

# Embedded Pulsating Heat Pipe for Improved Heat Spreading in CFRP Equipment Panels for Satellites

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To avoid hot spots on satellites for equipment mounted on Carbon Fibre Reinforced Polymer (CFRP) panels, there is an increasing demand for improved heat spreading. A technology investigated in this paper is embedding a Pulsating Heat Pipe (PHP) inside a CFRP sandwich panel, that is a meandering tube partly filled with Ammonia effectively achieving an enhanced conductive value above 10,000 W/m/K along the length of the tubing. Although the physics behind the operation of a PHP is not yet fully understood, it can be constructed based on experimental experience available at the Netherlands Aerospace Centre. The paper describes the design process, performance analysis, and manufacturing process of an Engineering Model (EM) of a 0.8 m<sup>2</sup> PHP panel. It concludes with performance tests done in a representative environment, achieving TRL 4 to 5. The EM panel has PAN based HT carbon fiber composite facesheet, a carbon foam layer with an embedded pulsating heat pipe tube supported by an aluminum honeycomb. The test program included leak testing, proof pressure testing, pressure cycle testing, burn-in testing, performance testing in various orientations, and thermal tests in vacuum. Based on prototype testing, it is expected that the PHP-panel can spread heat loads > 300 W/m<sup>2</sup>. The paper ends with an outlook on further research and potential applications.

## Nomenclature

BBM	=	Bread Board Model
CFRP	=	Carbon Fibre Reinforced Plastic
CTE	=	Coefficient of Thermal Expansion [K <sup>-1</sup> ]
DR	=	Design Requirement
EM	=	Engineering Model
ER	=	Environmental Requirement
ESA	=	European Space Agency
FPR	=	Functional Performance Requirement
HP	=	Heat Pipe
IR	=	Interface Requirement
NDI	=	Non-Destructive Inspection

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OR	=	Operational Requirement
PEP	=	Preparatory ESA Program (former Dutch national funding scheme)
PHP	=	Pulsating Heat Pipe
PRR	=	Physical and Resource Requirement
TV	=	Thermal Vacuum
VTR	=	Verification and Test Requirement

## I. Introduction

The objective of the Pulsating Heat Pipe (PHP) panel development is to develop a satellite structural panel with enhanced heat spreading capabilities to radiate the heat by radiation to the S/C internal environment.

A Pulsating Heat Pipe (PHP) is an undulating capillary pipe of approximately 1 mm internal diameter filled with a working fluid partly in liquid (slugs) and partly in vapour state (plugs) which transports heat from hot areas to cold areas by pulsating motion of the slugs and plugs. The motion is induced by evaporation of liquid below the hot spots. The created vapour pushes and keeps the adjacent slugs into motion. The main heat transfer is by sensible heat of the liquid parts and a small part by vaporization and condensation. Therefore the PHP has a larger temperature difference of approximately 15 K between hot and cold, compared to 0.1-1 K for a conventional heat pipe. A PHP embedded in an internal spacecraft panel is a low cost and low mass option for a conventional internal HP panel. In this paper first the EM PHP panel concept design is presented. Subsequently the design process from requirements to design is shown followed by the main thermal and mechanical analyses results and key breadboard model test results. An overview of the EM PHP manufacturing and the EM PHP panel test program is given and key results are shown. One test anomaly was found and is investigated.

### A. PHP EM Panel Concept

The Pulsating Heat Pipe engineering model (EM) shown in Figure 1 and Figure 2 is a Carbon Fiber Reinforced Polymer (CFRP) substrate with an embedded Pulsating Heat Pipe, which can function as a typical structural panel in spacecraft applications, with improved thermal performance. The objective is to create a low-cost heat pipe panel compared to a standard aluminum heat pipe panel with axial grooved heat pipes. Additional advantage is the capability to operate the panel in all orientations. This increases the spacecraft TV test flexibility.

The overall dimensions are 1000 mm in the pipe direction and 850 mm in the direction perpendicular to the pipes to allow for testing in the NLR TV space vacuum chamber. On the top face sheet electronics boxes are simulated by 6 heater plates which dissipate representative powers with a sum of 300 W/m<sup>2</sup> per total panel. The EM PHP design has a meandering ca 50 meters long stainless-steel tube with ammonia as working fluid. The PHP pattern with 48 parallel tubes is dense enough to effectively spread the heat.

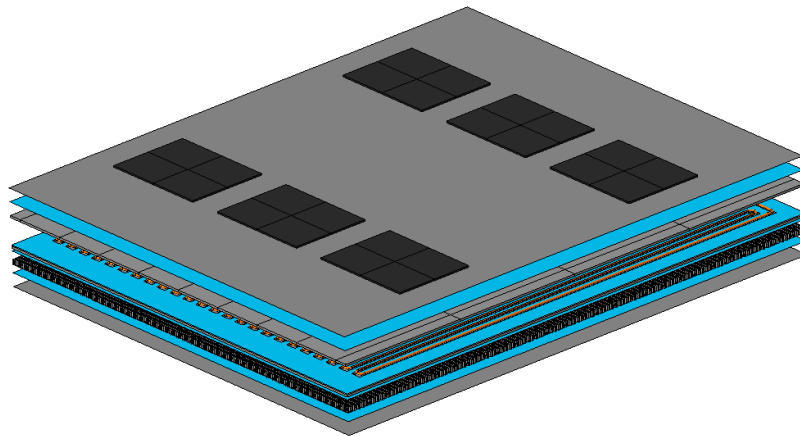
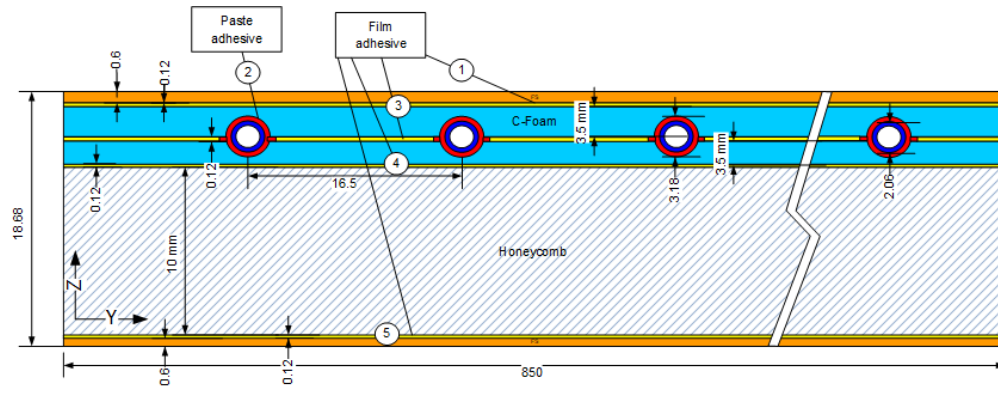


Figure 1: EM Panel exploded view with embedded PHP and 6 simulated electronics boxes

