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Low CTE Heat Pipe – Mounting of Aluminium Heat Pipes on CFRP facesheets

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Abstract

Today, telecommunication satellite structure is made of Aluminium. Consequently the equipment panels are honeycomb sandwich panels with an Aluminium core and Aluminium facesheets. High dissipative equipments are usually mounted on these panels. Surface mounted or embedded heat pipes are utilized in order to provide the adequate thermal conductivity between equipment and the radiators. The use of panels with CFRP facesheets is usually restricted to load carrying structures or structures supporting low dissipative equipment. The wider use of CFRP structures would be attractive for telecommunication satellites in order to save mass and for science missions to gain structural stability. However, there is no technology available for state-of-the-art heat pipes to be embedded or surface mounted on panels with a CFRP facesheet.

Within this study the main concern - the thermo-elastic compatibility of commonly used Aluminium heat pipes with carbon fibre structures is addressed and solved.

The first study phase was dedicated to the design, development and test. After the establishment of a specification and a requirement review an extensive technological state-of-the-art review lead to the final design – the “tunnel concept”. That is a CFRP tunnel containing the heat pipe which is pressed onto the facesheet with the help of a spring. Mechanical and thermal tests have been performed. Therefore a breadboard panel with a high-conductive fibre (K13C6U) with two surface-mounted and two embedded heat pipes has been built and tested. The second study phase will be kicked-off until mid 2016, with the goal of optimizing the contact conductance quality between the heat pipes and the facesheet. In addition, the in-plane heat transfer will be optimized by implementing the HiPer technology developed by Airbus DS NL. At the end a concept for accommodating "classic" Aluminium heat pipes in CFRP structures will be available, qualified to a TRL of 6.

This paper will address the state of the art technology review, the detailed design of the low CTE heat pipe mounting concept and the results of the mechanical and thermal test campaign.

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Definitions, Acronyms, Abbreviations

CFRP = Carbon fibre reinforced polymer
CTE = Coefficient of thermal expansion
HiPer = High Performance Radiator
HP = *Heat Pipe*
I/F = Interface

I. Context

Among other topics, the key objectives for technology improvement are mass reduction, higher thermal rejection capabilities, enhancing pointing stability and increase of performance. In this perspective, the use of CFRP based structures, with their high stiffness to mass ratio, contributes directly to two of these objectives, which are mass reduction and pointing stability.

This is why CFRP structures are currently used onboard telecom spacecraft mainly for “cold” structures as load carrying structures, antenna reflectors, feed support assemblies, solar panels, etc, but still not yet for hot structures such as payload, equipment and radiator panels. So, a key issue for Airbus DS is the development of technologies that will enable the universal use of CFRP structures also to hot applications. This implies the ability to achieve a very high power to mass ratio.

The domain of technologies to be investigated is twofold. Firstly, the aim is to improve the thermal conductivity of CFRP panels. Airbus DS is investigating these technologies with ESA. This includes the use of high performance thermal facesheets, either with fibres with very good conductive properties together with special resins or the implementation of new materials, such as HiPer with an outstanding thermal performance combined with economical attractiveness. A second field of investigation is improving the embedded heat pipe technology to CFRP panels. Here, the main issue is the CTE mismatch between the state-of-the-art Aluminium heat pipes and the CFRP panels. Therefore ESA launched a technology study “Low CTE Heat Pipes” with the aim to fill this technological gap. The objective of this study is to investigate the availability of technologies suitable to be applied for designing a Low-CTE heat pipe for a CFRP radiator panel. Thus, a representative Low-CTE heat pipe CFRP radiator panel will be developed and built up to verify the major performance and design requirements by tests.

The industrial project team consists of EHP[3] (for the general heat pipe design and development), Airborne[4] (responsible for designing the radiator), Airbus France[6] (contributing the team with their huge telecom satellite expertise) and Airbus DS Germany (as project lead and analysis authority).

The study is divided in 2 phases: During Phase 1 an extensive review of state of the art technologies and a trade-off between different concepts has been performed. As a result, the most promising concept, an Aluminium heat pipe moveably installed in a CFRP tunnel (Figure 1) has been found and subjected to further development and investigations. Critical technologies have been identified and supported by an extensive bread board test program, for which a significant number of mechanical test samples and coupons were manufactured. Finally a 300mm x 900mm breadboard radiator panel sample was manufactured and tested. This panel is equipped with five embedded and two surface mounted crossing tunnels, for inserting up to 4 heat pipes. This radiator sample provided first experiences for manufacturing a tunnel design CFRP Radiator sample and its thermal performance during thermal vacuum testing.

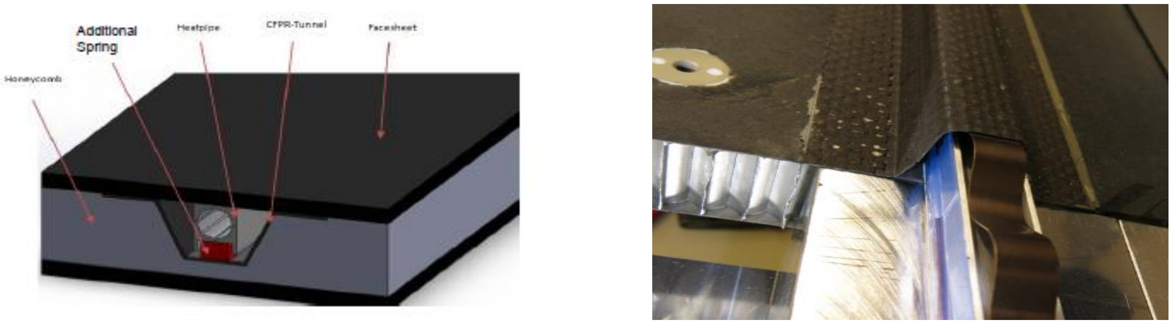


Figure 1: Spring fixated Heat Pipe installed in CFRP tunnel

The findings of Phase 1 will be further detailed and investigated in Phase 2. Especially the contact quality at the I/F between heat pipe and facesheet will be improved. Furthermore, the team is strengthened by Airbus DS NL[5], who contributes their HiPer technology.

II. State of the Art

The following paragraphs describe the State of the Art technologies and materials which are available for the design of a CFRP radiator panel and CFRP heat pipes with respect to an implementation on a telecom mission.

A. Heat Pipe Working Fluid

For the selection of a suitable working fluid the following requirements of the specification need to be considered:

- The diameter of the external and embedded heat pipes shall be such as the thickness of the most common used north south panels in telecom spacecrafts, which is in the range 11 mm to 12 mm.
- The operational temperature range for the Low CTE heat pipes shall be between [-40°C - +80°C], the non-operational temperature range shall be [-60°C - +100°C].
- The requested heat transport of the low CTE heat pipes shall be in the order of 110 Wm to 175 Wm

A major criteria for the selection of the working fluid is the below displayed liquid transportation factor. The liquid transport factor of a working fluid best describes the level of maximum thermal transport over the operating temperature range. It is the relation of fluid density, multiplied by liquid surface tension, multiplied by the latent heat and divided by the viscosity. If the value is high, then a high heat transport capability of the heat pipe can be expected. Figure 2 shows the liquid transport factor for several working fluids.

