New Packaging Techniques (NPT) to Increase the Power Density of Power Control and Distribution Units

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***Abstract*— For modern power electronic equipment designs, thermal control is the biggest challenge for achieving modular solution miniaturization and volume/ mass reduction. In addition, the reduction in electronic power component package sizes (SMD) for assembly on the PCB requires a special thermal control design, due to the low area of thermal contact. There are new materials and processes available in the commercial market but, in some cases, are not always applicable due to space application special requirements or environmental susceptibilities. The ESA New Packaging Techniques R&D program [1] addressed, in detail, the feasibility for a variety of materials and processes in a modular design solution, based on SMD power electronic devices (such as GaN). In particular, the Vapor Chamber technology applicability was addressed due to its high performance, low cost, and vertical modular fitness. A complete integrated design and test verification were completed, and the main activities and performance results are presented in this article.**

Keywords—Vapor Chamber, thermal control, modularity, power electronics, GaN, SMD power electronics.

I. INTRODUCTION

In general, power electronic equipment makes use of vertically assembled framed modules as a standard mechanical envelope for achieving better product modularity, scalability, and configurability (Fig 2). The vertical modular approach is a challenge for high-power electronics. Usually, the power dissipative devices shall be assembled closer to the frame base, getting the shortest distance for better thermal control (Fig. 2). This limitation imposes several drawbacks when there are high quantities of heat-dissipative electronic devices needing thermal control. Is necessary bigger frame length for accommodating the devices inline closer to the base frame, impacting the thermal contact into the frame center (frame arching), the electronic board optimization, and requiring a larger electronics bay area for assembling the equipment into the spacecraft.

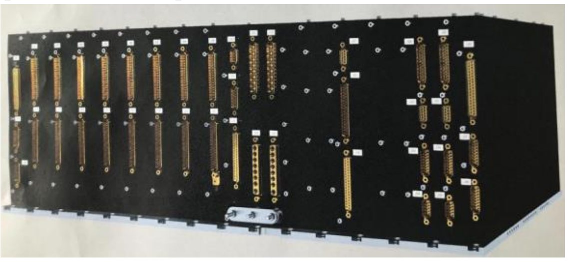

Fig. 1 PCDU Equipment Showing the Vertical Modular Approach (modules side by side)

Thermal control is the biggest challenge for modular solution miniaturization and mass reduction. How to remove the heat sources from the electronic board to the thermal sinks (equipment base) in a longer distance path. New Package Technologies were technically and cost-effectively evaluated to solve this challenge.

New types of power electronic components are concentrated in SMD (Surface Mount Device) packages that harness the dissipated power to the electric pads rather than to the package of the component itself. It is paramount to improve the thermal interface between “PCB pads/tracks” and “heat sink” while respecting Electrical Insulation.

Several options can improve the thermal control performance incrementally, but the main objective and purpose of this work was to propose a disruptive solution. One of the main results was the Vapor Chamber technology (chapter 3) pointed performance, which can work as heat pipes without the cold start issue. The feasibility of a Vapor Chamber applicability for space solutions was addressed. In priory, Vapor Chambers are not allowed for use in space, as the vapor chambers present non-solid content with leakage potential as propagation failure.

The Vapor Chamber (qualified supplier) performance proved as a high-potential solution for solving the thermal control of high-density SMD power devices at an electronic board level. The vapor chamber's high thermal conductivity in the plane axis turns the electronic board homogeneous in terms of thermal control.

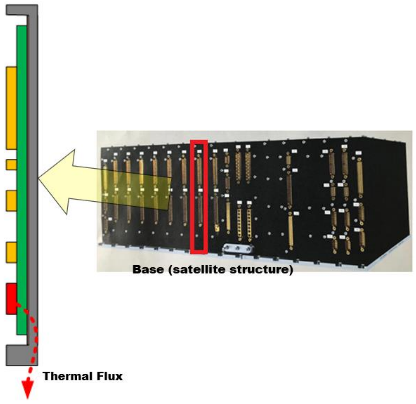

Fig. 2 Typical Vertical Modular Thermal Control

II. THE VAPOR CHAMBER TECHNOLOGY

Vapor chambers, also known as planar heat pipes or heat spreaders, are two-phase devices with a large, flat surface that efficiently spread heat from high power or high heat flux electronics. Vapor chamber use has surged in recent years, largely due to increases in power density resulting from shrinking die size. Notably, modern-day vapor chambers offer improved capabilities, enhancing their performance value proposition and application flexibility.

