MECOP – A Novel Two Phase Capillary Technology for the Thermal Control of Space Systems

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In the thermal control of space systems, two-phase fluid circuits based on capillary pumps, particularly Loop Heat Pipes (LHPs), are efficient and well-established devices. However, traditional LHPs have limitations that can hinder or even prevent their application in several applications: a. Heat is extracted in a localized manner through the small saddle of the evaporator, necessitating additional support from doublers or heat pipe banks, or requiring an increased number of LHPs; b. LHPs are typically delivered as pre-assembled, pre-charged, and sealed circuits, which can complicate integration into a spacecraft, particularly in cases involving to cross the pressurized shell of a space habitat; c. LHPs generally require a high degree of customization, leading to significant impacts on schedule and cost. The challenge that motivated the study outlined in this article was to develop a new two-phase capillary technology to overcome these limitations: being as compact, modular, and scalable as possible, enabling easy assembly and filling during the spacecraft system integration phase, including an evaporator capable of efficiently collecting heat from large or distributed areas, similar to a standard cold plate. The novel modular-LHP technologies proposed by Allatherm in recent years provided a foundation for pursuing these objectives through a comprehensive approach. A key element of the innovation is MECOP (Multievaporator Cold Plate), a multi-module evaporator designed for heat collection from extensive or multiple areas. This paper describes the development, technical details and verification of a modular LHP class featuring the MECOP evaporator. It also discusses its application in the thermal management of manned space infrastructures, demonstrating that the modular-LHP approach enables the effective and practical use of capillary heat loops to extract waste heat from a pressurized cabin. A review of the working fluids with long-term operation life with MECOP is given.

Acronyms and Nomenclature

A = Arrhenius factor

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ASHRAE = American Society of Heating, Refrigerating and Air Conditioning Engineers
ATCS = Active Thermal Control System
BB = Breadboard Model
CC = Compensation Chamber
CDRS = Carbon Dioxide Removal System
C_{lhp} = conductance of loop heat pipe
CP = Capillary Pump
dP/dT = slope of saturation pressure vs. temperature
E_a = molar activation energy
ECLSS = Environmental Control and Life Support System
EM = Engineering Model
ESPRIT = European System Providing Refueling Infrastructure and Telecommunications
ISS = International Space Station
$k(T)$ = reaction rate constant
LHP = Loop Heat Pipe
LL = Liquid Line
MECOP = Multievaporator Cold Plate
MECOS = Multievaporator Cold Sink
MDPS = Micrometeoroid and Debris Protection System
PDR = Preliminary Design Review
$\dot{Q}_{in}$ = net input heating power
R = universal gas constant
RM = Refueling Module
SMAC = Spacecraft Maximum Allowable Concentration
TCS = Thermal Control System
TCCS = Trace Contaminant Control Subassembly
$\bar{T}_{CD}$ = average temperature at condenser
$\bar{T}_{EV}$ = average temperature at evaporator interface
TL = Transport Line
TRL = Technology Readiness Level
TS = Thermosyphon
TVAC = Thermal Vacuum Chamber
VL = Vapor Line
WIT = Windows Interface Tunnel
Δt_e = experiment time duration (material compatibility test)
Δt_o = operation time duration
T = absolute temperature at which reaction occurs
T_e = experiment absolute temperature (material compatibility test)
T_o = operation absolute temperature

I. Introduction

THE new-generation space stations, both in cis-lunar environment and in Low Earth Orbit, have brought forth new requirements in the field of thermal control for pressurized space infrastructures. In the ISS, two classes of modules could be roughly distinguished: habitats, characterized by power dissipation levels in the order of 10 kW, the presence of an Environmental Control and Life Support System (ECLSS), and the possibility of utilizing resources from the station; and logistical modules, typically with power dissipations of a few hundred watts. While thermal management for the former had to rely on mechanically pumped fluid circuits, a purely passive approach was sufficient for the latter. The scenario appears different in the new missions: the wider tasks assigned to logistical modules lead to an increase in thermal dissipation of up to 0.5÷2 kW, operational flexibility is required, and thermal control autonomy is usually necessary.

An effective approach to addressing emerging challenges, particularly in applications where the level of power dissipation does not justify the complexity and costs of an Active Thermal Control System (ATCS), is the use of Loop Heat Pipes (LHPs). These systems are simple, passive, reliable, and capable of managing up to approximately 1 kW

per loop. Nevertheless, to the authors' knowledge, LHPs have never been used to transfer heat from inside a pressurized cabin to the external environment due to complications that, while generally affecting such devices, are particularly significant in this context.

Although two-phase fluid circuits based on capillary pumps are efficient and well-established for thermal control in space systems, traditional LHPs have, in fact, limitations that may hinder or even prevent their use in some cases:

a. LHPs are typically delivered as pre-assembled, pre-charged, and sealed circuits, which can complicate integration into a spacecraft, particularly in cases involving crossing the pressurized shell of a space habitat.

b. Heat is extracted in a localized manner through the small saddle of the evaporator, which necessitates additional support from doublers or heat pipe banks, or requires an increased number of LHPs.

c. LHPs generally require a high degree of customization, leading to significant impacts on schedule and cost.

d. LHP typical working fluids are not compatible with crew missions.

Examples do exist of LHPs implemented externally to pressurized modules, connecting the outer shell to radiators; however, this approach does not allow for the full potential of LHPs to be exploited in an effective design, due to the number of thermal interfaces and the inefficient heat-collection method.

Addressing these limitations could result in a significant improvement in the applicability of Loop Heat Pipes across a wide range of space missions. Above all, it represents an enabling factor for the efficient and straightforward use of these circuits on board orbital and planetary exploration infrastructure.

These premises have laid the foundation for a close collaboration between Thales Alenia Space Italia and Allatherm, which is developing an innovative concept for modular LHPs along with the necessary technologies for its implementation. The outcomes of this collaboration have led to the development of new thermal management architectures for efficient thermal control of pressurized modules, with the Modular Loop Heat Pipe technology as a cornerstone. The first planned application is the ESPRIT RM WIT module of the Gateway, having MECOP as the Thermal Control System baseline for the PDR.