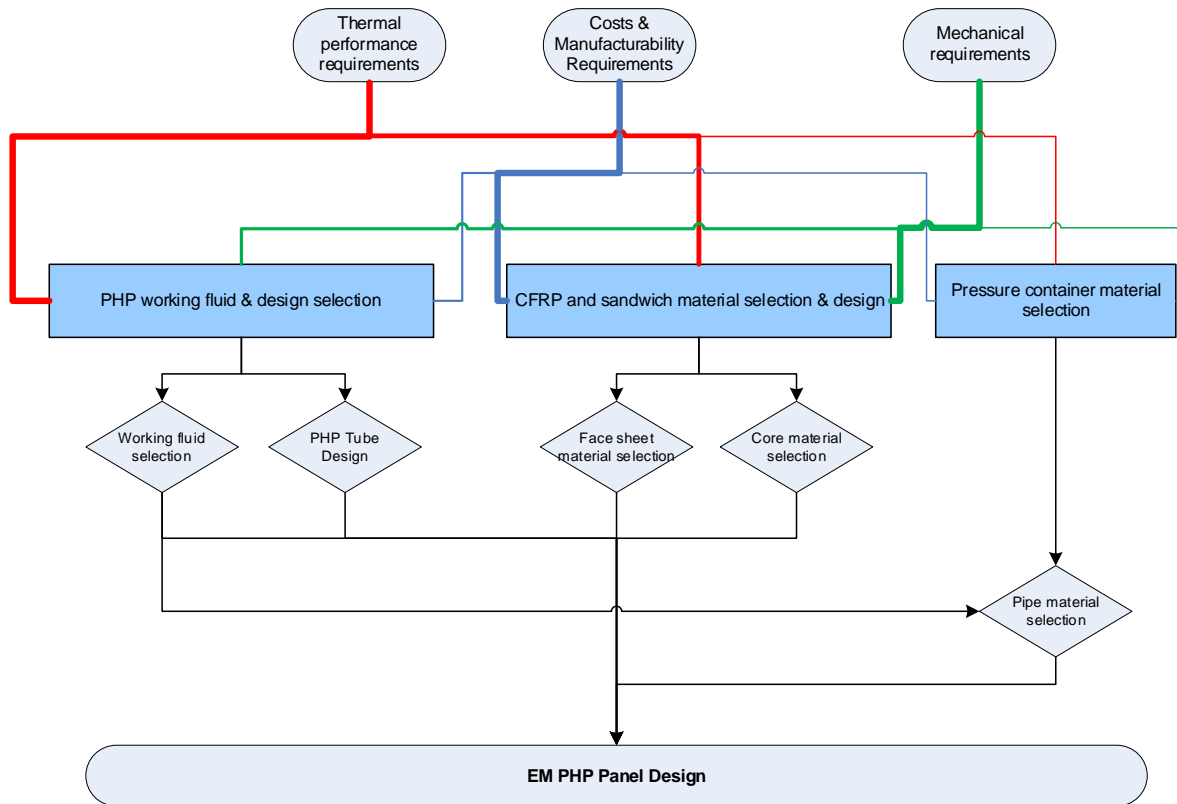


**Figure 2 PHP EM Panel cross section (all dimensions in mm)**

Locally the pitch has been extended to allow for installation of inserts in-between tubes. The PHP is embedded in layer of CFOAM to assure a defined thermal interface between tubes and face sheet. This is both for thermal performance and mass an effective option compared to alternatives. The total mass of the EM panel including ammonia charge is 8.4 kg/m<sup>2</sup>.

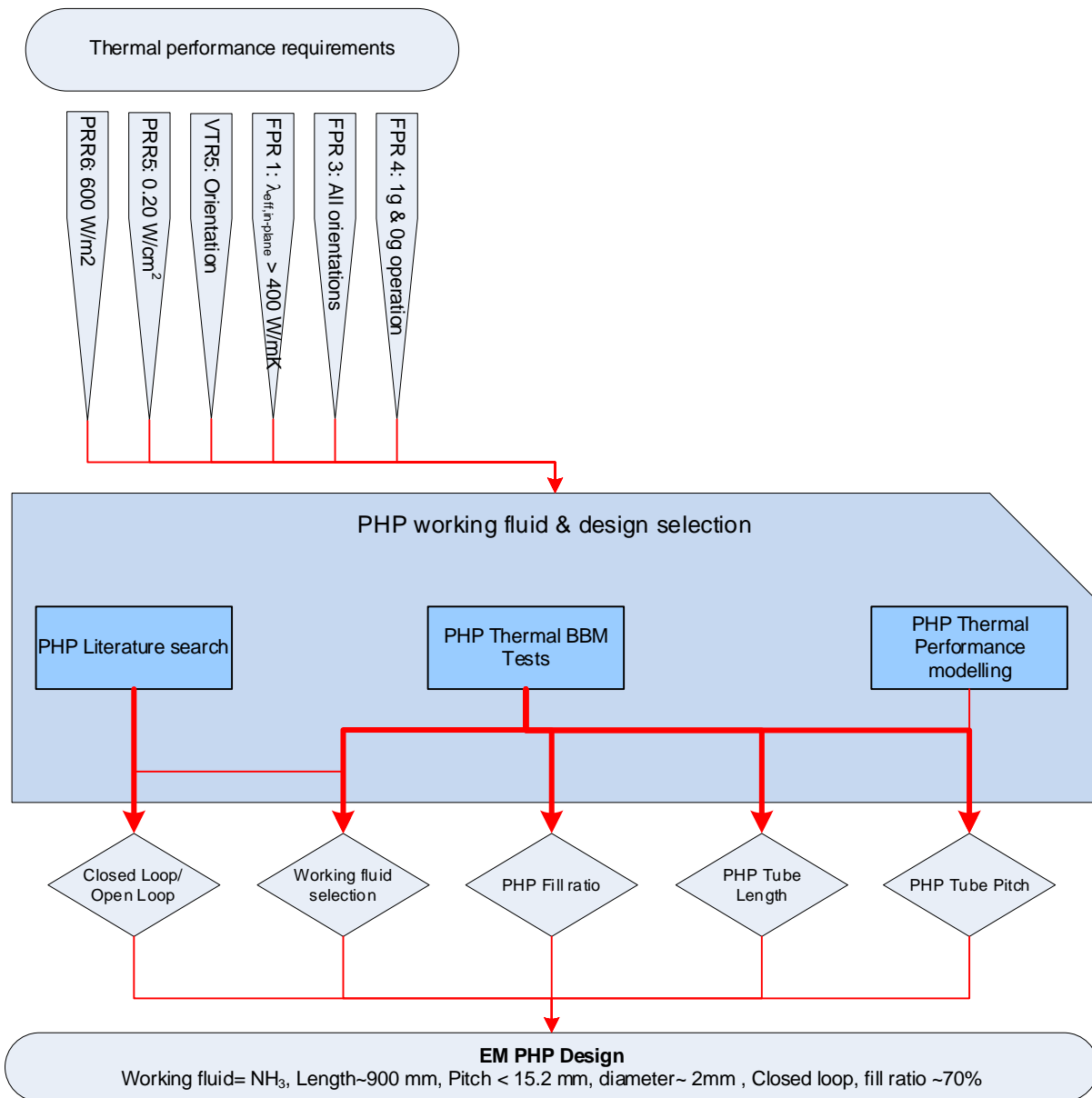
## II. Panel Design

The PHP EM Panel design is a result of the design decision tree as presented in Figure 3 which integrates and combines the results from PHP BBM tests, literature studies and preliminary analyses.