Working principles for vapor chambers (Fig. 3) and heat pipes are the same. As heat is introduced to the evaporator area, the working fluid turns to vapor which moves to areas of lower pressure. The condenser area, usually a finned structure, cools the vapor where it condenses back to a liquid which is absorbed by the wick and returned via capillary action to the heat source area.

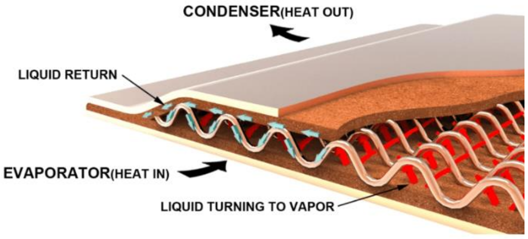

Fig. 3 Vapor Chamber Working Principle

III. DESIGN INTEGRATING THE VAPOR CHAMBER

The module was designed to achieve lower mass and at the same time maximize the thermal control. 24 electronic power dissipative elements (GaN transistors) were assembled homogeneous over the electronic board (PCB), the generated heat in each power electronic device was transferred to the below-assembled vapor chamber using a special layout, adding (double) electrical insulation between the frame and the electrical circuit on the electronic board (PCB).

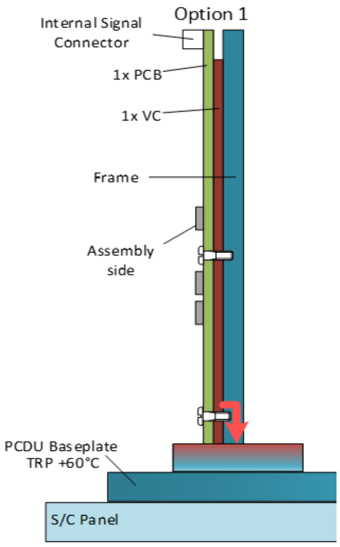

Fig. 4 Module Design - Cross-Section View

The vapor chamber was attached directly to the mechanical frame (Fig. 4). Usually, the mechanical frame has two main functions, mechanical support and thermal control by conduciveness means. The frame in our application was designed mainly for mechanical supporting purposes, saving final total mass, as no additional material was necessary for thermal control.

IV. PERFORMED TESTS AND EVALUATIONS

An evaluation of possible thermal control degradation under several environmental tests was performed [2] [3] [5]. Mechanical vibration, extensive thermal cycling, accelerated aging (life), microscope and x-rays metallurgic inspection, and extreme temperature operation under vacuum operation were performed. The main thermal interfaces were evaluated according to the achieved thermal resistance drift and mechanical parts integrity (loss of adhesion, cracks, or deformation) :

a- Thermally controlled base and the frame base.

b- Vapor Chambers and the frame base.

c- Electronic board bottom side and its bond contact to the Vapor Chambers.

d- Electronic devices package and Electronic board top/ bottom side.

Vapor Chamber Cold Start

The result presented no overshoot temperature during the monitoring time (Fig. 5), showing no issue for thermal control under frozen Vapor Chamber internal fluid. Due to the short lengths and low fluid volume, the vapor chamber safely performs the cold start when compared to the heat pipes.

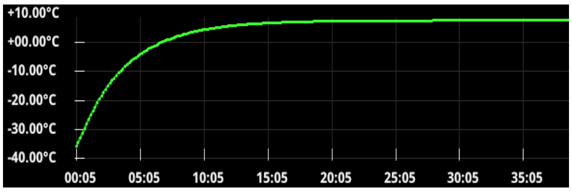

Fig. 5 Cold Start Temperature Transient (no overshoot)

The samples did not present any visible failure (no deformation or loss of mass/leakage) and kept the thermal conductivity performance over a low-pressure environment. The inner forces due to the pressure difference are very low when compared to the Vapor Chamber mechanical stiffness design.

Thermal Vacuum Cycling

Were applied 55 thousand cycles (~3 months 24/7 continuous test). The sample did not present any visible or measurable failure or degradation (no deformation or loss of mass/leakage) and kept the thermal conductivity performance. Microscope metallurgic inspections were performed over some parts, the results are commented on in the following chapter.

Microscope Metallurgic Inspections Test

Microscope metallurgic inspection after vapor chamber thermal cycling tests were performed. Evaluation and searching for thermal cycling effects, as structures cracks or delamination and vapor chamber internal walls loss of rugosity due to internal oxidation. The microscope metallurgic inspection revealed the vapor chamber manufacturing robust design. It is a stamped soldered tube with fused ends, and the tip (after the fluid is filled) is smashed and soldered. The point of attention for potential failures was the seal tip soldering.