II. Modular Loop Heat Pipes

Based on the limitations of traditional LHPs as argued in the introduction, the primary challenge that inspired the research discussed in this article was to create a new two-phase capillary technology being compact, modular, and scalable to facilitate straightforward assembly and filling during the spacecraft system integration process. Moreover, to obtain an evaporator that is able to effectively gather heat from large or dispersed areas, akin to a conventional cold plate. Finally, to identify crew-compatible fluids and characterize their performance. Modularity was pursued at both the evaporator and the overall LHP levels.

Problem of collecting spatially distributed heat is anything but new in two-phase heat transfer system design. In practical design, some sort of auxiliary means, such as pulsating heat pipe[1] or axially grooved heat pipe[2] are used to concentrate heat to a single LHP evaporator, that can then transfer heat to a remote condenser. Extra thermal interfaces on the way to condenser and limited heat transfer capability of heat pipes are the drawbacks for such systems. LHP with a large size flat evaporator, 190×190 mm, was made and tested to transfer 140W of power[3]. However, such systems tend to rely on evaporator that is held horizontally in gravity field, so that the space above (where the liquid is coming from) works as CC. Another approach is to create multievaporator LHP. Heat loops with several distributed evaporators were researched for at least the last 30 years[4], a review[5] on the subject lists various attempts to create stable systems. Two evaporators and two condensers[6] is one of the most well studied configurations. The instability of multiple LHP evaporators connected in parallel was tackled with flow regulators at condenser exits, or thermoelectric modules on CCs for setpoint control. In a few cases, two, three[7] or four[8,9] evaporators were combined and connected to a single condenser.

A more holistic approach to the development of multievaporator LHPs has been adopted by Allatherm in collaboration with Thales Alenia Space Italia. The task has shifted towards creating a basic modular element that, when assembled in various quantities and configurations, would form a multievaporator component, tailored for LHP applications. The advantage of such paradigm is a fixed building block with optimized and settled manufacturing processes and quality assurance for the core element: CP consisting of the primary wick, envelope, vapor port and the end caps. Designing such a building block with the highest possible performance capabilities is crucial for widest possible applicability of multievaporator assemblies. Such element was designed in Allatherm under the name Altom, see Figure 1. Altom(14), Altom(10), Altom(7) are CPs of three different characteristic diameters, having the outer diameter of the wick of 14 mm, 10 mm and 7 mm respectively.

The use of strong and inert stainless steel or copper body makes Altom compatible with a wide range of working fluids, both in terms of chemical compatibility and ability to withstand the high pressure specific to high-performance

fluids like ammonia. A distinct feature of the Altom is side vapor outlet, making serial connection of them possible, which is described in the patent[10]. Same CPs could be also connected in parallel, which is reflected in article[11] and patent[12]. Hydraulic and capillary linkage is provided by manifolds, which are essentially the only parts that need update in technical drawings from one configuration to another one, as CCs also become a part of modularity. A suitable size can be chosen from manufacturability point of view or available space envelope and multiplied to reach the necessary volume.

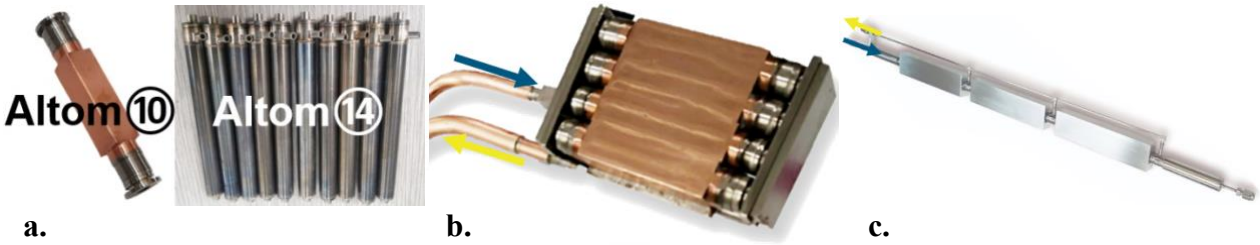
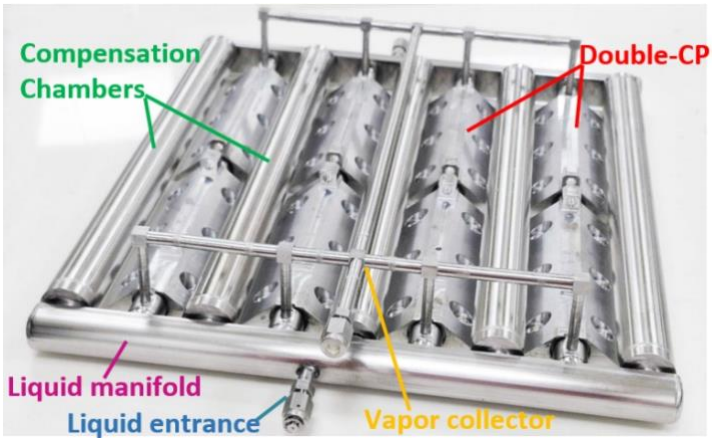


Figure 1. Altom – building block of modular evaporator (a), assembled in parallel (b) and in series (c).

In the frame of projects funded by the European Space Agency, the next step forward was made with the development of a modular LHP evaporator comprising a grid of interconnected CPs and CCs. The device was named Multievaporator Cold Plate (MECOP) because it was designed to collect heat from large flat surfaces, like a conventional Cold Plate. MECOP has gone through extensive testing at breadboard and engineering model levels, currently being at TRL6.

MECOP EM[1314] has 250 × 250 mm² flat heat collection area with 4 lines of double CPs soldered into prismatic-shape aluminum saddles (see Figure 2). 5 CCs with the total volume of 0.45 liters are arranged compactly in-between the CPs. The number of CPs and CCs can be tailored to a specific application without redoing structural analysis. The pressurized part is made of AISI 316L stainless steel, both the body and wicks (primary and secondary). In the manufactured configuration (with 5 CCs), up to 12m long transport lines can be used with a high-performance refrigerant such as ammonia and 6-8m with less performant refrigerants, depending on the heat load and its temperature limits.