**Figure 3: EM PHP panel decision tree**

The starting point of the decisions tree are ESA requirements which are divided in thermal requirements indicated in red, cost & manufacturability requirements indicated in blue and mechanical requirements in green. The relative importance of the requirements for a selection process is presented with the thickness of the corresponding line. Three main selections are given in the blue rectangles for which separate detailed decision tree are made. Two are explained in more detail below. The PHP working fluid selection & design selection, shown in Figure 4, is only determined by the thermal performance requirements shown at the top of the decision tree. Three sources of information are used to come to the final design. First the PHP literature search with information on PHP working fluids and PHP test results. The PHP Thermal BBM tests are the main source of information used to define the working fluid, the fill ratio, the tube length and tube pitch. Thermal analyses were used to verify the overall PHP performance.



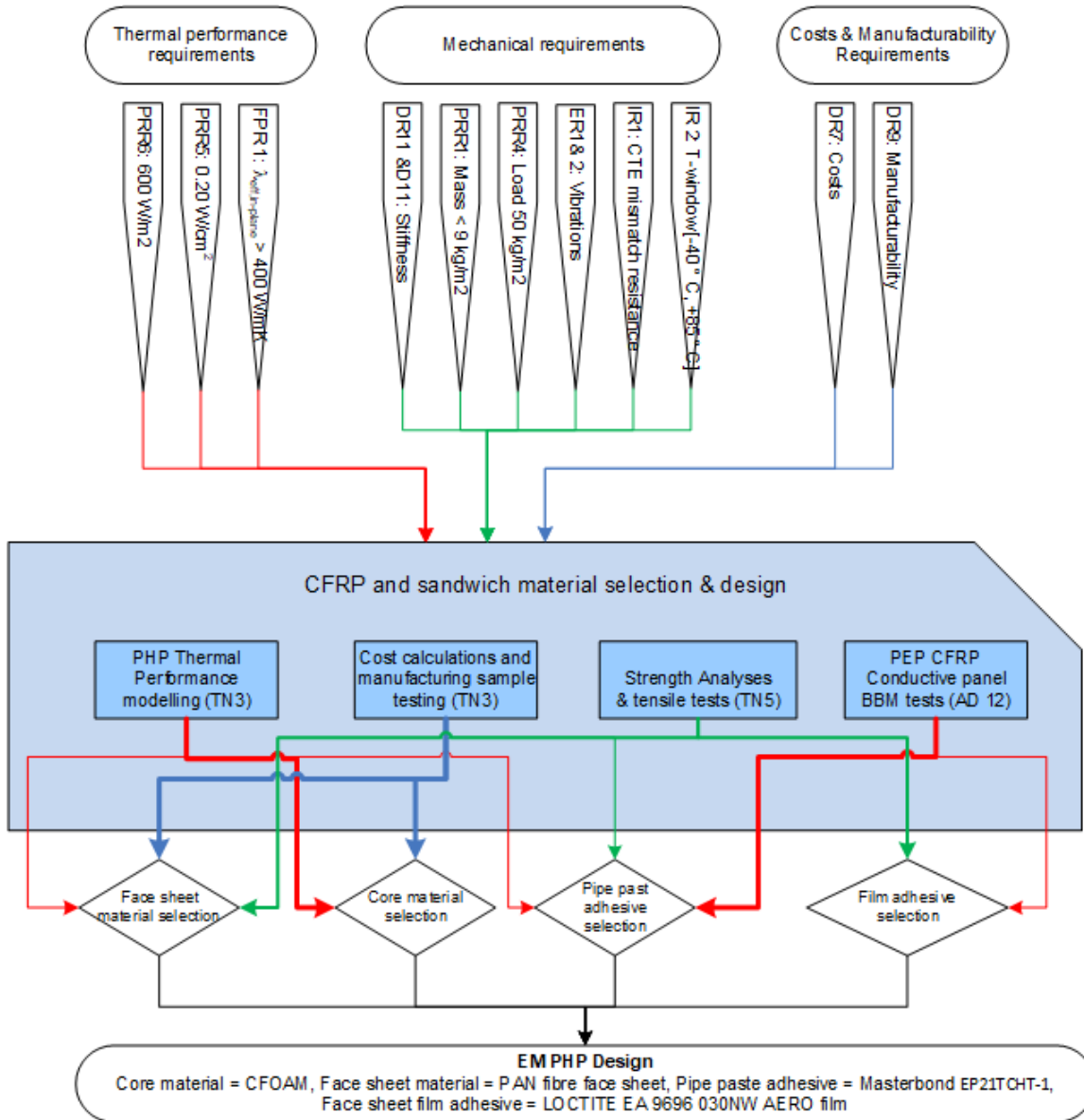
**Figure 4: Detailed Decision tree PHP working fluid & design selection**

The selection process led to the following design decisions:

- The baseline is a closed loop PHP design with NH<sub>3</sub> as working fluid and an optimal fill ratio of 70%

- A 1 m length PHP panel design with several heat sources and distributed surfaces area's for radiative cooling is technically feasible. No division in smaller compartments is needed.
- BBM results result in PHP tube with 10,000 W/mK effective conductivity

The structural material and design decision tree is shown in Figure 5. The main design drivers here are thermal performance and costs. The pure mechanical requirements have only influence on the adhesive connections and honeycomb thickness. The structural decisions are based on PHP thermal modelling, cost estimations, strength analyses and supporting tensile tests and manufacturing sample tests, and experience with adhesives from previous projects.



**Figure 5: Detailed Decision tree CFRP and sandwich material selection & design**

The following selections were made:



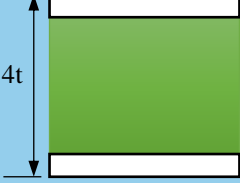
- The baseline PHP Face sheet material is CFRP with PAN Fibres. The gain in thermal performance (2.2 °C) of pitch fibres did not compensate the additional cost.
- The baseline PHP core material exists of C-foam HTC 35 layer to embed the PHP pipes and a standard aluminum honeycomb for the general structural function.

- Masterbond EP21TCHT-1 is selected as the flexible adhesive to embed the PHP pipes into the C-foam. Other bonded connections are less critical and are addressed by standard LOCTITE film adhesives.

To assure carbon foam particles from the panel side are contained the sides of the carbon foam are taped with Kapton tape.

### A. Structural analysis and adhesive sample tests

Sandwich structures offer outstanding stiffness and strength for low weight. The sandwich concept is based on placing thin, high strength skins on a thick, lightweight core. A higher core thickness increases the stiffness and strength for minimal weight gain as illustrated below in Figure 6 . It follows clearly that using a lightweight core only adds little weight while increasing the stiffness significantly. For the considered PHP sandwich panel, a 10 mm thick aluminium honeycomb core is used in combination with 2x 3.5mm bonded CFOAM cores creating a total core height of 17mm with a 0.6 mm CFRP face sheet on both sides. For the analyses a 17 mm core height with aluminum core properties is assumed while considering the mass of the PHP tubing assembled in the CFOAM summing up to a total panel mass of 6700 grams considered as a distributed load over the area of the panel.

