature tests. Each heater is bent 5 times with an angle of 180 degrees over a cylindrical pole with 3-millimeter diameter in both directions, and is then restored. Visual inspection is then performed, and DC resistance measurement is compared to the initial value, to check if the change is within +/- 1% or +/- 0.2 ohms (whichever is greater).

Tests are currently ongoing and the full ESCC qualification is expected to be reached within 2025.

CONCLUSIONS

We have developed a new type of heater in response to some requests from the medical and space markets.
The new product is called PPH (Pure Polyimide Heater) and the presented case studies reveal several key advantages of this new technology. These include (see Table 1):

- Meeting Specific Requirements:
  - The new technology addresses specific client requirements that existing solutions fail to meet, such as high temperature, very low outgassing and ultra-precise dimensional control.
- Enhanced Performance:
  - The new technology offers superior performance in demanding conditions, such as high temperatures and high-radiation environments.
- Improved Thermal Properties:
  - The new technology provides optimal heat transmission, crucial in applications involving heaters at high power density.
- Increased Reliability:
  - By overcoming issues like FEP delamination, the new technology enhances device reliability and lifespan.
- Higher level of miniaturization:
  - The PPH has a reduced thickness and is able to fit curved surfaces and to embed sensors.

For this development, we solved some very interesting technical challenges, like reaching the limits of our laminating capabilities, involving high pressure and temperature for extended periods. We have also focused on managing these processes and tuning the production process to enhance the workability of the thin material.

The PPH has undergone an internal qualification test campaign, furthermore it has been UL-qualified, and it is currently under ESA qualification (ESCC QPL).
The development of this new technology offers significant advantages across medical, aerospace, and scientific research sectors. The case studies highlight the importance of innovation in IRCA s.p.a. in addressing specific challenges and improving performances. Further discussions should focus on leveraging these advantages to expand the applications of this new technology.