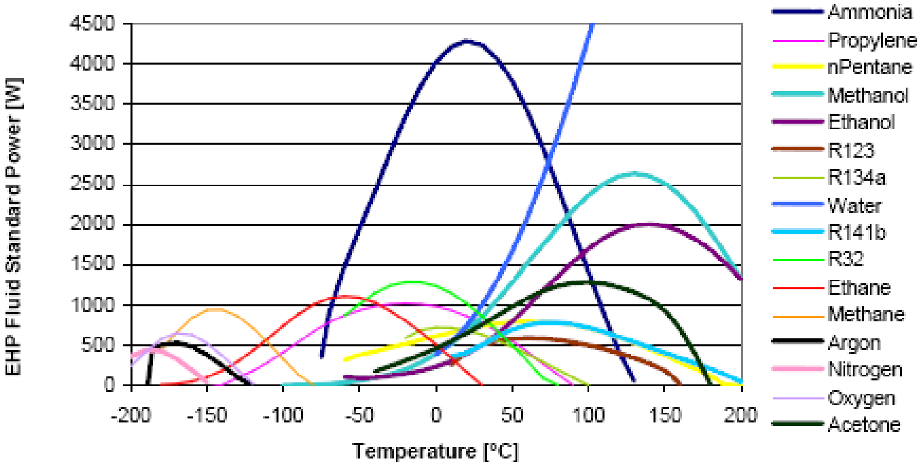


Figure 2: Liquid Transportation Factor for selected working fluids[1]

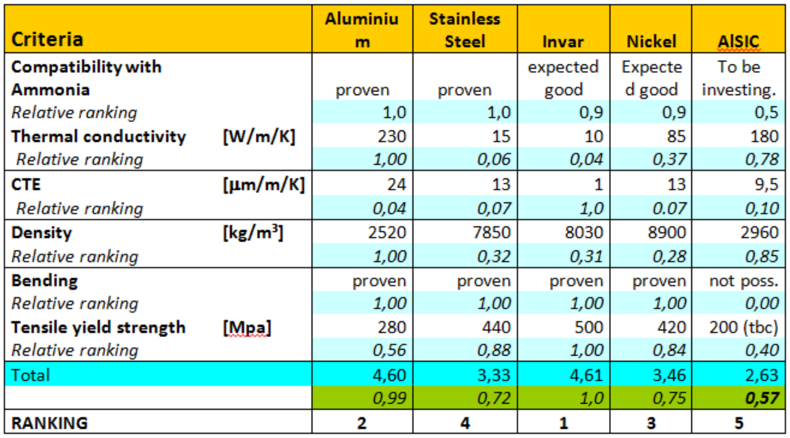
For the required temperature range from -40°C to + 80°C Ammonia has the highest liquid transport factor as well as considerable high and sufficient vapor pressure over the whole temperature range. Thus Ammonia is selected as the candidate working fluid for the Low-CTE heat pipe.

B. Heat Pipe Container Material

The compatibility of the wall material and capillary system (wick or open axial grooves) with the working fluid is a key issue for a proper long lifetime operation of a heat pipe. The main chemical compatibility problems are:

- Generation of non-condensable gas products resulting from the decomposition of working fluid, outgassing or chemical reactions between working fluid and container material and wick.
- Decrease in heat transport capability of the wick, due to wick plugging by solid precipitate, the dissolving of the wick in the working fluid or the increase of fluid viscosity due to dissolved reaction products
- Failure of container wall due to galvanic (low temperature) corrosion of wall or the solution of the wall material into the fluid (at higher temperatures).

Table 1 shows the trade-off performed on candidate materials for the selection the container material for the Low-CTE heat pipe. It is generally accepted that Aluminium/Ammonia heat pipes as well as stainless steel/Ammonia heat pipes are well proven and space qualified concepts. Considering the goal of developing a low CTE heat pipe solution, thee table was completed by considering some other candidate materials, such as Invar, Nickel and AlSIC



Criteria		Aluminium	Stainless Steel	Invar	Nickel	AlSIC
Compatibility with Ammonia		proven	proven	expected good	Expected good	To be investing.
Relative ranking		1,0	1,0	0,9	0,9	0,5
Thermal conductivity	**[W/m/K]**	230	15	10	85	180
Relative ranking		*1,00*	*0,06*	*0,04*	*0,37*	*0,78*
CTE	**[µm/m/K]**	24	13	1	13	9,5
Relative ranking		*0,04*	*0,07*	*1,0*	*0.07*	*0,10*
Density	**[kg/m³]**	2520	7850	8030	8900	2960
Relative ranking		*1,00*	*0,32*	*0,31*	*0,28*	*0,85*
Bending		proven	proven	proven	proven	not poss.
Relative ranking		*1,00*	*1,00*	*1,00*	*1,00*	*0,00*
Tensile yield strength	**[Mpa]**	280	440	500	420	200 (tbc)
Relative ranking		*0,56*	*0,88*	*1,00*	*0,84*	*0,40*
Total		4,60	3,33	4,61	3,46	2,63
		0,99	*0,72*	*1,0*	*0,75*	***0,57***
RANKING		**2**	**4**	**1**	**3**	**5**

Table 1: Trade-Off of container materials[1]

The two candidate concepts that got the highest ranking for the development the Low-CTE heat pipes are

- Invar/Ammonia heat pipes

The Invar Ammonia heat pipe has the advantage that there is no CTE mismatch between heat pipe container material and the CFRP panel structure, so that the heat pipe can be directly bonded to the CFRP facesheets. The disadvantages of the Invar concepts are the high mass of the heat pipe and the poor thermal conductivity of the container material. Further there is a small risk in the field of compatibility of working fluid with container material, which needs to be investigated.

- Aluminium/Ammonia heat pipes

The Aluminium/Ammonia heat pipe is a well proven and qualified heat pipe concept. It fulfils all requirements such as low mass, high thermal conductance between heat pipe external flange and heat pipe vapour, bending and low manufacturing costs, except the CTE mismatch between heat pipe and CFRP facesheet. Here some mechanical and thermal features need to be added to achieve a feasible concept. Both principal concepts have been investigated in more detail in the preliminary design phase which is described in paragraph III - Concept Trade-Off Studies.

C. CFRP Panel

Facesheet

The design driving requirements for the panel and hence for the facesheets are good thermal conductivity in-plane, high stiffness, good flatness and low mass. For the breadboard model the K13C6U fibre was selected for the facesheets, due to availability, price (MOQ) and previous experience with this fibre by Airborne. This also determined the choice of resin for the prepreg, the RS3 resin. The thermal conductivity of the K13C6U fibre is 530 W/mK. Table 2 shows the properties of the manufactured and tested facesheets with two types of quasi-isotropic layups.

Thickness	Plies	Layup	Estimated actual thickness	Remark
0.3	3	0/90/0	0.27	Type 1
		-45/-0/+45		Type 2

Table 2: Skin properties

Core design and sandwich bonding

To investigate the influence of the core two different core densities have been included into the breadboard model. EA9394 is an adhesive paste with great heritage (Airborne) also for solar panel substrates.