	Solid laminate	Sandwich core thickness $t$	Sandwich core thickness $3t$
			
Stiffness	1.0	7.0	37.0
Flexural strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

**Figure 6: Sandwich structures concept and effect on stiffness and weight**

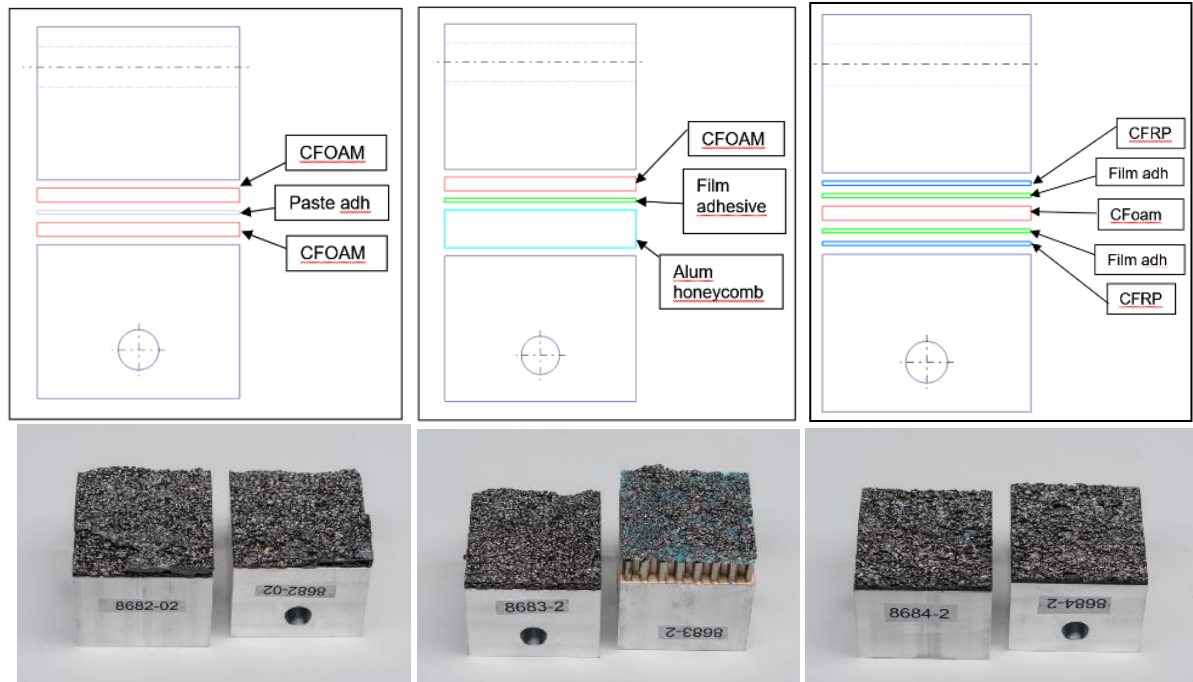
In Table 1 the eigenfrequencies of the PHP sandwich panel are given and all above the 100 Hz requirement.

**Table 1: PHP Panel Eigenfrequencies for different boundary conditions**

Case	Description	Eigenfrequency [Hz]
15a	Rectangular flat plate; all edges fixed	205
16a	Rectangular flat plate; all edges simply supported	112
17a	Rectangular flat plate; two long edges are fixed, one short edge is fixed and one short edge is simply supported	182

As no major challenges in panel mechanical design were found the focus shifted to optimizing and verifying the adhesive connections and corresponding testing. Test coupons were made to verify the different connections with the flatwise tensile test (ASTM C297) method. The objective was to demonstrate the adhesive strength was not the limiting factor, so demonstrating the samples failed in the foam, honeycomb or face sheets. Therefore test samples were made with several combinations of adhesive, foam, honeycomb and face sheets.

The left sample shows the connection between two layers of CFOAM by Masterbond past adhesive. Although the sample failed on the CFOAM demonstrating acceptable adhesive strength, the sample manufacturing showed the Masterbond penetrated in the CFOAM resulting in considerable additional mass. Both the CFOAM-honeycomb connection (middle sample) and the CFOAM-face sheet connections showed adequate strength and little to no adhesive penetration into the CFOAM.



**Figure 7: Test sample lay-out and pictures of typical test samples after test**

**Left: CFOAM – Masterbond – CFOAM coupons ASTM C297**

**Middle: CFOAM – Film adhesive Loctite – Aluminum Honeycomb coupons ASTM C297**

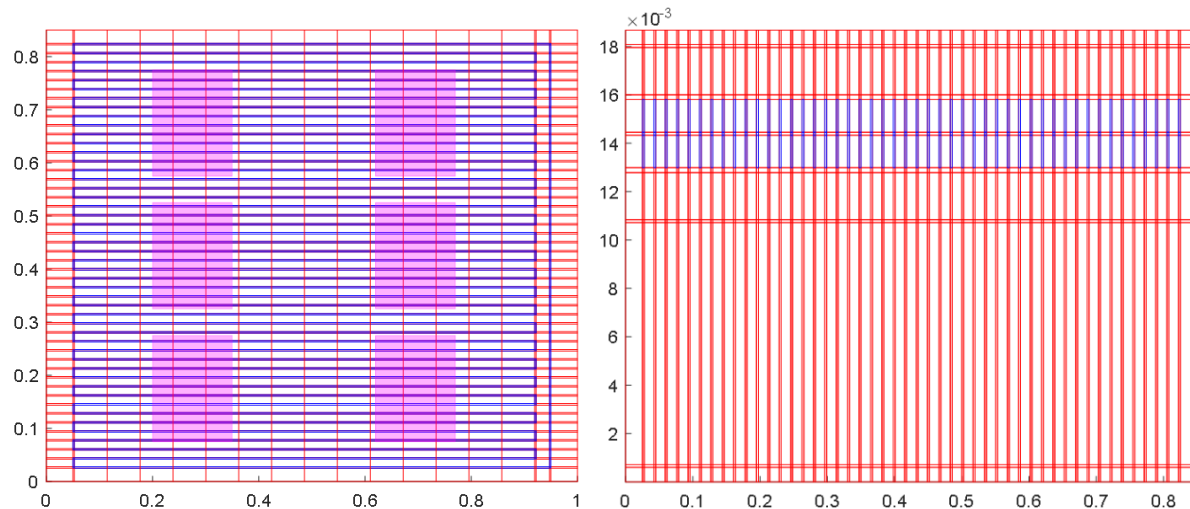
**Right: CFRP – Film adhesive Loctite – CFRP coupons ASTM C297**

The general conclusion of the BBM adhesive sample testing was that the Loctite film adhesive can be used for the structural bonding of the different components while the Masterbond will only be used for the non-structural, functional (thermal conduction) bonding of the PHP tubing to the surrounding CFOAM for both mass and strength reasons. This translated into Loctite sheet adhesive foil connecting the two layers of the CFOAM and only Masterbond adhesive paste applied directly around the tubes.