Thermal Vacuum Tests

The unit was placed into the thermal vacuum chamber to evaluate the thermal resistances (Fig. 6).

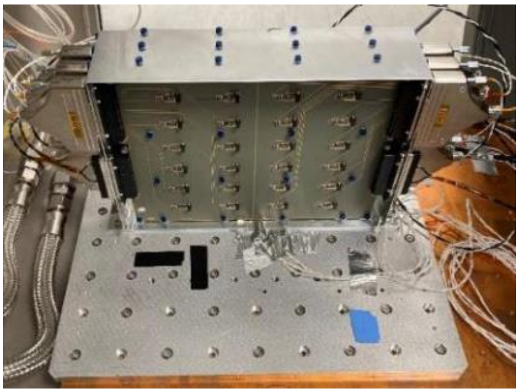

Fig. 6 Thermal test setup inside a thermal vacuum chamber

After an 8-hour bakeout at 70 °C the thermal cycling was started. 5000 thermal cycles with a period of 8 minutes and a minimum of 25 K temperature span. In addition to a thermal cycle profile evaluation also the thermal resistances of the assembled electronic components (GaN power transistors) were compared, before and after cycling. In Fig. 7 there is no visible difference in performance (changes within measurement errors), and no additional hotspots can be seen. This indicates that the thermal interfaces have not degraded.

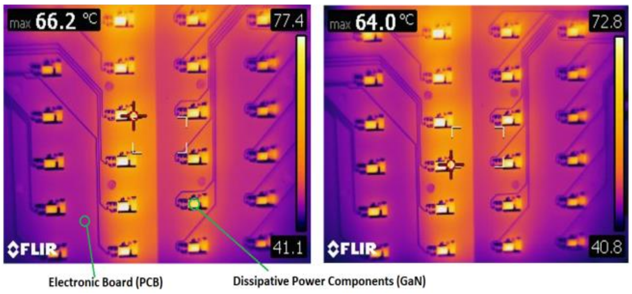

Fig. 7 Thermal images. Left before and right after 5k thermal cycles

Search for Structural Deformation/ Flatness checking.

General dimensional sizes were kept lower than 0.05mm, and flatness over the main mechanical surfaces before and after thermal testing was below 0.05 mm in every 100x100 mm. There was no change in the surface's flatness or presence of mechanical deformations.

Verify Bonding by Glue (Assembled frame/PCB).

A negative pressure (pull force) of 700 psi was applied on the glued parts' edges according to ASTM D1002 at a 100°C environmental temperature. No adhesion or cohesion failure occurred during the test [4].

Vibration Tests

The results (before and after the vibration tests) were similar to the thermal cycling tests. No significant deviations in the thermal control performance or mechanical degradation were observed

V. THERMAL CONTROL PERFORMANCE EVALUATION

The thermal control test experiments had the objective of evaluating the thermal control's overall performance. There are two main requirements related to the thermal control performance:

- To achieve the lowest temperature drift (gradient) between the dissipative elements assembled over the PCB, allowing the same thermal design for multiple block channels of circuit elements over the PCB.
- To achieve the lowest thermal resistance between the dissipative elements assembled over the PCB and the frame base contact interface (frame foot).

Several batches of preliminary tests were performed, in a way to observe the main gaps and possible improvements for the design, the original mechanical frame design was modified several times. The main interest was to minimize the thermal resistance path between the junction of the power devices to the frame base (under controlled temperature). The board surface temperature was measured by a thermal infrared camera and some temperature contact sensors on monitoring points. Two main experiments for the total power loss of 60W (medium-power) and 120W (high-power) were performed. The total power was shared between the 24 GaN devices (~2.5W and 5W per device respectively).

A very low drift of GaN package temperature over the PCB area was achieved. A specific worst performance in the second column and over the specific last top elements of the columns, where the GaNs are not assembled over a minimal area of the vapor chamber. Was observed drift of only ~1°C @ 60W (~2°C @ 120W) from the top to base elements.