Part	Type	Panel conductivity (W/m/K)	Remarks
Low density core	CRIII 3/8 5056 0.0007P	λx=5.9, λy=5.7, λz=0.8	Milled to a height of 21.0mm
High density core	CRIII 1/4 5056 0.0015P	λx=6.6, λy=6.0, λz=1.9	Height 21.0mm
Adhesive paste	EA9394	-	

Table 3: Core properties

III. Concept Trade-Off Studies

To decide on a concept of how to mount heat pipes on CFRP facesheets a detailed concept trade-off was performed. This included the establishment of a preliminary design, mechanical and thermal analyses, as well as selection of materials including compatibility considerations. The mass as well as the mechanical and thermal performance has been compared to a conventional Aluminium panel as reference. This aluminium honeycomb panel is derived from an Airbus DS standard platform configuration, containing surface mounted and embedded heat pipes (Figure 3).

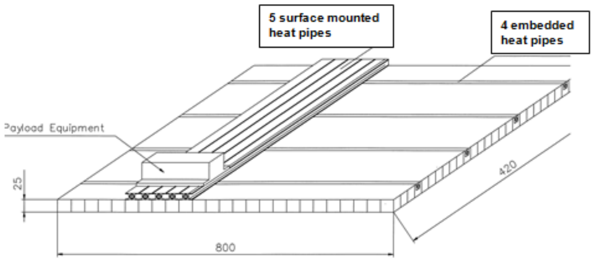
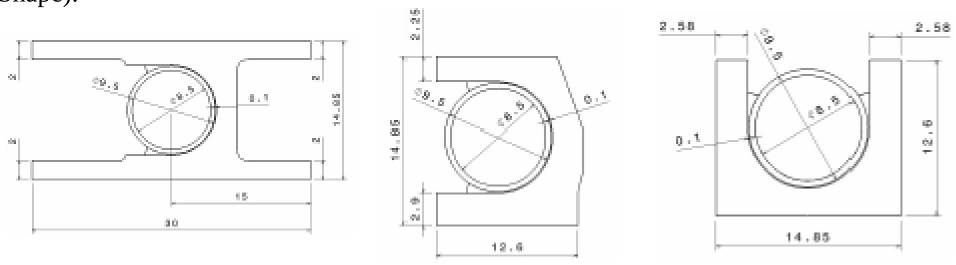


Figure 3: Aluminium Panel Reference Configuration

Seven concepts have been further investigated with respect to the requirements of a heat pipe installation on a CFRP facesheet.

A. Invar heat pipe concepts

Three of these concepts consider a Low-CTE heat pipe that is based on Invar as heat pipe tube material. Invar has a CTE value around 2.0E-6 1/K which fits very well to the CTE value of CFRP facesheets for the CFRP radiators. Since heat pipe profiles made from Invar cannot be produced as extrusion profile with intergraded H-shaped flanges an external saddle needs to be added to the Invar tube heat pipes for equipment mounting. The following three saddle shapes (Figure 4) are applicable to either surface mounted heat pipes (H-Shape) or embedded heat pipes (C-shape and U-Shape).



H-shape C-shape U-shape

Figure 4: Saddle design

Considering these saddle shapes three different assembly concepts were detailed and analysed. This included the gluing of the Invar tube into a single CFRP flange as well as the soldering of an Invar tube to a single metallic saddle or multiple Aluminium flanges. The findings of the different concepts are briefly summarized below:

Concept 1 is an Invar Heat Pipe with a single metallic Saddle. The saddle is made from AlSiC, which has been selected as the most suitable material, due to its thermal performance. The remaining CTE mismatch especially between saddle and Invar tube lead to high stresses in the brazing joints. This makes this concept technically non feasible. For the same reason this is also applicable to an Invar Heat Pipe with multiple Aluminium Saddles (Concept 3).

Concept 2 is an Invar Heat Pipe with a CFRP flange. A saddle made from high conductive CFRP has a good thermal conductance along the fibres, but a very poor thermal conductance across the fibres. Assuming a C-shaped CFRP saddle the heat path is going from the outer layer of the CFRP saddle (at equipment side) to the inner layer of the saddle (at heat pipe side). This generates large thermal gradients. The not existing CTE mismatch between flange and facesheet has the drawback of high manufacturing costs.

Concept C3X is a variation of concept 3 with an Invar heat pipe and Invar saddles. On the one hand the thermal conductance of Invar is low, but on the other hand there is no CTE mismatch between heat pipe and CFRP facesheet.

Another variation is Concept C3Y which considers Invar heat pipe with CeSiC saddles. CeSiC is a very brittle material; and thus parts made of CeSiC are very sensitive to any non-symmetrical mechanical loads. Since for the embedded heat pipes no non-symmetrical mechanical loads are expected CeSiC saddles can be used here.

The trade-off resulted in three technically feasible Invar heat pipe concepts, which are either Invar and CFRP saddles or CeSic saddles for embedded heat pipes only.

B. Aluminium heat pipe concepts

Four concepts are based on already qualified Aluminium/Ammonia standard heat pipes. To these ones some sort of attachment or manipulation elements need to be added in order to handle the large CTE mismatch between aluminium and CFRP radiator facesheets.

The idea of Concept 4 is to allow "movement" of a conventional Aluminium heat pipe within externally added saddles made from Aluminium. The gap between heat pipe and saddle is filled with high thermal conductive paste in order to provide the heat transfer between the parts. There is the risk of freezing of the paste for temperatures below -20°C providing mechanical loads to the saddles and facesheets. Thus sample testing is necessary to demonstrate the mechanical performance. Mass and thermal properties are moderate compared to the reference concept.

Concept 5 considers a conventional Aluminium heat pipes pressed onto the facesheet with flexible interfaces as displayed in Figure 5. This flexible interface increases the overall mass and the manufacturing effort significantly. In addition the technical feasibility of the concepts needs to be investigated carefully.

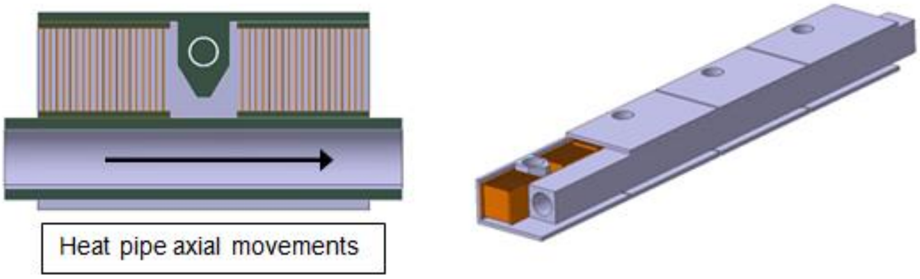


Figure 5: Aluminium heat pipe with flexible I/Fs

Concept 6 is a conventional Aluminium heat pipe wrapped in CFRP fibres (Figure 5Figure 6) to restrict the Aluminium heat pipe from change in length.