### **B. Thermal performance prediction and PHP BBM tests**

To evaluate and verify the thermal performance of the EM PHP panel design under several combinations of input powers and environment temperatures, a thermal node model has been developed, see Figure 8.

The thermal conduction is related to the bulk material, the respective node dimensions and layer thicknesses. For the nodes that include a PHP tube the effective axial conduction when operational is calculated using 10.000 W/m/K for the tube cross section and corresponding length and is deduced from BBM test results. The PHP conduction value is set to nearly zero to calculate a non-operational PHP leaving only the tube wall to conduct heat in axial direction.

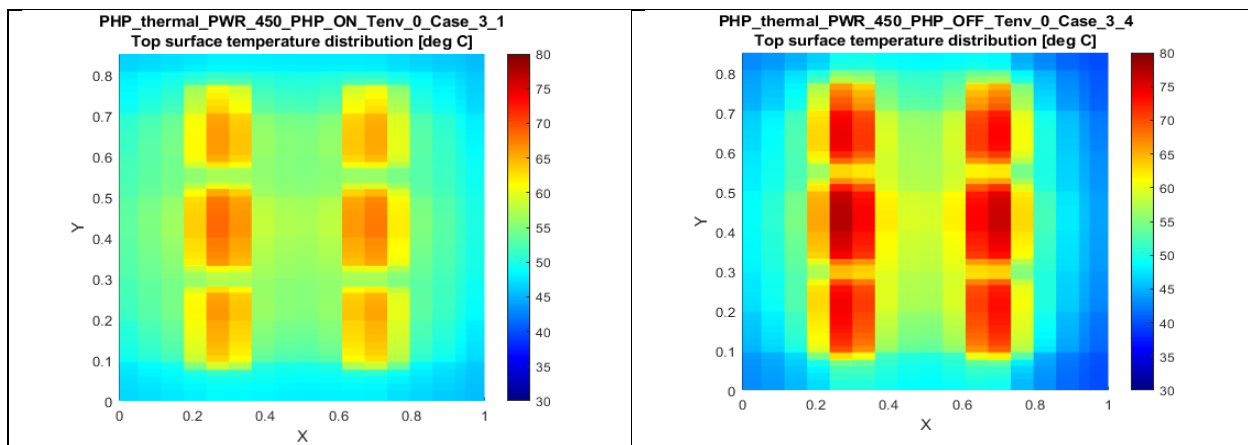


**Figure 8 : Geometry overview of the node distribution in the thermal model. On the left-hand side the top view node geometry is depicted. The right-hand side shows a cross section overview of the node distribution in the thermal model. All dimensions are in meters. The PHP nodes are depicted in blue.**

**Table 2 Thermal model prediction results for the evaluation cases. Temperatures below 60°C are marked light green, between 60°C-70°C dark green, between 70-80°C orange and above 80°C red.**

		PHP ON			PHP OFF		
Pwr [W/m <sup>2</sup> ]	T_env [°C]	0	20	40	0	20	40
	150		26.1	42.6	59.8	29.3	45.7
300		48.6	62.7	77.8	54.7	68.6	83.6
450		68.6	81.0	94.5	77.4	89.6	103.0

The evaluation results are presented in Table 2 and show that the PHP panel can transport a heat load of 300 W/m<sup>2</sup> for average environmental temperatures. Figure 9 shows the differences in top surface temperature predictions for both operational as well as non-operational PHP for a heat load of 450 W/m<sup>2</sup> at an environmental temperature of 0°C.



**Figure 9 Difference in temperature levels between PHP ON (left) and OFF (right) for the EM panel**

The conclusion is that the EM PHP is suited to fulfil the thermal requirements. Furthermore, the higher the heat load, the more effective the PHP is. By the application of the CFOAM there is a built-in contingency for PHP malfunction. An active PHP effectively spreads the heat by using the available panel area more efficiently reducing the peak temperatures up to 10°C in the extreme cases.

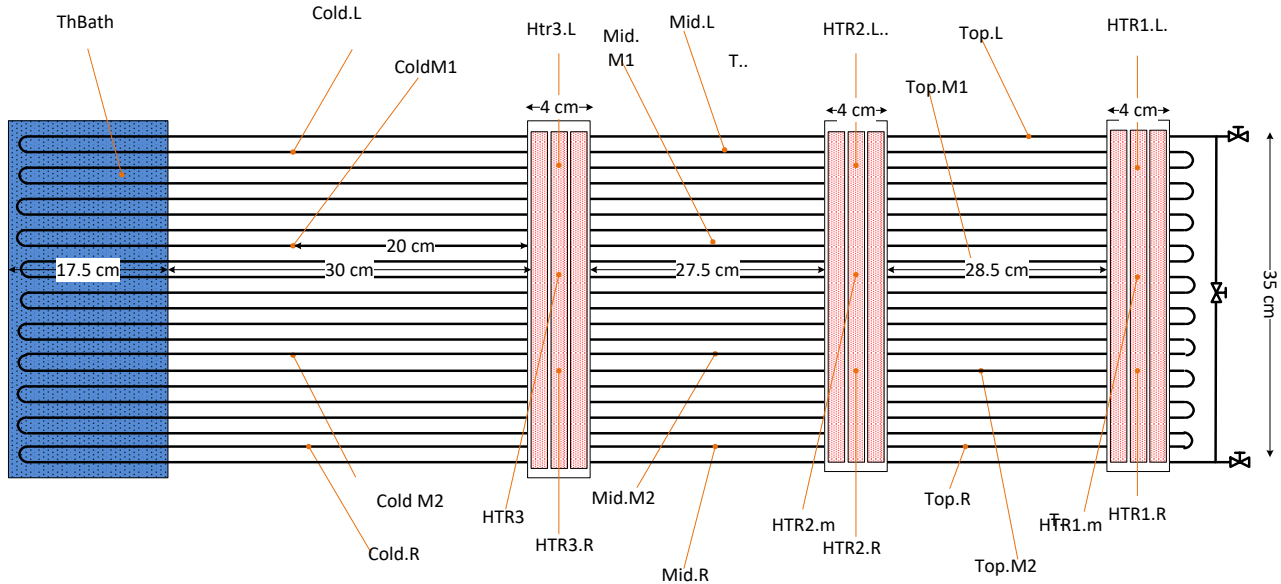
To reduce the development risk also PHP BBM tests were performed to verify PHP operation under the most challenging conditions. The objectives of the PHP BBM tests were:

- To verify the performance of an ammonia filled PHP
- Determine an PHP effective tube conductivity to be used in the PHP thermal model
- To verify the optimum fill ratio for an ammonia filled PHP with representative dimensions
- Verify the maximum PHP tube pitch for reliable operation
- Verify the feasibility of 1000 mm length PHP panel
- Verify PHP BBM operation in horizontal and vertical (gravity non-assisted orientation)

The majority of the test were performed with BBM prototype 2 with 22 passages and is depicted in Figure 10 and Figure 11.



