IberEspacio
Growing for Space

PROJECT:	**Flat Loop Heat Pipe Evaporator based on AM Technologies**
CLIENT:	**ESA**

TITLE:

FLAT LOOP HEAT PIPE EVAPORATOR BASED ON ADVANCED MANUFACTURING TECHNOLOGIES

EXECUTIVE SUMMARY

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1. INTRODUCTION

1.1 SCOPE

This document presents the Executive Summary of the “Flat Loop Heat Pipe Evaporator based on Advanced Manufacturing Technologies” project. The objective of this document is to concisely summarize the findings of the contract.

1.2 ACRONYMS AND DEFINITIONS

Table 1-1 : Acronyms and Definitions

Acronym	Meaning
AD	Applicable Document
AM	Additive Manufacturing
BBM	Breadboard Model
CC	Compensation Chamber
HW	Hardware
IE	IberEspacio
LHP	Loop Heat Pipe
QM	Qualification Model
RD	Reference Document
SLM	Selective Laser Melting

2. DOCUMENTATION

2.1 REFERENCE DOCUMENTS

Table 2-1 : Reference documents

[RD]	Reference	Title	Issue
[RD1]	TEC-MTT/2015/3878/In/SL Appendix 1 to AO/1-8528/15/NL/KML	Statement of Work	1/2
[RD2]	ET065-O-001	Proposal for Flat LHP Evaporator Based on Advanced Manufacturing Technologies In answer to ITT AO/1-8528/15/NL/KML	1
[RD3]	ET065-TN-0001	AM literature and patent review	2
[RD4]	ET065-TN-0002	AM Flat LHP Evaporator Requirement	2
[RD5]	ET065-TN-0004	Material and Process Characterisation Test Report	1
[RD6]	ET065-TN-0005	Evaporator Preliminary Design and Coupons/Breadboards Test Plan	2
[RD7]	ET065-TN-0006	COUPONS AND BREADBOARD TEST REPORT	2
[RD8]	ET065-TN-0008	AM FLAT EVAPORATOR EM LHP MANUFACTURING PLAN	1
[RD9]	ET065-D-13300_20190426.stp	CAD design	1
[RD10]	ECSS-E-ST-32-10C Rev.1	Structural factors of safety for spaceflight hardware	1
[RD11]	ECSS-E-HB-32-23A	Threaded fasteners handbook	1
[RD12]	ET065-TN-0007	AM FLAT EVAPORATOR EM LHP DESIGN REPORT	2
[RD13]	ET065-TN-0009	AM FLAT EVAPORATOR EM LHP TEST PLAN	3
[RD14]	ET065-TN-0010	AM Flat LHP Evaporator EM LHP Test Procedures	2
[RD15]	ET065-TN-0011	AM FLAT EVAPORATOR EM LHP THERMAL TEST REPORT	1
[RD16]	ET065-TN-0012	AM FLAT LHP EVAPORATOR FINAL REVIEW AND PROPOSAL FOR FURTHER WORK	1

3. PROJECT DRIVERS AND OBJECTIVES

Loop Heat Pipes (LHPs) are two-phase devices employed for heat-dissipation purposes which, thanks to their capillary structure, transfer heat in micro-gravity or gravity environments for distances up to several meters.