Material: AISI 316L, AW6082-T6 saddles
Wicks: AISI 316L, R=1µm pores, 47% porosity
Heat collection area: 250×250 mm
Interface surface finish: Ra<0.8µm
Footprint: 300×350 mm
CC volume: 0.45L
Mass: 3.9 kg



Figure 2. MECOP EM with key parts and characteristics.

While modularity at the evaporator level provides the advantages described so far (particularly the capability to extract heat from extended surfaces), modularity at overall LHP level is the key factor that enables practical and efficient usage of such devices in the thermal management of pressurized infrastructures. The concept of basing the LHP design on standard building blocks available in stock, utilizing quick VCR fluid connections (sealed before flight in case of

long missions), and developing a portable charging station make it feasible and easy to assemble the MECOP heat loop by parts and charge it with the working fluid at the spacecraft integration site.

III. MECOP Working Fluids

Ammonia (R717 per ASHRAE classification) is the "go-to" working fluid for most two-phase heat transfer systems, unless there are restrictions on use of this high-pressure, toxic and flammable fluid. For that, all pressure-bearing parts of MECOP are designed to withstand ammonia vapor pressure up to 70°C (33 bar) with proof factor of 1.5, although MECOP was routinely tested to 62 bar pressure (which corresponds to 80°C ammonia pressure with factor of 1.5).

For TCS of pressurized modules with crew onboard, the leak failure mode of any LHP-based system is reviewed from multiple points of view:

- Continuation of thermal control function (solved by system redundancy – multiple LHPs per heat load)
- Toxicity of fluid at concentration of full LHP discharge being dispersed within the cabin atmosphere
- Flammability of fluid at this concentration
- Fluid compatibility with ECLSS, primarily with the equipment for tracing and removal of contaminants

Thus, in addition to ranking known refrigerants by their thermophysical properties (saturation pressure, dP/dT, vapor and liquid figure of merit, freezing point and critical temperature), ISO 817 refrigerant classification scheme by toxicity and flammability comes to help for initial screening, which must also consider refrigerant legislative status affected by its global warming potential and ozone depletion potential.

With the goals set, a deep assessment of the nominally safe (nonflammable, low toxicity) R1233zd(E) refrigerant showed its lower thermal performance and higher (although low) toxicity w.r.t. other candidates. Thermophysically similar high-pressure refrigerants such as R134a and R152a (respectively, 21 and 19 bar vapor pressure at 70°C), safe even from medical point of view (used as medical propellants for inhalation), have other drawbacks: R134a requires a high energy demand for production and R152a is flammable. Furthermore, both of them belong to hydrofluorocarbon class of chemical substances that might potentially damage currently used ECLSS equipment.

Table 1. Working fluids in MECOP EM development.

Fluid	R717	R600	R1233zd(E)	R152a	R134a
Safety Class	B2L	A3	A1	A2	A1
Surf. tension at **20**°C, mN/m	21	12	15	10	9
Liq. density at **20**°C, g/cm^3	0.77	0.57	1.28	0.91	1.23
Boiling temp., °C	-33.3	-1.0	18.5	-23.9	-25.9
Pressure at 7**0**°C, bar	33.0	8.2	5.1	18.8	21.1
Material compatibility test	✓	✓	✓	✓	✓
MECOP BM tests	✓	✓	✓		
MECOP EM tests	✓	✓			✓

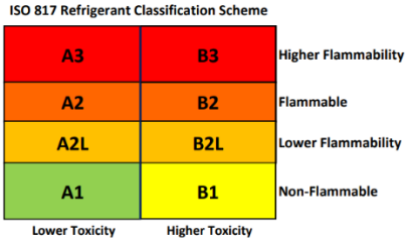


Figure 3. Refrigerant safety classes.

R600, n-butane fluid, has advantageous thermophysical properties for use in two phase heat loops with long transport lines (high surface tension and dP/dT characteristic). It is a simple, nonhalogenated alkane, without implications for ECLSS or for the crew, except that with large volume of leaked butane its concentration might exceed Spacecraft Maximum Allowable Concentration (SMAC) of 1600 ppm (assessed as 10% of butane lower explosive limit of 1.6%). The calculation for such assessment should consider the LHP charge, the cabin volume and the leak rate. The physiological leak is so small that it is fully neutralized by the ECLSS before concentration exceeds SMAC. A gross leak from a LHP into the cabin can only be associated with unexpected incidents involving the internal part of the loop, for example a kick from astronauts. The loop is a welded stainless-steel circuit subjected to qualification and acceptance based on ECSS standards for pressurized vessels. Damages from incidental loads can be prevented by proper mechanical sizing and by implementing dedicated protection.

Among safe refrigerants, butane is prominent for high performance characteristics in combination with low vapor pressure of 8 bar at 70°C and 10 bar at 80°C, for which MECOP design has proof factor of 5-6, further decreasing the probability of failure.

Spacecraft LHP must operate maintenance-free, with a typically required service time of 15 years. Over such a long period, working fluids might decompose and release non-condensable gas, which is result of elevated temperature and fluid contact with LHP metallic components (that may react or act as catalyst for decomposition). To assess this negative effect, material compatibility test is performed, which is accelerated by use of higher temperature in test than when LHP is in service on orbit. Projection of accelerated test results onto temperature range of interest is done with help of the Arrhenius equation:

$$k(T) = A \cdot e^{-\frac{E_a}{R \cdot T}} \tag{1}$$

where k is the rate constant, T is the absolute temperature, A is Arrhenius factor, E_a is the molar activation energy for the reaction (here: decomposition reaction), $R = 8.314 \frac{\mathrm{J}}{\mathrm{mol \cdot K}}$. For most gases[15] the activation energy lies in the range of 200 to 300 kJ. These values correspond to pyrolysis reaction and seem to be overestimated, while in practice fluid decomposition can be accelerated from catalytic effect of metallic alloys, especially containing nickel and chromium. For example, platinum alloys[16] lower activation energy of dehydrogenation of n-butane: pure platinum gives 100.5kJ/mol while PtSn alloy gives 63.14 kJ/mol. Another publication[17] considered thermal stability and decomposition behavior of R1234ze(E), where 105kJ/mol was the value obtained for the activation energy of decomposition reactions. Therefore, $E_a = 100$ kJ/mol is a conservative estimate for accelerated material compatibility tests. From the definition of chemical reaction rates, the amount of gas formed is proportional to the reaction rate and time duration, i.e. $\propto k(T) \cdot \Delta t$. Then, one can relate operation on orbit for time Δt_o at temperature T_o to operation in test experiment for time Δt_e at temperature T_e by:

$$\Delta t_e = \Delta t_o \cdot \exp\left(-\frac{E_a}{R}\left(\frac{1}{T_o} - \frac{1}{T_e}\right)\right) \tag{2}$$