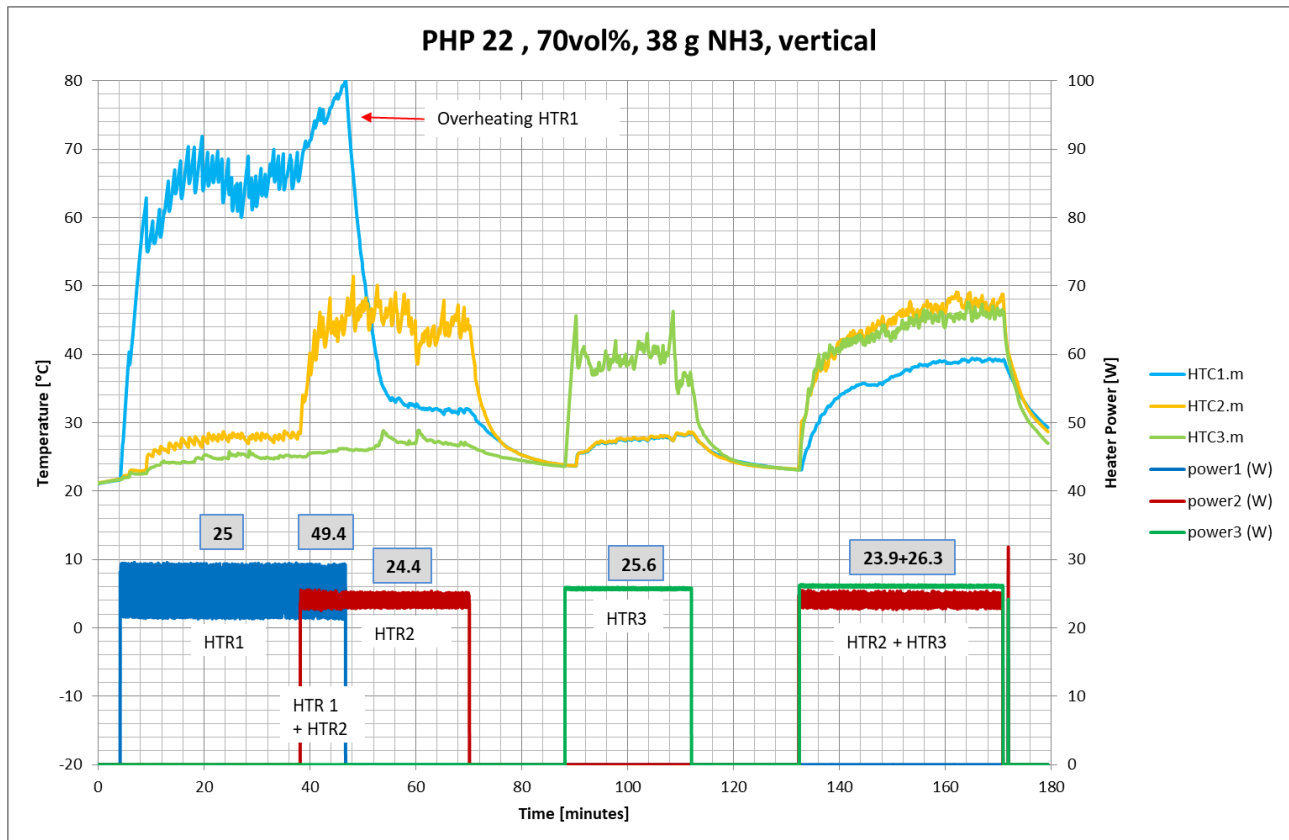
**Figure 10: Picture of the PHP22 test set-up prototype 2**



**Figure 11: Dimensions of the PHP22 test set-up prototype 2**

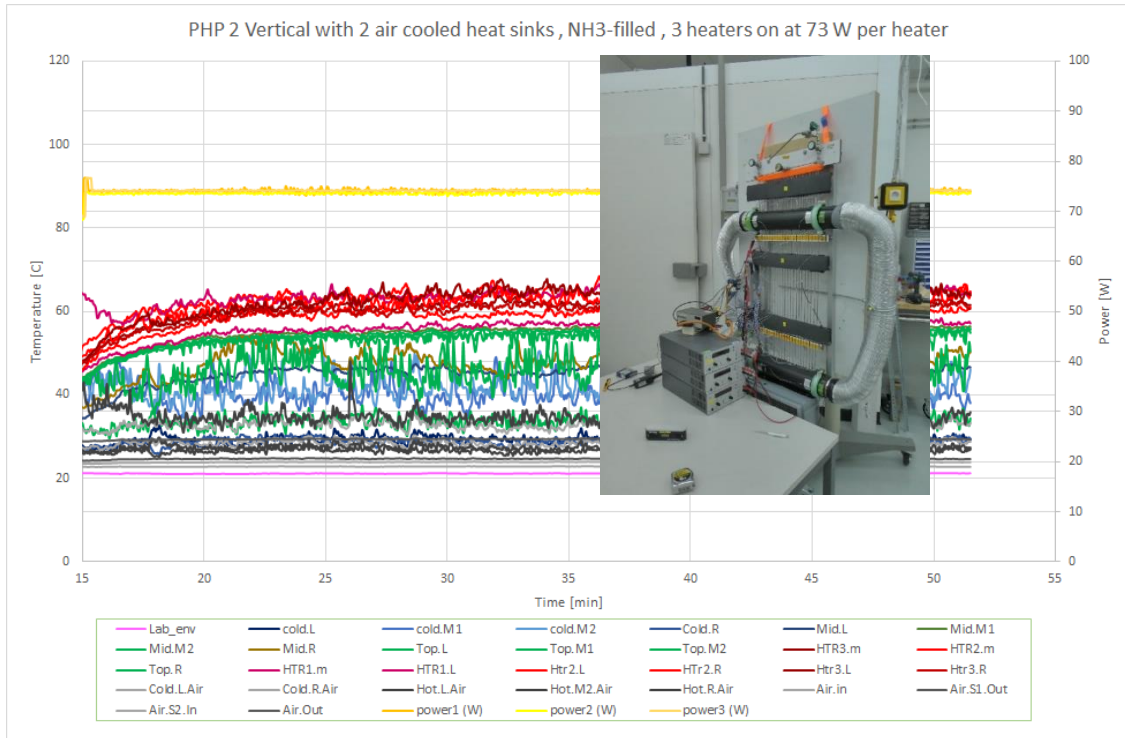
The first batch of tests were made with one cold source indicated in blue on the left in Figure 11 in which heater configurations with heater 1, the most right and furthest away from the cold source showed to be problematic. Performance tests in horizontal and vertical orientation showed similar results. The results in vertical orientation are shown in Figure 12. Heat was applied with foil heaters at three sections. On each section 25Watt can be applied separately but also combination of heater sections is possible. Cooling was performed with a water flow around the tubes of the condensing section. In Figure 12 the heater section temperatures are shown for various heater cases.

Preliminary conclusion was that the tubing length from heater 1 (HTR1) to the heat sink of about 1 meter was at the edge of the transport capability of the PHP as overheating occurred with heater 1 powered with 25 Watt shown at the left of Figure 12. The PHP operated according to expectation with heaters 2 and 3 in single and combined mode as can be seen on the right side of Figure 12.



**Figure 12: PHP 22 with 70vol% NH3 in vertical orientation and combined heater test at 40°C and 49 Watt.**

As the PHP EM panel contains multiple cold areas around the heater zones it was decided to perform a test with BBM prototype 2 with multiple cold areas by cold air. This set-up and a test result are shown in Figure 13.