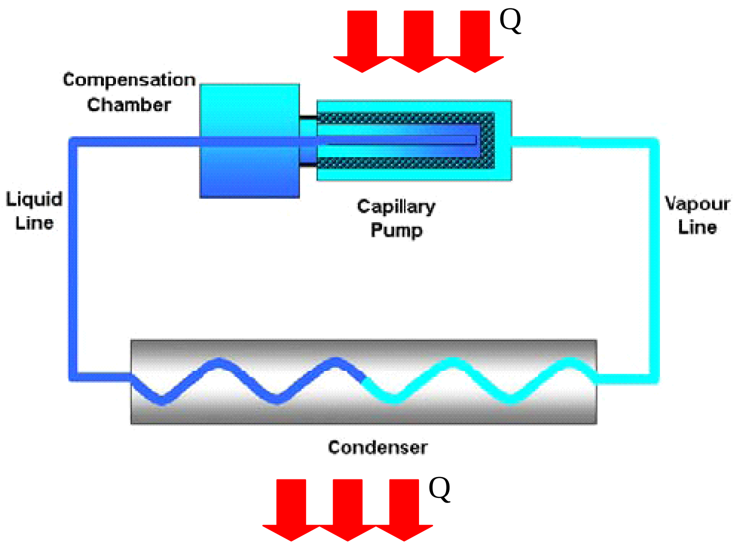

Figure 1: LHP scheme

The usual shape of an LHP evaporator is cylindrical, driven by the pressure-resistance requirement. However, the majority of the heat-releasing HW (e.g. electronic units) present a flat interface, which requires an adapter (i.e. saddle) that can negatively impact on the thermal performance of the LHP.

Project Driver 1: Remove interface adapters between LHP evaporators and heat-releasing HW in order to improve thermal performance.

Approach to Project Driver 1: Try to implement flat evaporators.

In the past, there had been attempts to manufacture a flat evaporator using conventional methods, however the results indicated that this approach was unfeasible. The recent developments in additive manufacturing have indicated an improvement in the potential options for manufacturing such flat evaporators using these new techniques.

Project Driver 2: Find feasible approaches for the manufacturing of flat evaporators.

Approach to Project Driver 2: Evaluate additive manufacturing processes.

The conjunction of both Project Driver 1 and 2 set the foundations for the objectives of this project, which can be summarised as follows:

Objective 1: Assess the feasibility of manufacturing a flat LHP evaporator by means of Additive Manufacturing processes.

Objective 2: Evaluate the additive manufacturing processes through tests such as material characterisation, compatibility, pressure cycles, welding, bubble point or capillary pumping

Objective 3: Perform a thermal test in order to evaluate the thermal performance of an LHP with a flat evaporator

Objective 4: Compare the performances of a flat evaporator with a qualified LHP employing a similar sintered material.

This report will set forth in the following lines the sequence of the different developments and activities that have been performed in order to accomplish the aforementioned objectives.

4. PARTNERS

The project has been executed by the three following companies:

Company Name	Type	Country	Role
Iberespacio	Prime	Spain	Lead the project with the experience of the company in thermal subsystems, including LHPs
FADA-CATEC	Subco Indirect	Spain	Additive manufacturing expert, providing consulting and manufacturing services
Thales Alenia Space Italia	Subco Indirect	Italy	Space prime, providing the satellite-level perspective in the project.

5. PROJECT RESULTS

The project was divided into two different and sequential phases: a) evaluation of the feasibility of the Additive Manufacturing Flat Loop Heat Pipe Evaporator and b) detailed design, manufacturing and performance test. Next sections describe each of these phases.

5.1 EVALUATION OF THE ADDITIVE MANUFACTURING FLAT LOOP HEAT PIPE EVAPORATOR FEASIBILITY

As the initial step in the evaluation of the feasibility of an Additive Manufacturing Flat Loop Heat Pipe Evaporator (AM Flat LHP Evaporator), Iberespacio and CATEC-FADA performed a review of the existing literature and relevant patents. The main conclusions of this review were as follows:

- Only a few works had been published about the additive manufacturing techniques applied to the manufacturing of two-phase heat transfer devices.
- Water and methanol are the most frequently working fluids in flat LHPs evaporators. However, a sufficiently low operating temperature (below 50 °C) is difficult to obtain with this approach.
- Cu or Cu-Ni alloys have been used for the envelope material and Ni or Cu for the wick, driven by material compatibility.
- Additive manufacturing and Select Laser Melting has proven to be suitable alternatives in the manufacturing process of thermal management HW.
- There were not any patents similar to IE's intended application.