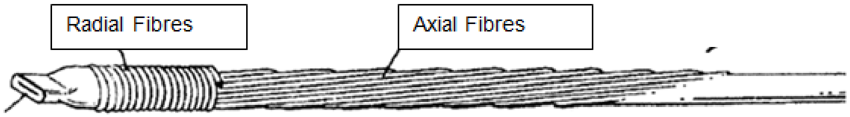


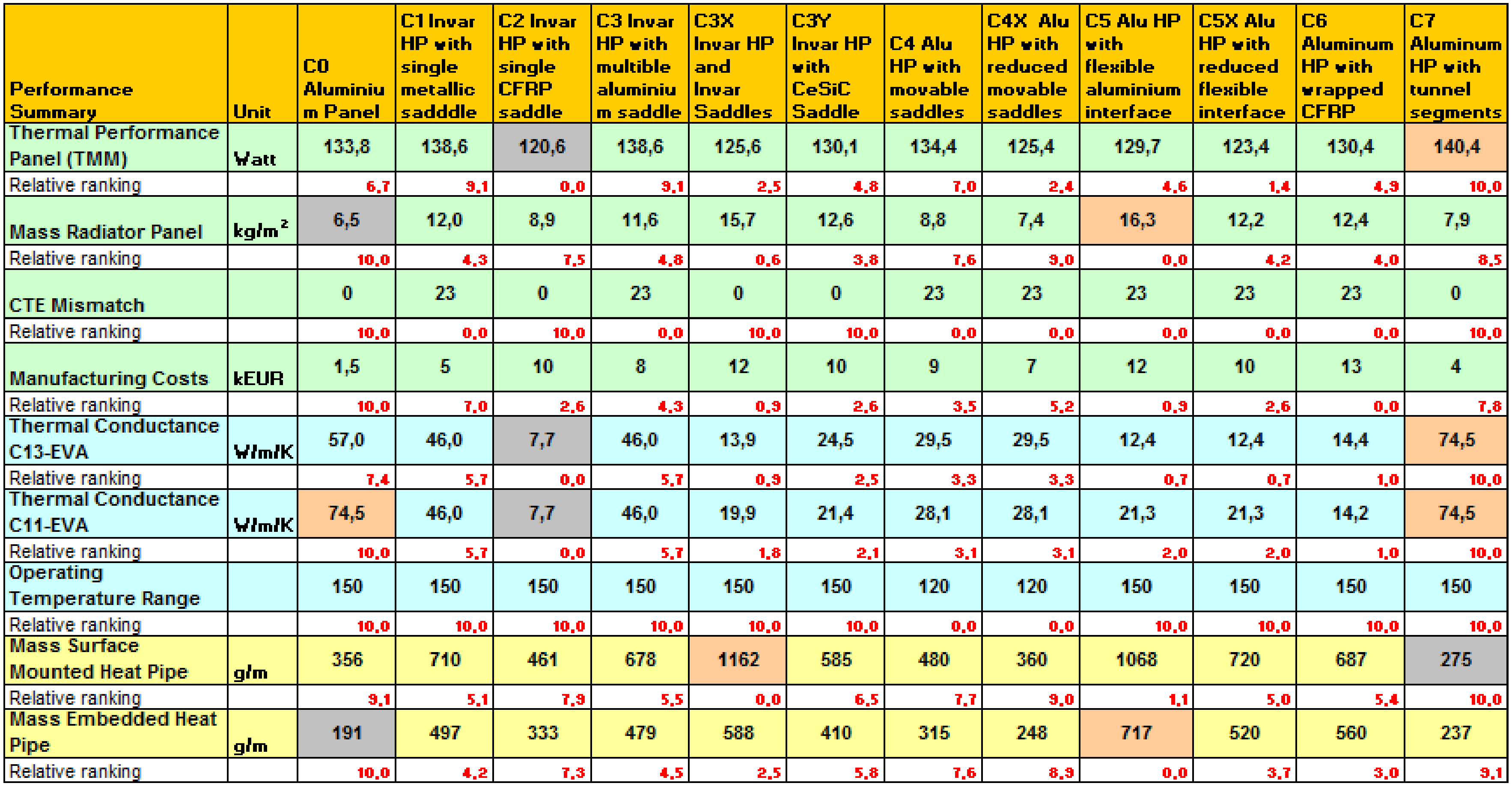
Figure 6: Heat pipe wrapped in CFRP fibres

Mounting saddles made from Aluminium are attached to the heat pipes. The concept has a poor thermal performance due to the high thermal resistance through the CFRP layer. Furthermore bonding of Aluminium parts to CFRP is challenging. Consequently, the concept is technically critical with tendency to be technically not feasible.

Concept 7 considers a conventional Aluminium heat pipe which is movable in tunnel segments. The heat pipe is pressed onto the facesheet with the help of a wave spring. The tunnels can be either embedded or surface mounted. Thermal interface foils are used to enhance the thermal conductance between heat pipes and facesheet. In terms of mass the concept is only slightly heavier (237g/m) than the Aluminium reference panel (191g/m).

C. Trade-Off evaluation

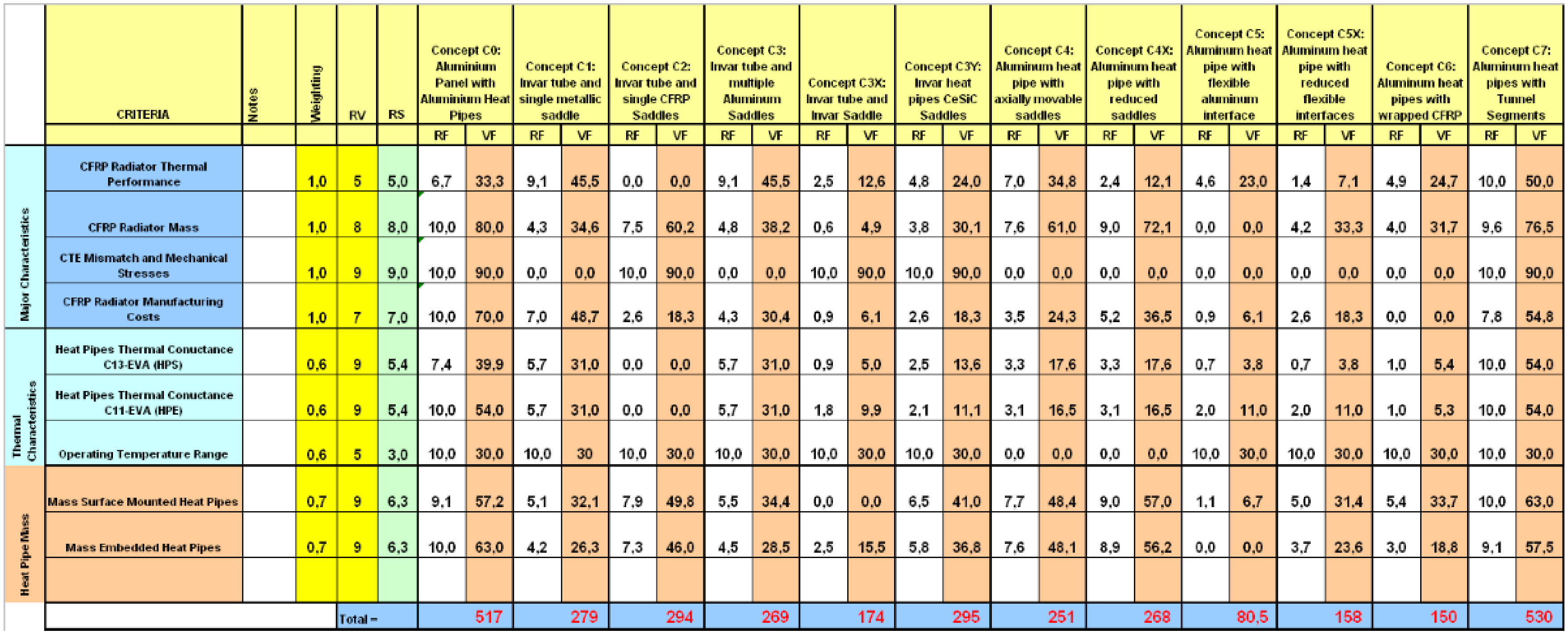
After performing the preliminary design of the different concepts a decision making process has been conducted. Table 4 shows the key criterion of all considered concepts. The concepts were compared per performance criteria and ranked relatively.