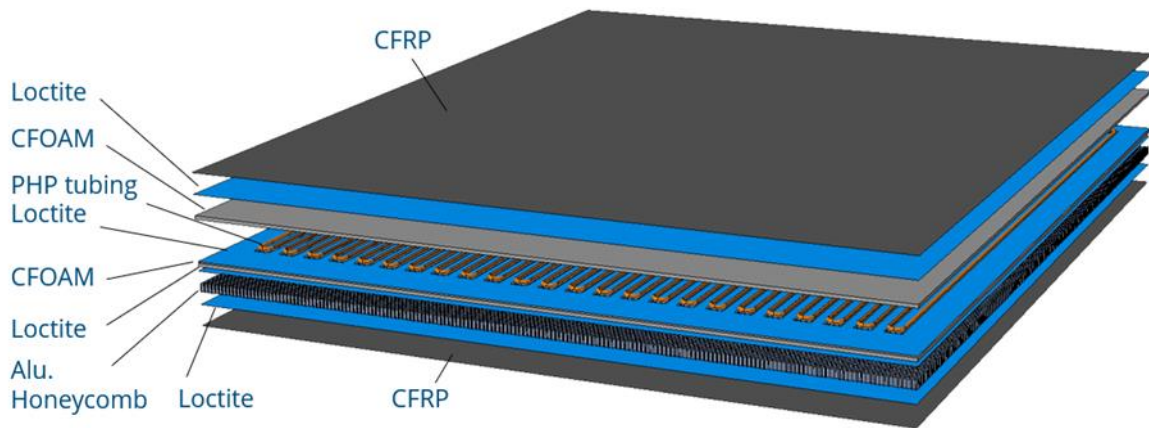


**Figure 13: Prototype 2 test results with air cooling on two locations with all 3 heater sections at 73 W**

This additional test demonstrated that with multiple cold sources all tests with all heaters switched on simultaneously the PHP works well and even up to 73 W/heater which is equivalent to 521 W/m<sup>2</sup> if normalized to 1 m<sup>2</sup>. In some single heater cases however the results were as low as 179 W/m<sup>2</sup>, but far better than with one cold source. In the EM PHP panel the heaters simulating the electronics boxes are located not in such extreme locations therefore the results gave enough confidence to continue with a 1-meter long EM PHP panel design.

### III. Panel Manufacturing and Test

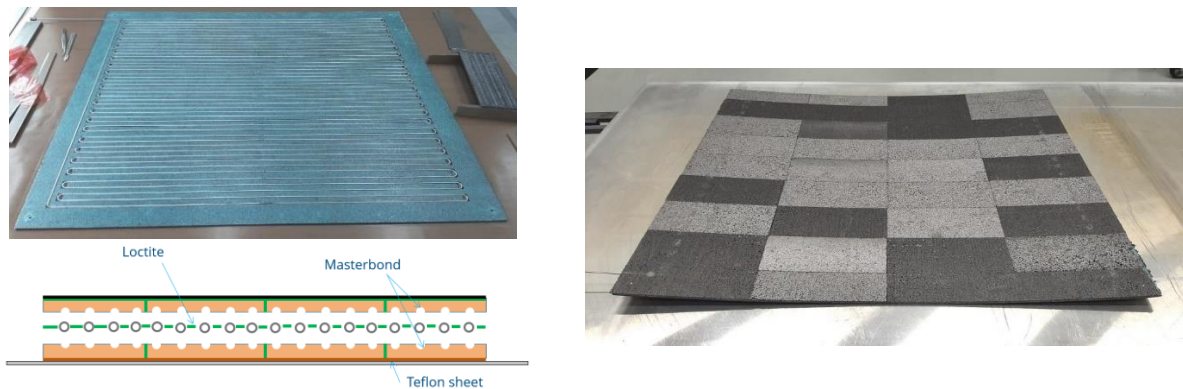
The final EM Panel construction is shown in Figure 14.



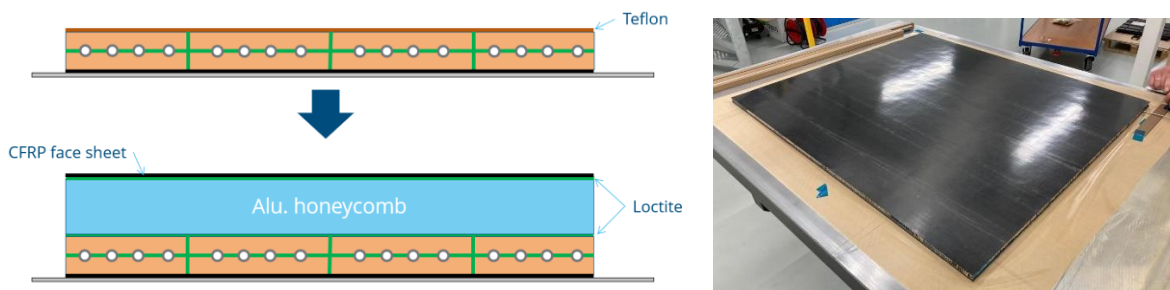
**Figure 14 PHP EM Panel construction**

The main manufacturing steps are:

- PHP tube bending, welding and leak testing
- Standard CFRP face sheet manufacturing and NDI
- Machining of the carbon foam material in tiles
- Bonding of the face sheet to carbon foam tiles and carbon foam machining for PHP embedding
- Machining of second carbon foam layer and machining for PHP embedding
- Assembly PHP tubing in CFOAM sandwich subassembly (see Figure 15) with adhesives and curing
- Final assembly of the PHP sandwich panel (see Figure 16) with sheet adhesives and curing



**Figure 15: Assembly of the PHP tubing in the CFOAM sandwich section with top side provided with the CFRP face sheet.**



**Figure 16: Cross section sketch showing the final assembly steps for the PHP sandwich panel**

Throughout the manufacture and assembly NLR took care to ensure air paths for evacuation of entrapped air. From the PHP sandwich assembly manufacturing experience NLR recommends the following:

- Larger CFOAM tiles are needed to reduce the manufacturing cost and handling complexity
- The sub assembly of the PHP embedded in CFOAM requires a symmetric build-up to avoid distortion (curvature), a CFRP face sheet on both sides could be considered.

#### IV. EM PHP Panel Tests Campaign and test results

PHP EM panel test campaign sequence is shown in Figure 17. The first test done on the panel was a Pressure Cycle Test (PCT1) to verify the integrity of the tubing under operational pressure cycles. For a reference of the final panel performance initial tests are done under ambient conditions (Ambient Test 1) and in thermal vacuum (TVT1) having the PHP tube not filled with Ammonia. This allows to conduct a Leak & Proof Pressure Test under vacuum conditions while having the PHP installed in a TV chamber during TV Test 1. Both the Ambient Test 1 and TV test 1 were used to measure the heat spreading capabilities with the PHP non-operational as a reference for the operational test cases in air and vacuum after filling the PHP tube with Ammonia. The operational test includes the running-in the PHP for an extended period of time in a laboratory environment (Burn-in Test). Until the burn-in test all test showed results according to expectations.