The conclusion of this research completed Objective 1 as follows:

Satisfaction of Objective 1: The feasibility of manufacturing a flat LHP evaporator by means of additive manufacturing processes is confirmed. Thanks to it, Iberespacio proposes a preliminary design:

a. A stainless-steel miniature flat LHP evaporator
b. Dimensions: 80 mm x 50 mm x 8 mm and a heating spot area of 50 x 50 mm
c. Complemented by a set of requirements established by Thales Alenia Space Italia (also with the support of Iberespacio)

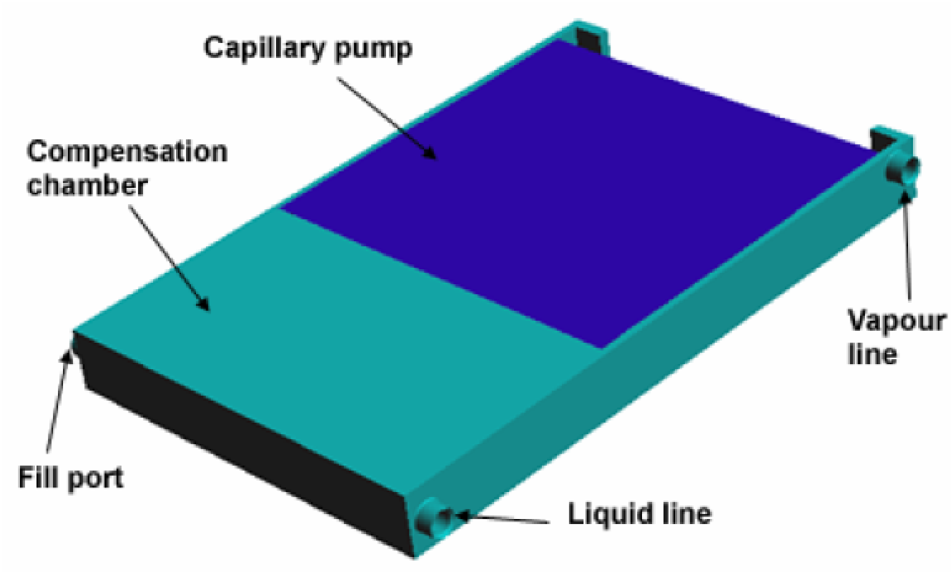

Figure 2: Preliminary Design

The next step was to look for a trade-off between the flat LHP evaporator concept, AM techniques, materials and the cleanliness techniques of porous materials in order to select the optimal manufacturing route. To this end, Iberespacio performed a material and process characterization campaign on Selective Laser Melting (SLM) applied on a set of Compensation Chamber (CC) samples (a chamber next to the evaporator which regulates the liquid quantity in the evaporating area) as well as on 3D-printed porous wicks samples made of stainless steel 316L. FADA-CATEC (Spain), partner in the project, manufactured SLM samples. This characterization campaign let the team conclude the following:

- The 3D-printing porous wicks give suitable properties to be used as a primary wick.
- The SLM CC samples have been successfully welded to the SLM caps with electron beam. This was a point of concern in this campaign. Several trials were required until the welding process, performed with Electron Beam Welding, was successful.
- The materials are compatible with ammonia and Non-Condensable Gases have not been generated. These gases could impair thermal performances.
- The flat evaporator case shows suitable mechanical resistance to inner pressure, fulfilling the leak, proof and burst requirements.

With these results, 3 similar Breadboard Models (BBMs) of the AM Flat LHP Evaporator were designed, manufactured and tested. The design consisted of a compensation chamber with star-cross and pillar lattice structure and a 3-evaporator case. Both parts were manufactured by SLM and joined by Electron Beam Welding. For the primary wick, 3Dprinting technology was used since, as concluded during the previous research, this technique has the capacity to manufacture porous materials with porosities higher than 40 % and diameter porous size smaller than 5 µm.