Performance Summary	Unit	C0 Aluminium Panel	C1 Invar HP with single metallic sadddle	C2 Invar HP with single CFRP saddle	C3 Invar HP with multible aluminium saddle	C3X Invar HP and Invar Saddles	C3Y Invar HP with CeSiC Saddle	C4 Alu HP with movable saddles	C4X Alu HP with reduced movable saddles	C5 Alu HP with flexible aluminium interface	C5X Alu HP with reduced flexible interface	C6 Aluminum HP with wrapped CFRP	C7 Aluminum HP with tunnel segments
Thermal Performance Panel (TMM)	Watt	133,8	138,6	120,6	138,6	125,6	130,1	134,4	125,4	129,7	123,4	130,4	140,4
Relative ranking		6,7	9,1	0,0	9,1	2,5	4,8	7,0	2,4	4,6	1,4	4,9	10,0
Mass Radiator Panel	kg/m^2	6,5	12,0	8,9	11,6	15,7	12,6	8,8	7,4	16,3	12,2	12,4	7,9
Relative ranking		10,0	4,3	7,5	4,8	0,6	3,8	7,6	9,0	0,0	4,2	4,0	8,5
CTE Mismatch		0	23	0	23	0	0	23	23	23	23	23	0
Relative ranking		10,0	0,0	10,0	0,0	10,0	10,0	0,0	0,0	0,0	0,0	0,0	10,0
Manufacturing Costs	kEUR	1,5	5	10	8	12	10	9	7	12	10	13	4
Relative ranking		10,0	7,0	2,6	4,3	0,9	2,6	3,5	5,2	0,9	2,6	0,0	7,8
Thermal Conductance C13-EVA	W/m/K	57,0	46,0	7,7	46,0	13,9	24,5	29,5	29,5	12,4	12,4	14,4	74,5
Relative ranking		7,4	5,7	0,0	5,7	0,9	2,5	3,3	3,3	0,7	0,7	1,0	10,0
Thermal Conductance C11-EVA	W/m/K	74,5	46,0	7,7	46,0	19,9	21,4	28,1	28,1	21,3	21,3	14,2	74,5
Relative ranking		10,0	5,7	0,0	5,7	1,8	2,1	3,1	3,1	2,0	2,0	1,0	10,0
Operating Temperature Range		150	150	150	150	150	150	120	120	150	150	150	150
Relative ranking		10,0	10,0	10,0	10,0	10,0	10,0	0,0	0,0	10,0	10,0	10,0	10,0
Mass Surface Mounted Heat Pipe	g/m	356	710	461	678	1162	585	480	360	1068	720	687	275
Relative ranking		9,1	5,1	7,9	5,5	0,0	6,5	7,7	9,0	1,1	5,0	5,4	10,0
Mass Embedded Heat Pipe	g/m	191	497	333	479	588	410	315	248	717	520	560	237
Relative ranking		10,0	4,2	7,3	4,5	2,5	5,8	7,6	8,9	0,0	3,7	3,0	9,1

Table 4: Concept Trade-Off

The relative ranking was multiplied by the weighing factor and relative value (RV) of the criteria, which lead to a relative score (RS) as presented in Table 5.



	CRITERIA	Notes	Weighting	RV	RS	Concept C0: Aluminium Panel with Aluminium Heat Pipes		Concept C1: Invar tube and single metallic saddle		Concept C2: Invar tube and single CFRP Saddles		Concept C3: Invar tube and multiple Aluminum Saddles		Concept C3X: Invar tube and Invar Saddle		Concept C3Y: Invar heat pipes CeSiC Saddles		Concept C4: Aluminum heat pipe with axially movable saddles		Concept C4X: Aluminum heat pipe with reduced saddles		Concept C5: Aluminum heat pipe with flexible aluminum interface		Concept C5X: Aluminum heat pipe with reduced flexible interfaces		Concept C6: Aluminum heat pipes with wrapped CFRP		Concept C7: Aluminum heat pipes with Tunnel Segments	
						RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF	RF	VF
Major Characteristics	CFRP Radiator Thermal Performance		1,0	5	5,0	6,7	33,3	9,1	45,5	0,0	0,0	9,1	45,5	2,5	12,6	4,8	24,0	7,0	34,8	2,4	12,1	4,6	23,0	1,4	7,1	4,9	24,7	10,0	50,0
	CFRP Radiator Mass		1,0	8	8,0	10,0	80,0	4,3	34,6	7,5	60,2	4,8	38,2	0,6	4,9	3,8	30,1	7,6	61,0	9,0	72,1	0,0	0,0	4,2	33,3	4,0	31,7	9,6	76,5
	CTE Mismatch and Mechanical Stresses		1,0	9	9,0	10,0	90,0	0,0	0,0	10,0	90,0	0,0	0,0	10,0	90,0	10,0	90,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	10,0	90,0
	CFRP Radiator Manufacturing Costs		1,0	7	7,0	10,0	70,0	7,0	48,7	2,6	18,3	4,3	30,4	0,9	6,1	2,6	18,3	3,5	24,3	5,2	36,5	0,9	6,1	2,6	18,3	0,0	0,0	7,8	54,8
Thermal Characteristics	Heat Pipes Thermal Conuctance C13-EVA (HPS)		0,6	9	5,4	7,4	39,9	5,7	31,0	0,0	0,0	5,7	31,0	0,9	5,0	2,5	13,6	3,3	17,6	3,3	17,6	0,7	3,8	0,7	3,8	1,0	5,4	10,0	54,0
	Heat Pipes Thermal Conuctance C11-EVA (HPE)		0,6	9	5,4	10,0	54,0	5,7	31,0	0,0	0,0	5,7	31,0	1,8	9,9	2,1	11,1	3,1	16,5	3,1	16,5	2,0	11,0	2,0	11,0	1,0	5,3	10,0	54,0
	Operating Temperature Range		0,6	5	3,0	10,0	30,0	10,0	30	10,0	30,0	10,0	30,0	10,0	30,0	10,0	30,0	0,0	0,0	0,0	0,0	10,0	30,0	10,0	30,0	10,0	30,0	10,0	30,0
Heat Pipe Mass	Mass Surface Mounted Heat Pipes		0,7	9	6,3	9,1	57,2	5,1	32,1	7,9	49,8	5,5	34,4	0,0	0,0	6,5	41,0	7,7	48,4	9,0	57,0	1,1	6,7	5,0	31,4	5,4	33,7	10,0	63,0
	Mass Embedded Heat Pipes		0,7	9	6,3	10,0	63,0	4,2	26,3	7,3	46,0	4,5	28,5	2,5	15,5	5,8	36,8	7,6	48,1	8,9	56,2	0,0	0,0	3,7	23,6	3,0	18,8	9,1	57,5
				Total =			517		279		294		269		174		295		251		268		80,5		158		150		530