Material compatibility thermosyphons (see Figure 4, a), manufactured with all key components of MECOP, such as AISI 316L envelope and porous wick, were charged with R717, R600, R134a, R152a and R1233zd(E) and set to operation at constant heat source temperature. At the time of writing, 22 months have passed with all the fluids except R1233zd(E) showing flawless operation. R1233zd(E) did show signs of non-condensable gas formation after one year of test, but, because of high test temperature (135°C setpoint), this corresponds to hundreds of years at 70°C (by Arrhenius equation). R152a and R134a require almost 10 years to prove their stability for 15 years at 70°C, but 15 years threshold at 60°C is passed, for the rest of the fluids 15 years operation at 70°C is granted.

As it is explained in section IV, MECOP design is well optimized and tested for operation with R717 (ammonia), suitable for uncrewed use scenario or for application outside the pressurized module, and for refrigerants like R1233zd(E), R134a and R600 (n-butane), among which butane is an all-around viable choice for crewed use cases.

IV. MECOP EM Test Campaign

The very versatile nature of MECOP posed a challenge for testing from the very beginning. The breadboard stage demonstrated operation with R717, R600 and R1233zd(E) using 2m lines with MECOP both in ambient and in vacuum. The timeframe for the engineering model coincided with the preliminary planning of the TCS for the Gateway ESPRIT WIT module. So, the test campaign evolved to provide the data for the system-level assessment of MECOP technology, while adhering to the qualification test sequence of capillary driven loops according to the ECSS-E-ST-31-02C standard.

The EM test campaign used two manufactured MECOP units, EM1 for functional performance testing and EM2 for mechanical tests. For the EM, the anticipated transport line length was increased to reach more than 10 m (to cope with the reference applications), which was demonstrated in a dedicated test setup with a throttle valve installed in a short vapor line and applying representative hydraulic resistance controlled by pressure differential measurement. In one of the settings, butane-charged MECOP LHP transferred 500 W with a 60 mbar pressure drop on the vapor line, which is equivalent to an 18 m long vapor line of 6mm inner diameter.

Table 2. Test campaign of MECOP EM development.

Tests performed	TS	EM1	EM2
Proof test	✓	✓	✓
Leak test	✓	✓	✓
Material compatibility test	✓		
Full thermal performance test		✓	
Reduced thermal performance test			✓
Pressure cycle test			✓
Mechanical test			✓
Lifetime test		✓	

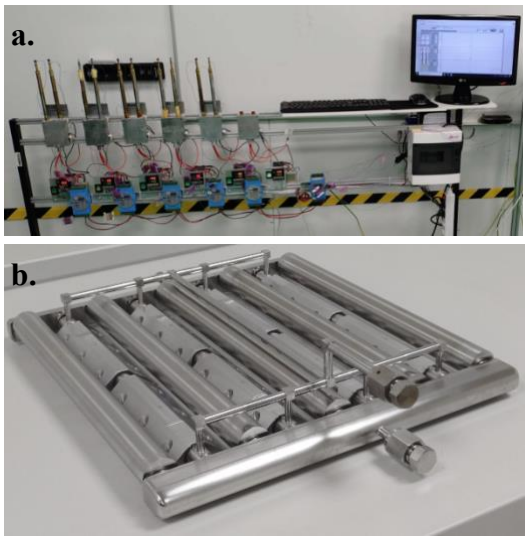


Figure 4. Compatibility thermosyphons (a), MECOP EM2 – structural model (b).

For the medium transport line length scenario, MECOP LHP was assembled with 6 m transport lines, for which the MECOP CC volume was sufficient even with rather large inner diameters of 8 mm for the vapor line and 4 mm for the liquid line. Such length of lines is sufficient for routing from the inside of a medium-sized pressurized module to the surface mounted external radiators.

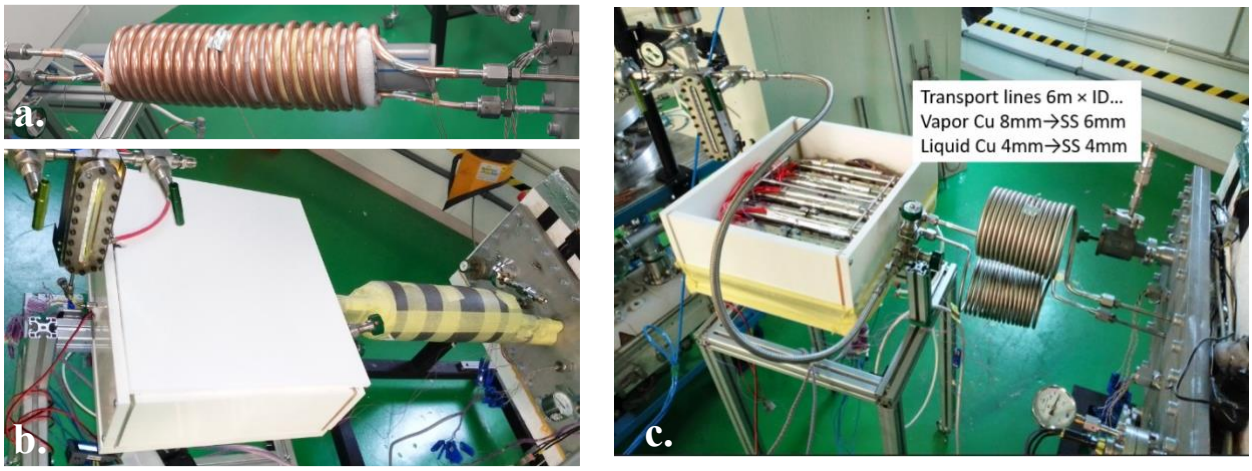


Figure 5. Test setup: with wide copper lines and narrow stainless-steel lines.