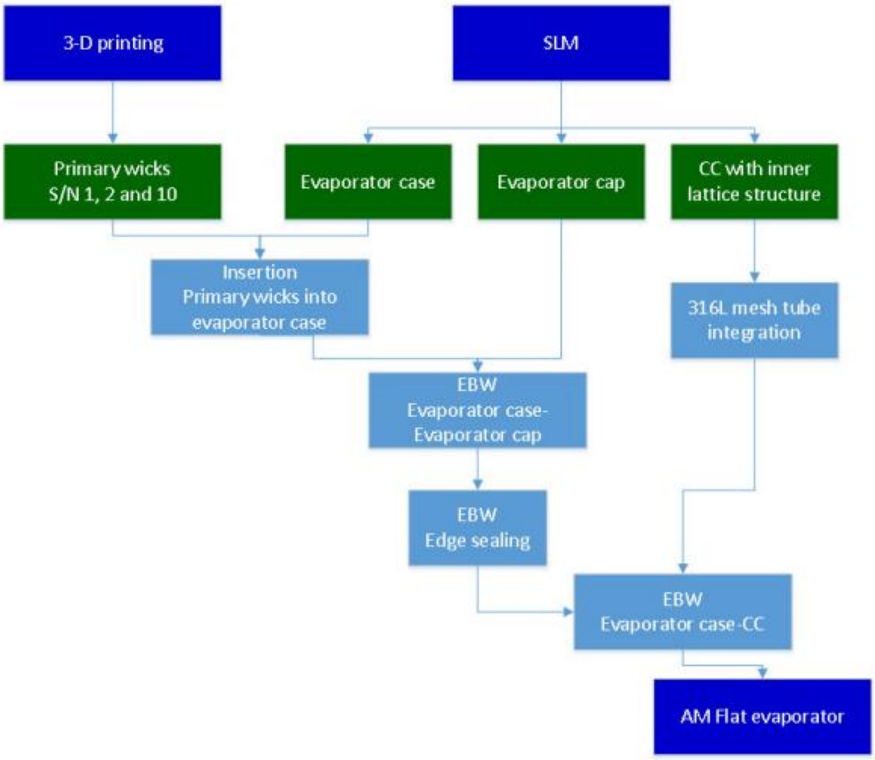

Figure 3: AM Flat LHP Evaporator - BBM Design

Figure 4: AM Flat LHP Evaporator - BBM

The results of the test campaign were promising since they showed that the capillary properties of the 3D-printing primary wicks could be used as a capillary pump for the LHPs in a real application. In addition, leak, proof and burst tests also provided successful results (for example, the burst test satisfied the requirement of 104 bar with a 100 % margin). Comparing the performance between the BBM of the AM Flat LHP Evaporator with the classical cylindrical evaporator, the team observed that the AM Flat LHP Evaporator BBM had a similar performances as the one of a classical evaporator (Figure 5). Even more promising was the fact that further improvements in the welding process between the evaporator and the CC could lead to higher thermal performances for the Flat Evaporator in future designs.

LHP conductance (W/K)_chiller 0ºC				
Evaporator	**10 W**	**20 W**	**40 W**	**60 W**
Cylindrical_with mass	0.3	0.7	1.5	2.5
ET065_without mass	0.3	0.6	1.5	2.6

Figure 5: Classical evaporator (*cylindrical_with mass*) vs AM Flat LHP Evaporator (*ET065_without mass*) conductance. *With mass* and *without mass* mean different configurations of the mass attached to the evaporator. This differentiation was made in order to obtain a fair comparison.

At this point, Objective 2 was fully satisfied:

> **Satisfaction of Objective 2:** Successfully evaluated the additive manufacturing processes through tests such as material characterisation, compatibility, pressure cycles, welding, bubble point and capillary pumping. The results indicate a promising design.

The satisfaction of this objective laid the foundations of the second phase of the project, where the detailed design, manufacturing and performance test were performed.

5.2 DETAILED DESIGN, MANUFACTURING AND PERFORMANCE TEST

The first step of this phase was the detailed design of the AM Flat LHP Evaporator based on the BBM results. The main improvement with respect to the BBM was the inclusion of two supports in the SLM CC in order to fulfil the mechanical requirements.

In order to verify the performances of the evaporator in different working conditions, the EM was designed in such a way that it allowed the testing of the LHP with and adverse elevation of 550 mm.

Finally, as an important step in the validation of the concept, the EM was mechanically analysed in proof and burst pressures as well as in sine and random levels, showing its capacity to stand the required levels. Once these aspects were verified, the EM was manufactured.