Table 5: Concept Trade-Off evaluation[1]

In terms of thermal performance, mass and cost, none of the proposed low CTE heat pipe concepts is better than the current standard Aluminium / Ammonia heat pipes. The best low CTE concept is concept C3Y, which is an Invar heat pipe with CeSiC saddles attached. The disadvantage of CeSiC is the high young modulus which will destroy the integrity of the saddles by applying local mechanical loads. Thus this concept cannot be used for surface mounted heat pipes.

The concepts C4 and C4X, which are based on conventional Aluminium heat pipes, movable in external saddles, and thermal conductive paste in between, are the next candidates in the ranking. For these concepts two issues require further investigations:

- The potential freezing of the paste at temperatures below -30°C: The issue of freezing of the paste was investigated in a dedicated test programme using Arctic Silver and Arctic Ceramiques as thermal paste. The outcomes showed a freezing of both foils at -35°C which is not compliant to the required -60°C.
- the criticality of bonding of Aluminium parts to CFRP facesheets: The issue of bonding the embedded heat pipe to CFRP facesheet can also be solved by using saddles made from CeSiC material, which has a similar thermal conductance as CRFP..

The concepts C5 and C5X got the lowest ranking followed by concept C6, caused by the high mass of the heat pipes.

The concepts C1 and C3 achieved high rankings in the trade-off except for the CTE mismatch, which renders them technically not feasible due to the high stresses in the Invar heat pipe to saddles connection.

Concept C7 got the best results for the thermal cooling capability and this is even higher than for the Aluminium honey comb panel. In terms of mass and cost the values for C7 are better than for all remaining candidate concepts.

Thus concept C7 was selected as candidate for the detailed design, manufacturing and testing phase.

IV. Detailed Design and Analysis

In the following paragraph the developed detailed design and mechanical and thermal analyses of the selected concept are described. Apart from several samples for mechanical tests the goal of phase 1 was to develop a breadboard radiator panel. This breadboard consists of both embedded and surface mounted heat pipes. In the following each component of the design is described

A. Heat Pipe

The design of the Aluminium- Ammonia heat pipes is derived from a standard Aluminium heat pipe profile (Figure 7). Both, the embedded and surface mounted heat pipes are manufactured out of the same profile.

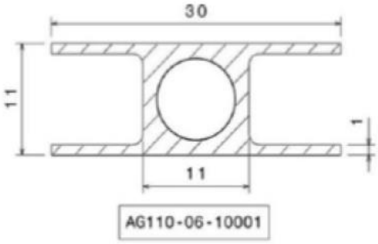


Figure 7: Standard aluminium heat pipe profile

The heat pipe is pressed onto the CRFP facesheet with a wave spring. To provide guidance for a spring element the profile is modified to the following shape (Figure 8).

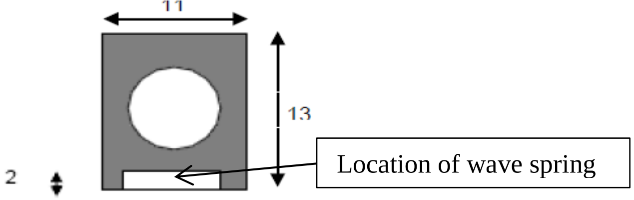


Figure 8: Modified heat pipe profile

B. Heat Pipe Fixation

The heat pipe fixation (Figure 9) is realized with an open tunnel, which presses the heat pipe via interface filler directly onto the radiator facesheet. The CTE mismatch between the CFRP facesheets and the standard Aluminium heat pipe is compensated, since the heat pipe is able to slide within the tunnel. To apply pressure on the heat pipe a linear wave spring is used between the tunnel and the HP. The tunnel design is identical for both the embedded and surface mounted heat pipes.

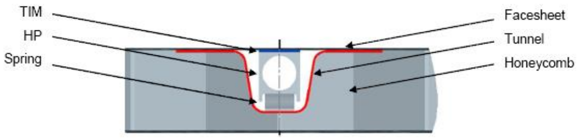


Figure 9: Fixation concept

To achieve the needed contact pressure for the respective filler material a linear wave shaped spring (Figure 10) will be used.

For the later described mechanical analysis the widest wave length of 30mm was considered. This is the worst case since the contact pressure is applied on a very small area only. According to the manufacturer wavelengths of 20-25mm are possible.

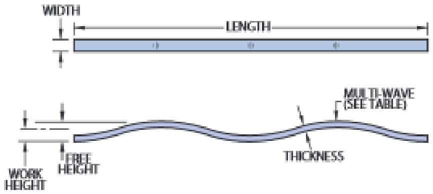


Figure 10: Wave spring design

C. Breadboard Radiator Panel

The design of the breadboard model has the dimensions as shown below (Figure 11). Two-thirds of the panel are made of a high density core (CRIII 1/4 5056 0.0015P), one third of the core has a lower density (CRIII 3/8 5056 0.0007P). The panel comprises two tunnels for surface mounted heat pipes and five tunnels for embedded heat pipes. Two bread boards with different facesheet lay-ups (Table 2) were manufactured.