Various condensers were used for the characterization tests. Helium atmosphere in chiller-cooled chamber provided controllable heat rejection settings with natural convection. Forced convection was used as well. The radiator size was limited by the space available in the TVAC chamber, 500×700 mm, while typical spacecraft radiators take larger areas, to be covered with the fluid line. The problem was solved by designing a compact condenser, with 5m × 5mm inner diameter serpentine line. The latter configuration, shown in Figure 6, was compatible with the MECOP EM1 and EM2, charged with R600.

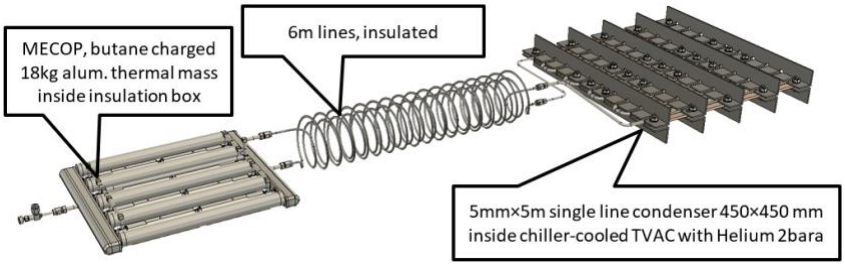


Figure 6. MECOP EM LHP setup with 6 m transport lines and 5 m line condenser.

The working fluids used on EM1 included R717, R600 and R134a. Change from one liquid to another showed that the heat leak from CPs into CCs could have vastly different characteristics depending on the working fluid properties, which is most profound during LHP transient operation. The heat leak in LHP is a two-phase heat and mass exchange, which requires a dedicated hydraulic circuit within the evaporator part of the heat loop. MECOP modular design allows to tailor the heat leak circuit of the standard CPs in the final stage before MECOP manifolds closure. The result of this tailoring is that MECOP LHP has nearly identical performance in the thermal test regardless of being charged with ammonia or with butane[14], like it is demonstrated in Figure 7. The tests included severe scenarios like successfully passing through rapid changes of the heat load from 100-150 W to 500 W and changing the heat sink temperature by switching from natural to forced convection (not typical for space radiators, but a severe cold shock test for LHP on ground). With forced convection, both fluids could transfer more than 700 W of power, which unfortunately was limited by condenser efficiency and heater limit.

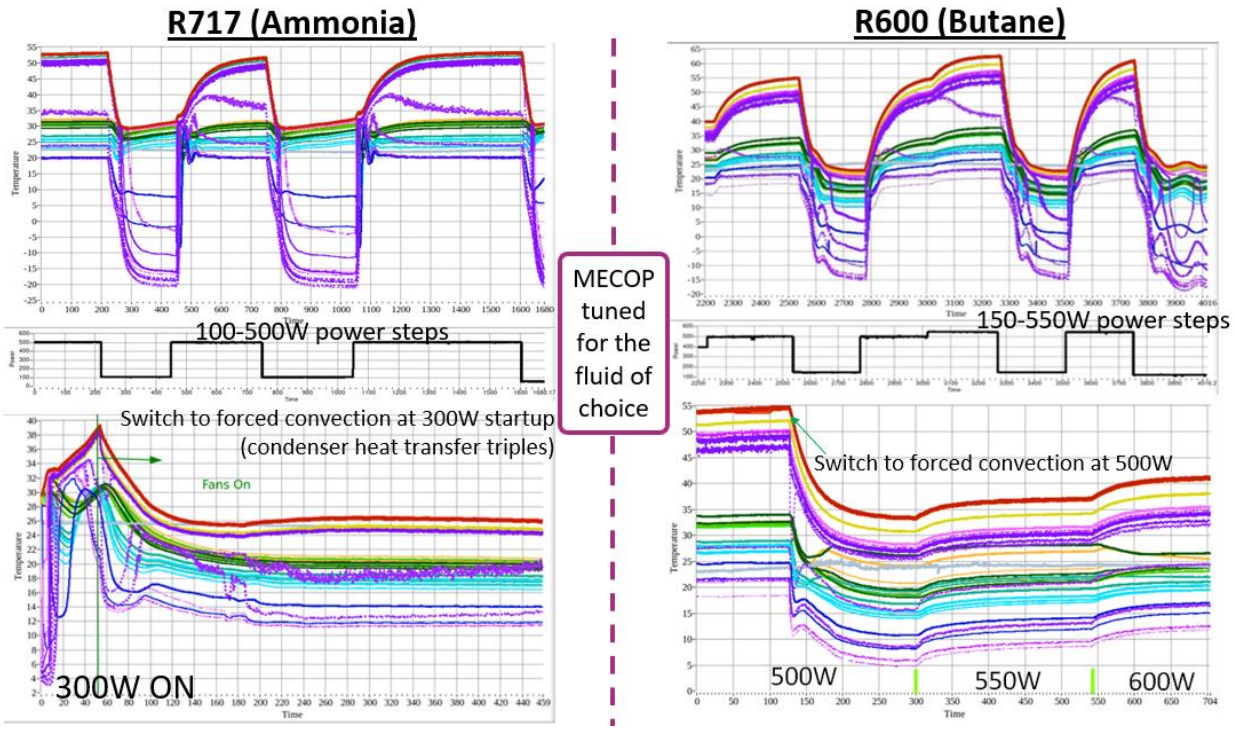


Figure 7. Transient shock cases of MECOP operation with R717 and R600.