TVAC Facility side view



NLR large movable Heat Sink

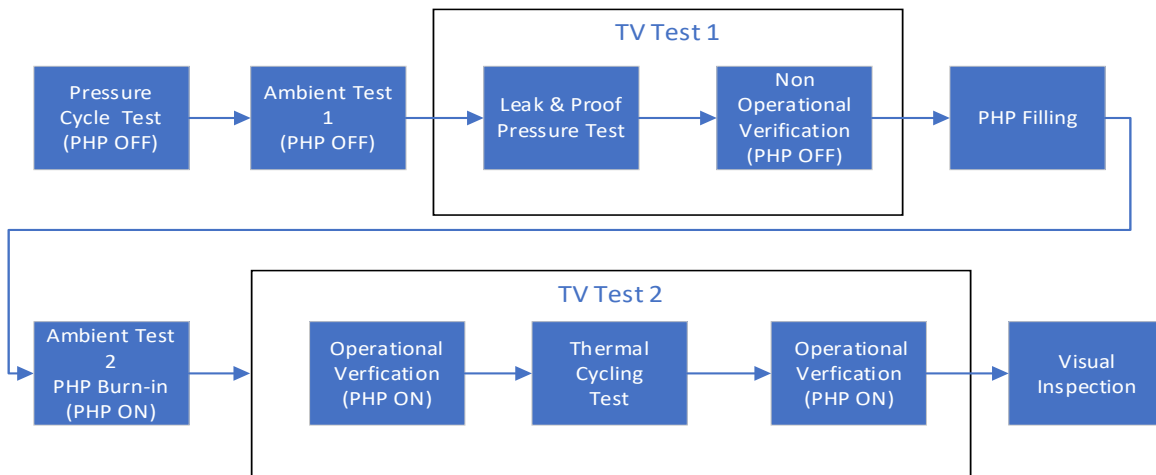
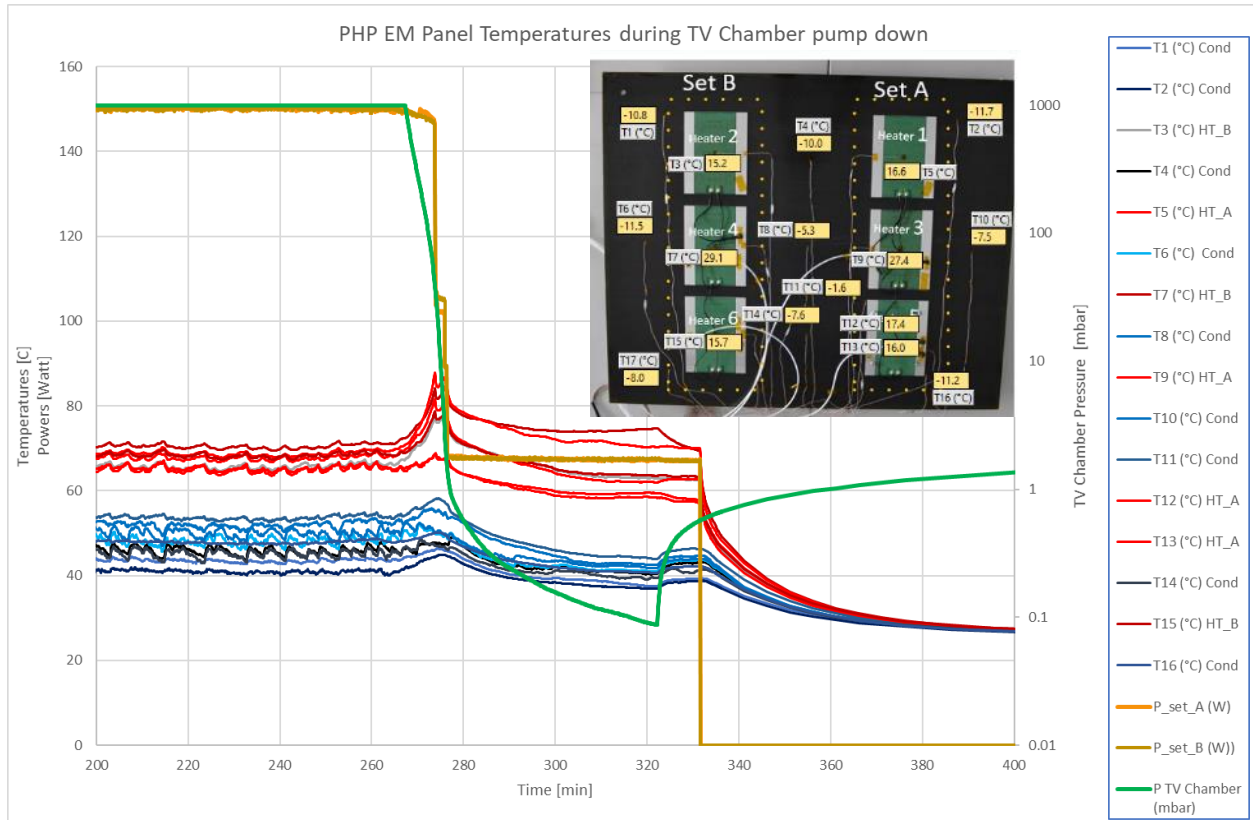


Figure 17: EM PHP Panel test flow (bottom) and NLR Thermal Vacuum Facility (top)

However during the first PHP panel operational test in vacuum the PHP EM Panel did not start-up. After re-pressurization the PHP panel was switched on at ambient pressure and worked directly again according to specification. Many additional attempts with power ranges, shroud temperatures levels followed without positive result. It was then decided to operate the PHP during TV chamber pump down and monitor the PHP operation. The results are shown in Figure 18. The power was set on 300 W (150 W on heater set A and B). On the left side of the



**Figure 18: PHP Test anomaly in vacuum conditions**

graph nominal PHP operation is shown. During pump down the PHP heater temperatures rapidly increase and heaters values are automatically reduced to avoid overheating. This happens at approximately 100 mbar. The PHP clearly stops operating. The PHP failure is until now not well understood. A root cause investigation is on-going with focus on a change in conductivity of the C-foam between ambient and vacuum. A reduction in C-foam conductivity could obstruct the heat path from heaters to PHP resulting in the anomaly. If this is the cause replacement of the C-foam with a better conducting material could solve the issue.

Panel delamination on the adhesive will also be checked by thermography scan. First results indicate however no delamination occurred.

## V. Conclusion

The development of a satellite structural panel with enhanced heat spreading capabilities to radiate the heat by radiation to the S/C internal environment is developed with a PHP embedded in a CFRP panel. The design rationale is explained together with the main analyses and BBM tests. This resulted in EM PHP panel design which was manufactured and tested. The panel worked according to expectations in ambient but failed under vacuum conditions. The anomaly is investigated. It is expected that with an alternative better conducting foam the anomaly can be addressed. The concept presented is a lightweight and cost-effective solution for internal spacecraft panels with moderate heat loads with the additional advantage that the PHP operation is independent of gravity which makes the solution flexible for S/C TV test campaigns.

## Acknowledgments

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