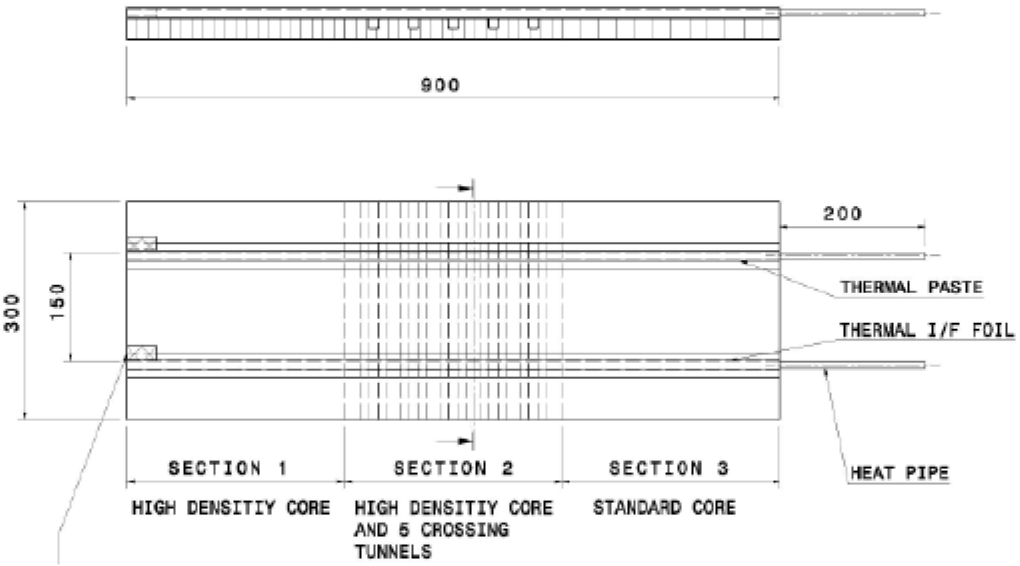


Figure 11: Breadboard panel design

D. Samples for mechanical testing

In addition to the breadboard model 26 samples for mechanical testing were designed and built. Therefore samples with high and low density cores (Table 3), two different facesheet lay-ups (**Table *2***) and room and elevated curing temperatures for the adhesive paste were built. This lead to 8 samples for Four-Point-Bending Tests to determine the bending capabilities of the panel, 6 Insert-Pull-Out samples to determine the core properties and 12 Flat-Wise-Tensile-Test samples to determine the bonding quality of the skin.

V. Integration and Testing

After manufacturing of the samples, the breadboard model and the heat pipes, all parts underwent the test logic as shown below.

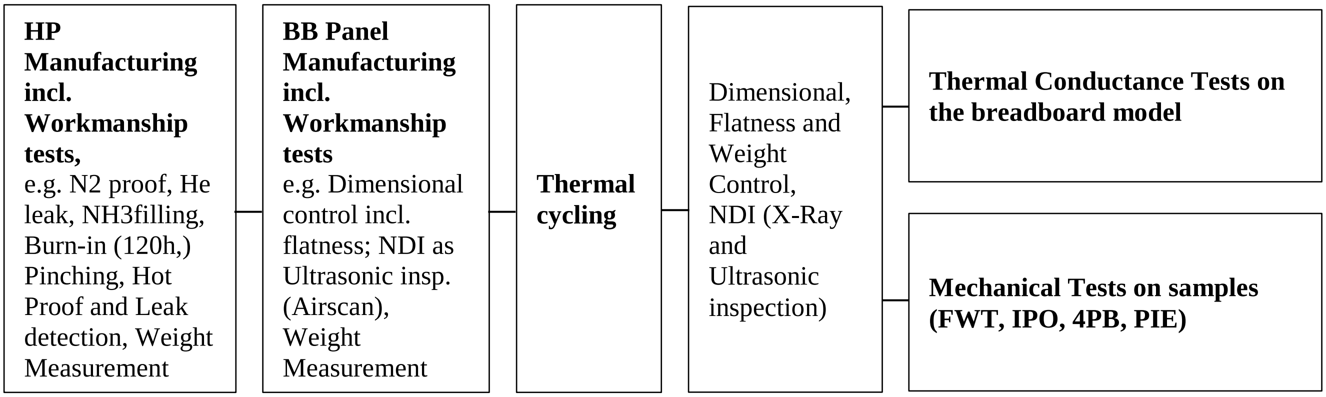


Figure 12: Breadboard and sample test logic

Heat pipe and breadboard panel manufacturing workmanship tests are standard processes of the respective manufacturers and are not described within this paper.

A. Thermal cycling

All mechanical test samples and the breadboards underwent 5 thermal cycles with extreme temperatures between -60°C and +90°C. After an initial facesheet delamination mostly of samples with a 0°/90°/0° layup (Type 1) after thermal cycling, this issue was investigated thoroughly. The manufacturing process was analysed and the minimization of moisture enclosure was achieved. A remanufactured type 1 4PB sample showed no delamination during an additional thermal cycling test.

The samples with the -45/-0/+45 skin lay-up showed no delamination in the post test inspection.

B. Mechanical Testing and Outcomes

The stiffness of a CFRP panel is 3-6 times the stiffness (depending of layup) of equivalent Aluminium panel.

On basis of the design guide of Hexcel (honeycomb supplier) intracell buckling is the most critical load case for an Aluminium panel.

Intracell buckling will occur at a 4 point bending load of 350 N, much lower than the failure load of the CFRP panels (700-820 N for Low density honeycomb). But of course buckling is no final failure. No good estimate of the failure load of an Aluminium panel under 4 point bending can be made with the current analytical method. This has to come from test/simulation or experience. Nevertheless, with the current information the mechanical performance of the Low-CTE heat pipe radiator shall be at least equal or greater to a comparable Aluminium radiator panel design.

C. Thermal Testing and Outcomes

The aim of the test is to show the feasibility of the integration of heat pipes into tunnels and a good thermal performance. This thermal performance is dependent on the contact conductance of the heat pipes to the facesheets as well as a good thermal conductance in plane of the panel. These properties lead to a good heat distribution over the panel and consequently good emission properties.

Therefore a TV test with different dissipation scenarios and TB phases is developed to verify the performance of the thermal design concept and to correlate the thermal model. During testing the breadboard is hanged above a cold plate horizontally inside the TV chamber. The outer facesheet is representing the radiator area and is pointing towards the cold plate. The cold plate will be temperature regulated on a constant temperature. The whole set up will be covered with a MLI with similar characteristics as for a typical flight configuration. To minimize the heat loss through the MLI, the chamber shroud will be regulated accordingly. The whole set up is in accordance with Figure 13:

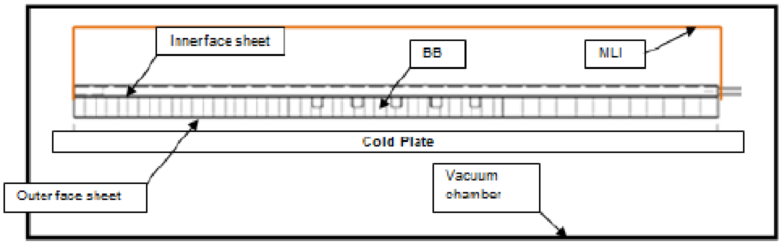


Figure 13: Breadboard panel TV test set-up

The breadboard is equipped with two surface-mounted and two embedded filled heat pipes (Figure 14). To assess possible filler material two filler types S900-graphite foil and U90K-polyurethan foil. Both have good thermal properties (6.0 - 7.5W/m/K), are compressible within the abilities of the wave spring and are space-qualified.
To simulate different dissipation scenarios five test heaters are installed. Whereas HTR01-04 are foil heaters, HTR05 is an embedded heat pipe profile which contains two cartridge heaters.