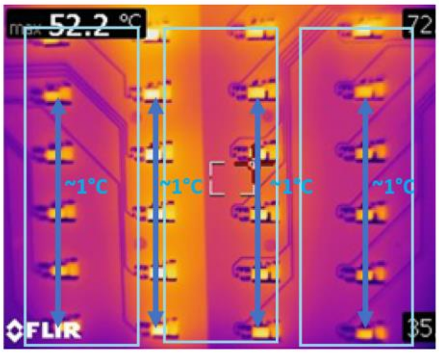

Fig. 8 Thermal View Showing the 3 Vapor Chambers Projected Position Under the PCB and the Total Temperature Drift @60W

Temperature Analysis – 60W

The measured frame base temperature (foot) was 38.9°C and the assembled devices (case) over the vapor chamber area (first and last column) reached ~61°C, a total increment of 31.1°C for a power dissipation of around 15W / column (6*2.5W), resulting in an average thermal resistance of ~2°C/W for the path. The thermal resistance of the vapor chamber to the base of the frame is the main contributor. This interface was already improved during the development and is planned a new process for the vapor chamber bonding to the frame for the next steps.

Temperature Analysis – 120W

The measured frame base temperature (foot) was 42°C and the assembled devices (case) over the vapor chamber area (first and last column) reached ~91°C, a total increment of

49°C for a power dissipation of around 30W / column (6*5W), resulting in an average thermal resistance of ~1.63°C/W for the path. The lower thermal resistance when compared to the 60W experiment is attributed to the better vapor chamber thermal conductivity due to the higher temperature.

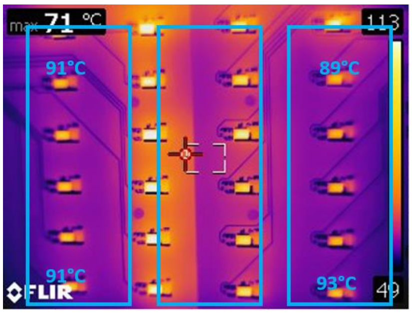

Fig. 9 Thermal View Showing the Vapor Chambers Position and Temperatures @120W

Were performed two evaluations regarding the direct impact of using the vapor chambers. The rough evaluation of the mass saving impact (simulation analysis) and the removing the vapor chamber effects, by replacing the vapor chamber elements with a solid aluminum dummies version (experimental).

Mass Saving Impact

By simulations and analysis was evaluated the necessary frame mass addition for achieving a similar vapor chamber thermal control. It was necessary to add around 2.1kg of aluminum mass (a block) for the 120W dissipation case and around 1kg for the 60W case. Considering a PCDU with 6 dissipative modules (60W) the total mass save would be around 6kg. A more realistic evaluation shall consider a total redesign for the module without vapor chambers. An average 4kg total saving mass can be considered a better evaluation, resulting in around 10% - 20% of the total mass saving for the whole equipment (standard PCDU mission design).

Removing the Vapor Chambers

Was performed a high-level evaluation impact of not using the Vapor Chambers for thermal control. The Vapor chambers were replaced by the same size solid aluminum dummies, and the 120W total power tests were repeated. A hot spot of +68°C (as delta) was verified, and an average temperature elevation by GaN assembled lines is presented in the below table (Table I), as a result of removing the vapor chambers and replacing them with equivalent dummies. Even the first line (6), closer to the base presented high benefits for applying the vapor chambers.

TABLE I. AVERAGE TEMPERATURE / DEVICES LINE

Position	with VCs	with Dummies	Delta
1	104.5 °C	166.8 °C	62.3 °C
2	95.3 °C	152.5 °C	57.3 °C
3	89.3 °C	143.5 °C	54.3 °C
4	84.0 °C	132.5 °C	48.5 °C
5	80.0 °C	123.8 °C	43.8 °C
6	72.0 °C	110.0 °C	38.0 °C

VI. CONCLUSIONS AND PROPOSED NEXT STEPS

The New Packaging Techniques activities covered R&D, designs, analysis, manufacturability, qualification, and test efforts for achieving a disruptive new thermal control proposition for space avionics, particularly power electronic SMD dissipative devices in a vertical modular product. The Vapor Chamber technology proposition presented the potential for a considerable product volume/mass reduction and a high-performance thermal control for the challenging application of high dissipative SMD elements assembled over a simple PCB board. Applications where the thermal control demands more mass than the structural, and/or where is required homogeneous thermal control for multi-channel electronic components blocks assembled on a single PCB are the main targets. Another advantage of the developed technology is the capability to implement a feasible thermal control for high dissipative hot spots caused by electrical failure. In terms of applicability, the developed technology presented potential applications for other space avionics products, such as high-power solid-state RF amplifiers (transponders) and high-power processing boards with multiple cores. The next steps are planned performance improvements, generating a higher fidelity vapor chamber model based on fluid flow and multi-phase operation, and the design validation in a true space mission (getting heritage, increasing the TRL).

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