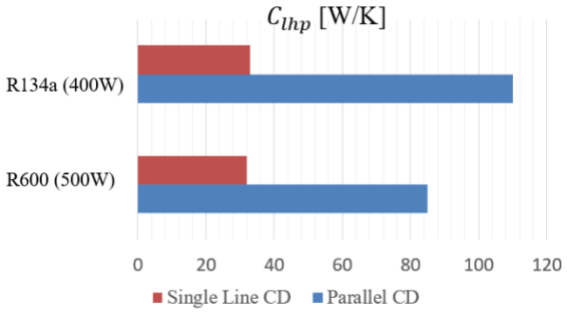


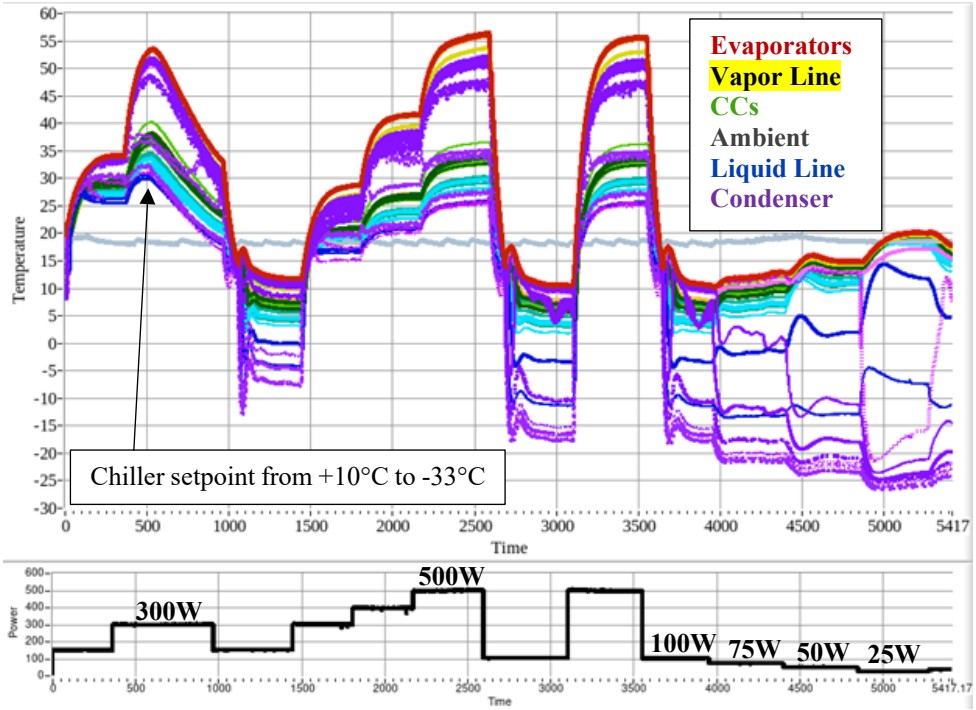
Figure 8. Crew-compatible working fluids and performance figures.

It is valuable to compare two refrigerants with potential for use in pressurized modules with crew onboard – R134a and R600. R134a, high-pressure and high-density refrigerant, could deliver higher overall heat loop conductance[13] (see Figure 8), defined as

$$C_{lhp} = \frac{Q_{in}}{\bar{T}_{EV} - \bar{T}_{CD}} \quad (3)$$

where $\dot{Q}_{in}$ is the net heating power and $\bar{T}_{EV}$ and $\bar{T}_{CD}$ are the average temperature at the MECOP interface (under saddles) and average condenser temperature, respectively. At the same time, the lower surface tension of R134a (which rapidly decreases with temperature) has limited the maximum transferred power in the given setup. R600, on the other hand, did not suffer from such limitation.

MECOP EM2, the structural model, has passed all the mechanical tests, including pressure cycling and vibration testing. The verification performance testing was done with R600 charge, 6 m lines and 5 m condenser. The performance closely matched the performance of EM1.



MECOP EM2
R600 fluid
VL 6m × 6mm
LL 6m × 4mm
5m-line condenser
natural convection
in helium

Figure 9. MECOP EM2 after all mechanical tests, operation with high and low heat load.

V. MECOP LHP Performance Modelling

Altom-LHP - the thermo-hydraulic mathematical model for MECOP LHPs was developed by Allatherm and implemented as a stand-alone software package with a graphical user interface (Figure 10, a) and the following features:

- The properties of the working fluids are stored in tabular form in the stand-alone text-files, allowing for easy expansion of the range of supported working fluids. This flexibility enables users to incorporate new working fluid options simply by adding a file containing the relevant thermophysical properties. These properties can be imported from established databases, such as NIST.
- Although the basic calculation mechanism of the model is based on a one-dimensional representation of the LHP, the program provides the possibility to configure the MECOP by connecting individual CPs into a single system with a common vapor manifold (Figure 10, b). The size of the MECOP is also taken into account when calculating its convective and radiative heat exchange with the environment. Another deviation from one-dimensionality is realized when calculating the condenser. The condenser is represented as a plate of specified thickness, with an embedded serpentine fluidic channel on its surface. The computational process for the condenser is performed iteratively. At each step, the model adjusts both the fluid distribution within the channel and the temperature field across the plate surface until the discrepancy between iterations falls below a specified accuracy threshold.
- The condenser modeling can be of independent interest, beyond its integration into the LHP. Therefore, the program includes the capability to simulate the condenser as a standalone device, without requiring full system integration. The program automatically determines the optimal placement of the S-channel on the condenser plate for a given plate size. Additionally, it supports dual S-channel condenser configurations, allowing for more complex thermal management scenarios. The model also accounts for the subcooling zone. For enhanced analysis, the program includes a visualization feature that generates a

temperature field map of the plate surface, providing a detailed graphical representation of heat distribution across the condenser (Figure 11).

Configuration of composite transport lines as sequential connection of tubes of different diameters. For each element it is possible to set the thickness and thermal conductivity of the wall, thus modeling the TL thermal insulation.