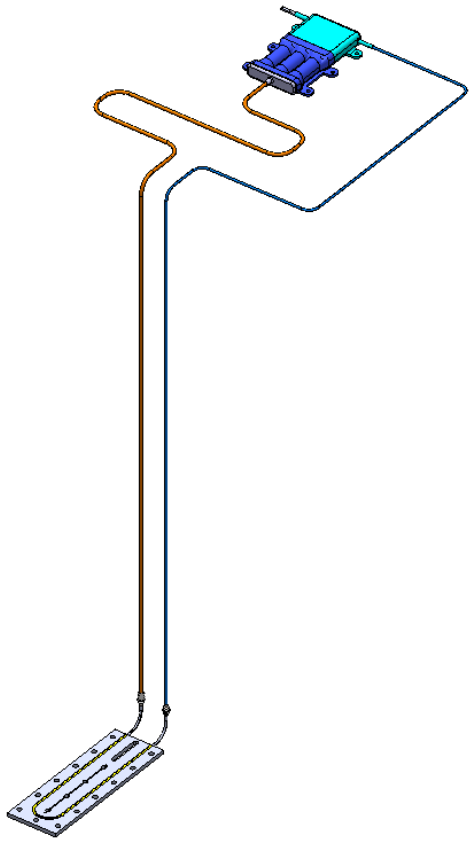

Figure 6: Adverse configuration

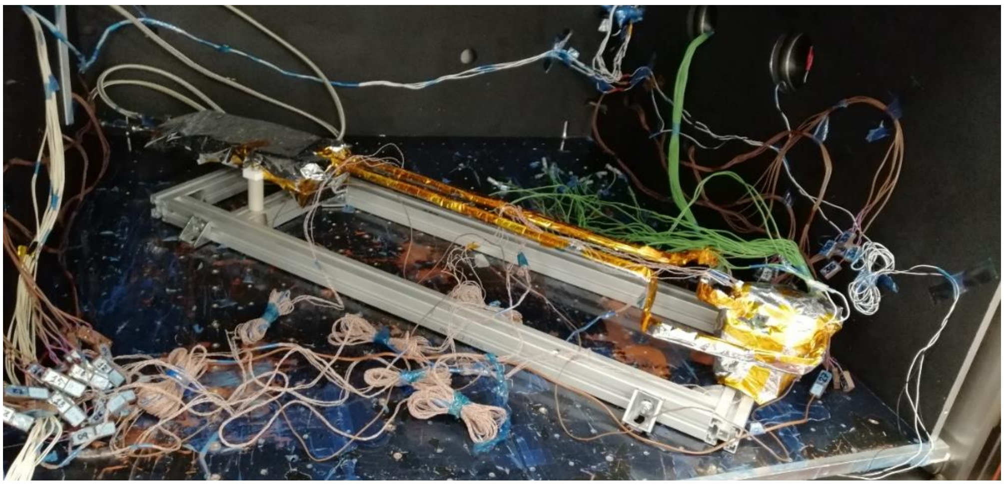

Figure 7: Picture of AM Flat LHP Evaporator EM test set-up for TVC tests

After the manufacturing inspection, the AM Flat LHP Evaporator EM was subject to a thermal test campaign. The test flow chart is shown in Figure 8. The main part of the test campaign was performed in a vacuum chamber.