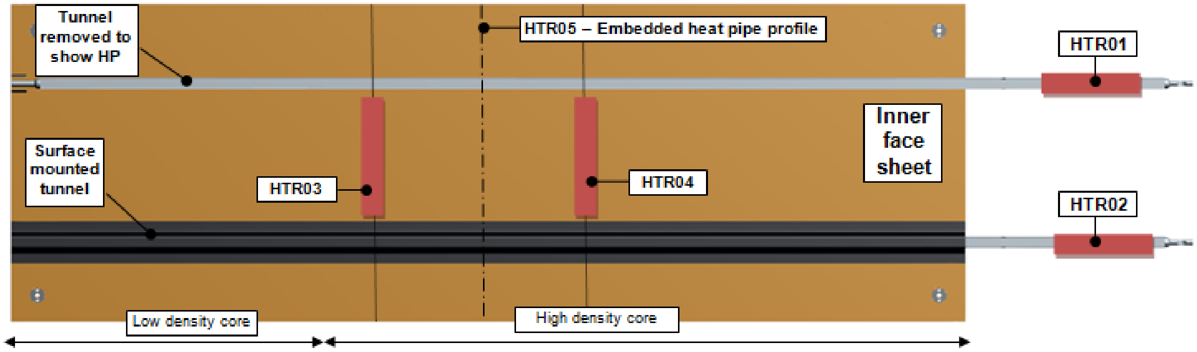


Figure 14: Test heater allocation

The following table (Figure 15) shows the temperature gradients of the internal and external facesheets as measured during the activation of HTR03 and HTR04. The outer facesheet shows a low temperature gradient (6K) on the outer facesheet within the embedded HP section, where in that case also the dissipation is applied.

BB		Measured temperatures [°C]		
Component		Average	Gradient	Max
Low density core	Outer face	-32.6	1.5	-32.0
	Inner face sheet	-30.7	0.9	-30.1
EHP section	Outer face	-20.7	5.6	-17.6
	Inner face sheet	-15.5	14.0	-8.2
High density core	Outer face	-31.2	2.8	-30.0
	Inner face sheet	-30.2	1.3	-29.6

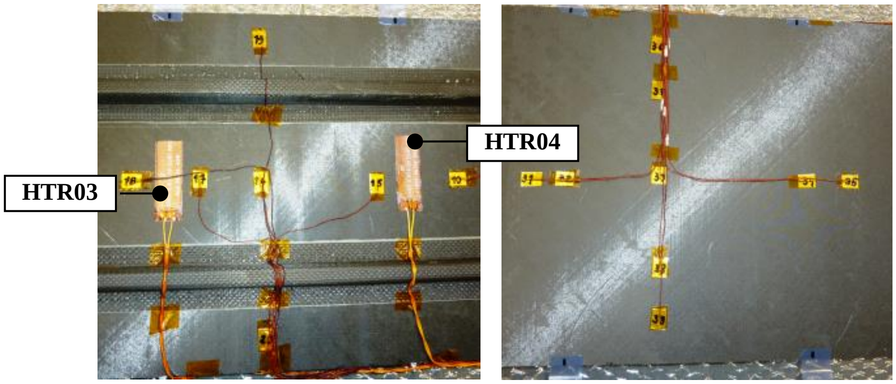


Figure 15: Temperature results and sensor/heater allocation of the EHP section (inner & outer facesheet)

The correlation of the conductance leads to contact conductance values of 250 - 300W/m²/K. Although, these values are less than expected the influence is less significant. Analyses showed that a contact conductance performance loss of 50% leads to reduction of heat radiation to deep space of less than 10%.

Outcomes of testing and integration

An insertion of heat pipes and springs guaranteeing undamaged filler materials is possible and has been performed successfully for both the 900mm long surface mounted heat pipes and the embedded heat pipes. In the frame of the breadboard test only filler foils have been used, but with the developed insertion method thermal filler pastes can be utilized also.

A facesheet thickness of 0.3mm is very fragile and the stability is limited. The breadboard shows a wavy surface (Figure 16) at the position of the embedded tunnels. The facesheet is not supported by a core in that area and can be deformed by hand easily. Also, during AIT the facesheets have to be handled carefully especially, where they are unsupported. Consequently, the contact pressure imposed by the wave springs is not enough to achieve the predicted values.

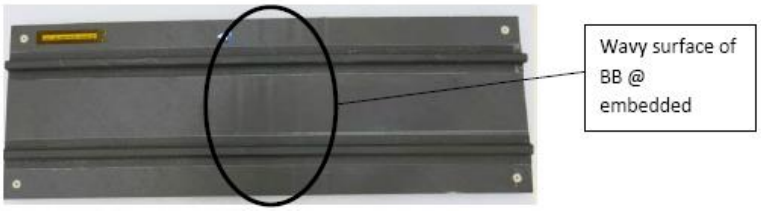


Figure 16: Breadboard with wavy facesheet

Outcomes of the thermal model correlation

The correlated contact conductance values are 6-7 times lower than predicted. The reasons are

- Lacking stiffness of unsupported facesheet (embedded HPs) and
- Consequently lacking contact pressure of wave springs

An option to improve the contact conductance is to increase the inner facesheet thickness to 0.6mm which has been investigated in the frame of the thermal analysis before. Apart from a slight mass increase this would stiffen the interface and additionally support the lateral heat transfer.

Though, the thermal performance is not only dependent on the achieved contact pressure of the heat pipes onto the facesheet but also the thermal characteristics of the panel have a significant impact. This has been shown with low temperature gradients on the outer facesheet in the embedded heat pipe section of <6K during the activation of HTR03 and HTR04 (Figure 13).

The thermal properties of the high density core (CRIII 1/4 5056 0.0015P 3.4) show advantages compared to the low density core especially close to dissipative components. Here the heat is conducted to the outer facesheet more effectively. Especially considering the high dissipation density on telecom panels the use of that core type is reasonable.

The comparison to an Aluminium reference panel (CRIII 3/8 5056 0.0015P, facesheet thickness 0.2mm) shows:

- The Low CTE heat pipe radiator provides less contact conductance between heat pipe and facesheet (CC_{LCHP}= 300W/m²/K; $CC_{ALRadiator}$ = 20000W/m²/K).
- The sandwich in-plane conductance of the Low CTE heat pipe radiator increases about 45%.
- The Low CTE heat pipe radiator has a comparable mass for the sandwich, but additional mass of about 0.2kg/m for tunnel, facesheet enforcement and spring have to be considered.

VI. Conclusion and Way Forward

During phase 1 of the study it has been achieved to work out a reliable method of integrating both embedded HPs and wave springs into the tunnels. A breadboard equipped with four working HPs has been thermally tested. The correlated contact conductance of the heat pipes is less than expected and predicted. Nevertheless a uniform and high average temperature was achieved on the outer facesheet of the heat pipe section.

Delamination issues of facesheets after manufacturing have been thoroughly investigated and solved. The production process of the panels is reliable. The unsupported facesheets show waviness at the position of the embedded tunnels. This easily leads to damages and also a lacking stiffness, which is needed to achieve a reasonable contact pressure between heat pipe and facesheet.

These two points define the way forward and work which has to be done in the next phase of the study. Phase 2 will be kicked-off with the improvement of the stiffness of the unsupported facesheets. Also the design of the chosen spring will be reconsidered. The findings will be firstly verified with smaller scaled samples, containing either one embedded heat pipe or one surface-mounted heat pipe. Once a reliable design is found a breadboard radiator with crossing heat pipes will be build and thermally (cycling and performance) and mechanically (vibration) tested.

As a great benefit, Airbus DS NL will join the study. The idea is to use their highly thermally conductive HiPer foil instead of costly pitch fibres (K13C6U).

Acknowledgments

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