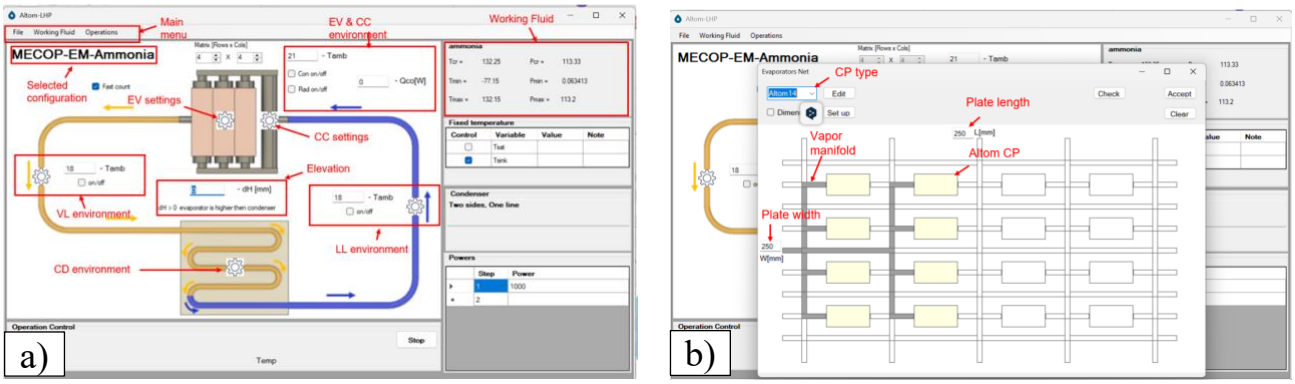


Figure 10. a) Altom-LHP software user interface (main settings window) and b) MECOP configuration window.

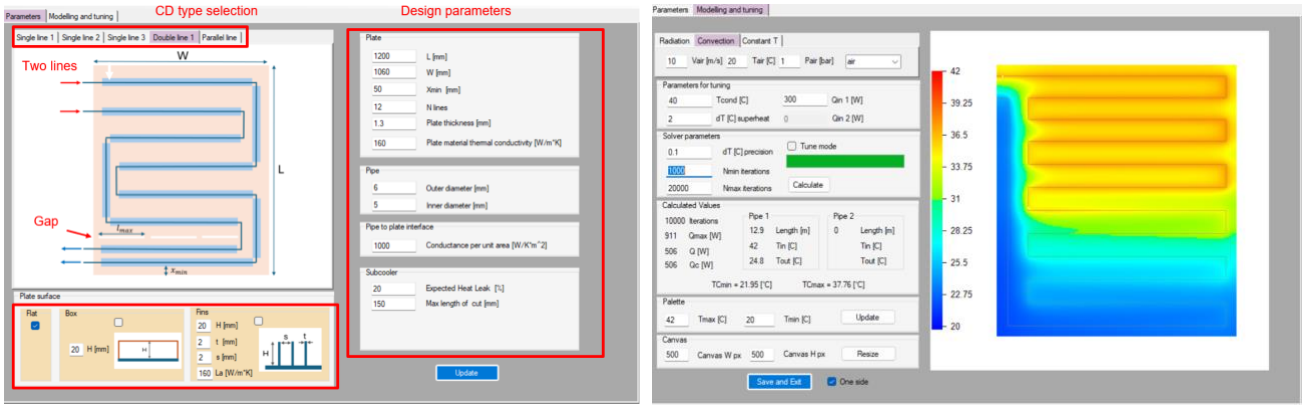


Figure 11. Altom-LHP Condenser Set-up and results of condenser modeling.

Software uses both analytical and empirical correlations for calculation on the hydraulics and heat exchange of MECOP-based two-phase heat loop. MECOP building blocks (Altom CPs) can be assembled in different layouts. For system engineers, Altom-LHP provides graphical and tabular export of calculation results (steady state, EV, CD, LHP conductance values and others).

As can be seen from the MECOP LHP test results presented in the previous section, the stabilization of the LHP can extend to several hours (Figure 9). This behavior is primarily attributed to the large thermal mass of MECOP and the significant volume of working fluid circulating in the loop. Given the potential application of the device in systems with multiple heat sources and inherently variable heat release, it is reasonable to expect that, in practical scenarios, the MECOP LHP will operate in a transient mode for most of its runtime. This highlights the importance of modeling stabilization processes and transitions between different non-stationary states. To address this, the program incorporates a transient simulation model, which is fine tuned currently for fast and accurate calculation. The core of this model focuses on the stabilization of heat and mass exchange processes within the compensation chambers, accounting for a variety of influencing factors such as heat exchange with bayonets, the core of capillary pumps and the environment. Figure 12 presents an example of the performance (power ramping) test simulation, illustrating the LHP transient response and stabilization dynamics.