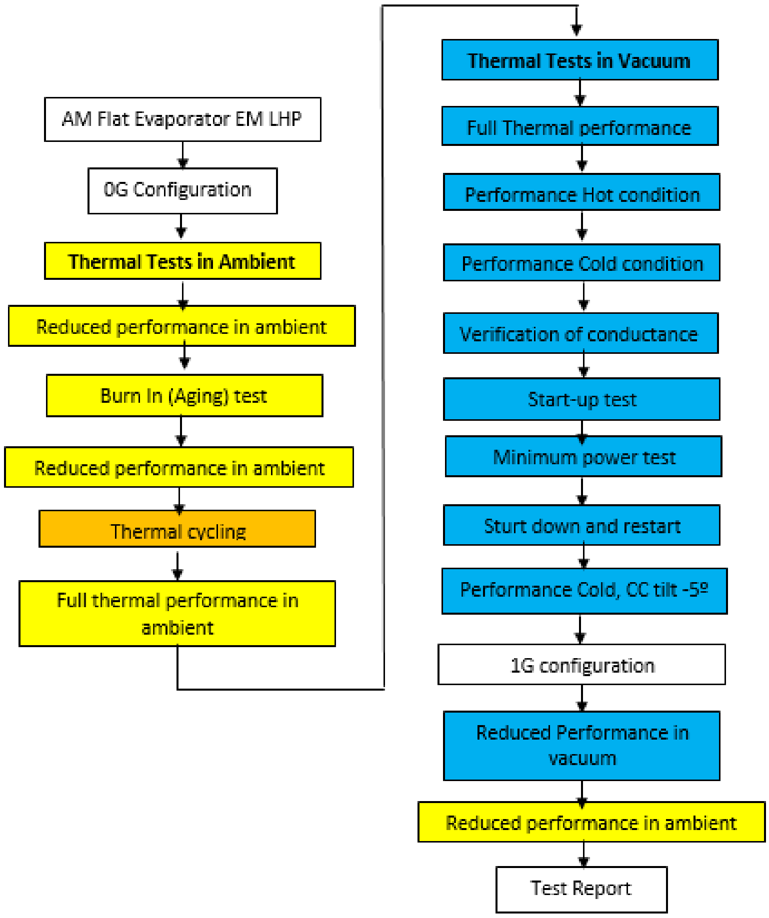

Figure 8: Test flow chart for the AM Flat LHP Evaporator

The results of this test campaign were the following:

1. The LHP sustained up to 236 W without dry out, what is significantly higher than the required 70 W.
2. The LHP starts up and operates stably in the required power ranges and conditions.
3. The LHP did not show deformation nor degradation after aging and thermal cycling tests.
4. The LHP was able to shut down and restart.
5. The LHP was able to sustain dynamic rapid changes of power within the required range of power (5 to 70 W).
6. Negative tilt of the compensation chamber does not lead to conductance degradation.
7. In the ambient and vacuum test, the comparison of total LHP conductance reveals that the AM Flat LHP Evaporator has advantage vs. a qualified LHP employing a similar sintered material.

Thus, the results of the test campaign let us achieve the last objectives of the project (Objectives 3 and 4):

Satisfaction of Objective 3: The thermal test campaign has successfully evaluated the thermal performance of the LHP with a flat evaporator, satisfying the expected results.

Satisfaction of Objective 4: The performances of the AM Flat LHP Evaporator has been compared with a qualified LHP employing a similar sintered material, showing better performances for the flat evaporator technology.

Thus, the second phase of the project was able to demonstrate how a flat LHP evaporator manufactured by AM processes cannot only be a feasible option but also can provide an improvement with respect to the current technology.

Based on the specification elaborated by the potential customer (Thales Alenia Space) and the results of the project, the next steps proposed in the AM Flat LHP Evaporator development process consist of:

- Consolidation of the Qualification Model (QM) specification .
- Design of an AM flat evaporator QM.
- Preparation of qualification test plan, set-up and procedures.
- Manufacturing of the QM.
- Conduction of the qualification test campaign.

6. CONCLUSIONS

This project has developed and tested a novel flat LHP evaporator configuration through a BBM and an EM, both manufactured using state-of-the-art additive manufacturing technologies. This novel configuration permits the removal of the saddle which is usually implemented as the interface between the conventional cylindrical evaporators and the flat heat-releasing HW. In the end, the elimination of such an interface redounds upon the thermal performance of the LHP, significantly improving its conductance.

Both the BBM and EM have been subject to extensive test campaigns aiming at the concept validation. The successful results of these campaigns prove that the AM Flat LHP Evaporator concept can be considered a promising alternative to conventional cylindrical evaporators.

The project team proposes as the next step in the development route the preparation and execution of a qualification test campaign. In parallel, Iberespacio suggests that further work is needed focused on the development and improvement of the additive manufacturing technologies in order to optimize the performance of the system.