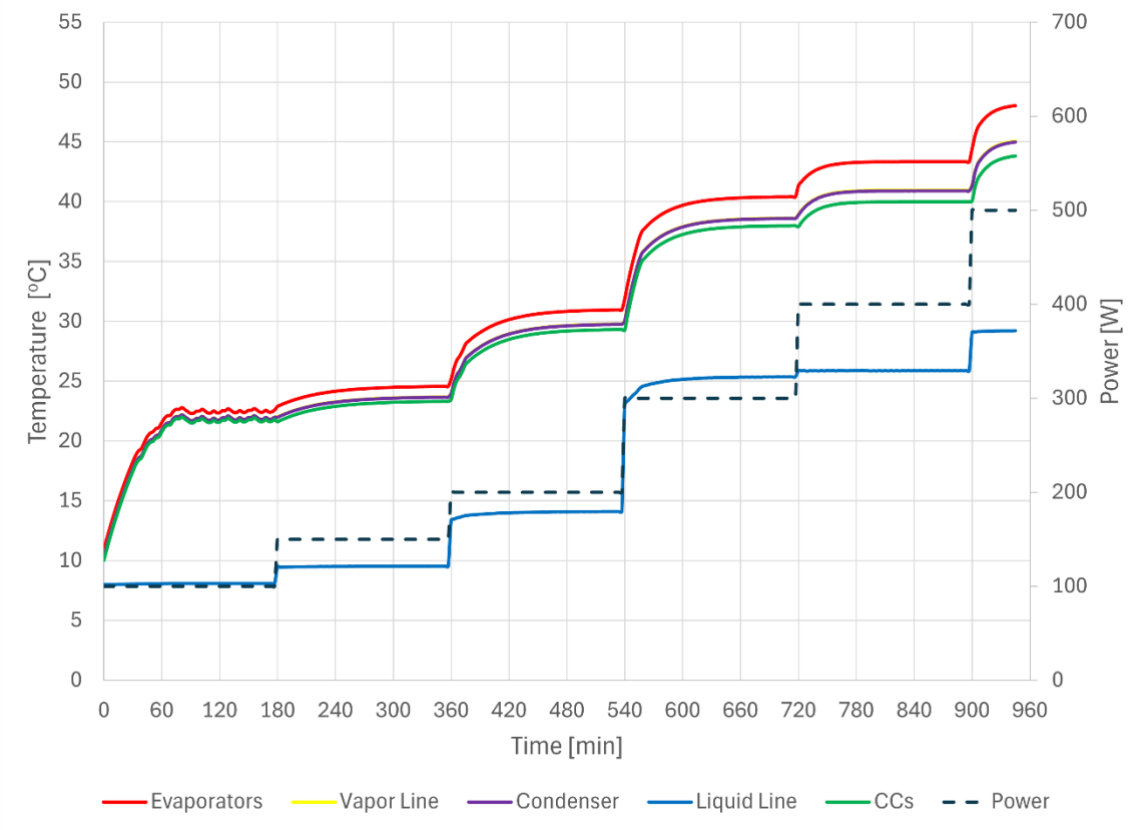


Figure 12. Modelling of MECOP LHP transient behavior.

VI. Versatility for System Level TCS Modularity

Benefits of MECOP system modularity go beyond the specific objectives of current R&D activities and are associated with every LHP delivery. On a single MECOP heat loop level, these benefits are:

- Single time full qualification of manufacturing processes and the product
- Manufacturing of a particular LHP is done from batch manufactured and stocked Altom CPs, which reduces the lead time
- Modularity means scalability of evaporator part to different workspace, heat collection area and total heat load, as long as structural design requirements do not exceed those used for qualification
- The custom system design is supported by Thermal Mathematical Model (TMM) that uses fluid properties, MECOP configuration (grid connection of CPs and CCs) and thermal exchange in every part of the heat loop, reducing the number of real performance tests required.
- MECOP heat loop can be assembled by parts at the spacecraft integration site and charged with Allatherm-developed infrastructure, which simplifies logistics and integration
- A single MECOP LHP can solve tasks that normally require multiple LHPs.

Thus, MECOP heat loops working on butane can be used, safely and reliably, for large and small heat loads within the pressurized spacecraft. Examples of suitable heat loads are electronic boxes, heavy duty electric drives or rechargeable batteries, or even the air in the cabin, provided that MECOP is equipped with an air heat exchanger of sufficient capacity. The latter configuration is currently being developed with MECOP saddles equipped with fins, yielding the Multievaporator Cold Sink (MECOS).

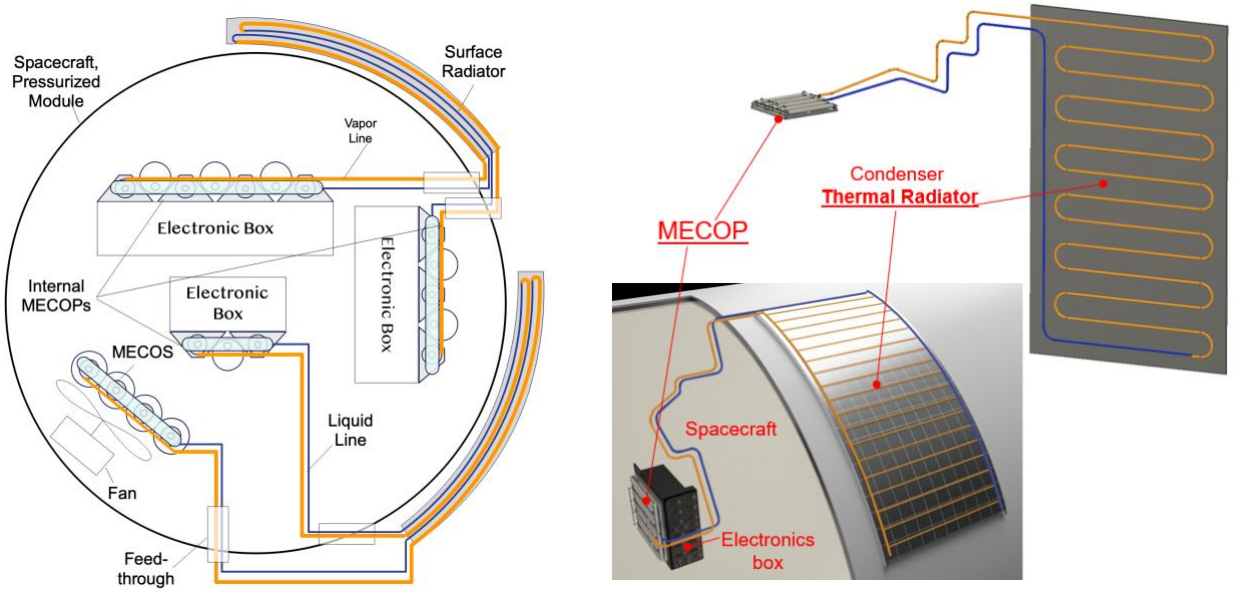


Figure 13. MECOP/COS-based TCS for spacecraft module: schematic (left) and render image (right).

Figure 14 deals with a single-loop two-phase heat transfer system. However, different architectures can be supported by the MECOP/MECOS solutions. On the ISS pressurized modules, a cascade mechanically-pumped system is used, with an internal single-phase loop running on water and an outer loop with ammonia, absorbing heat from water in a dedicated heat exchanger and delivering it to large-area radiators. Similar approach, but with passive capillary driven loops, could be realized with MECOP technology, see Figure 15. The external loop can use ammonia as a high performant refrigerant to deliver heat to a large, potentially remote radiator. This way, MECOP modularity is taken to a system level, thanks to MECOP compatibility with different working fluids, performing on a vastly different scale. Such configuration can manage tens of kilowatts and be a serious alternative to ATCS.

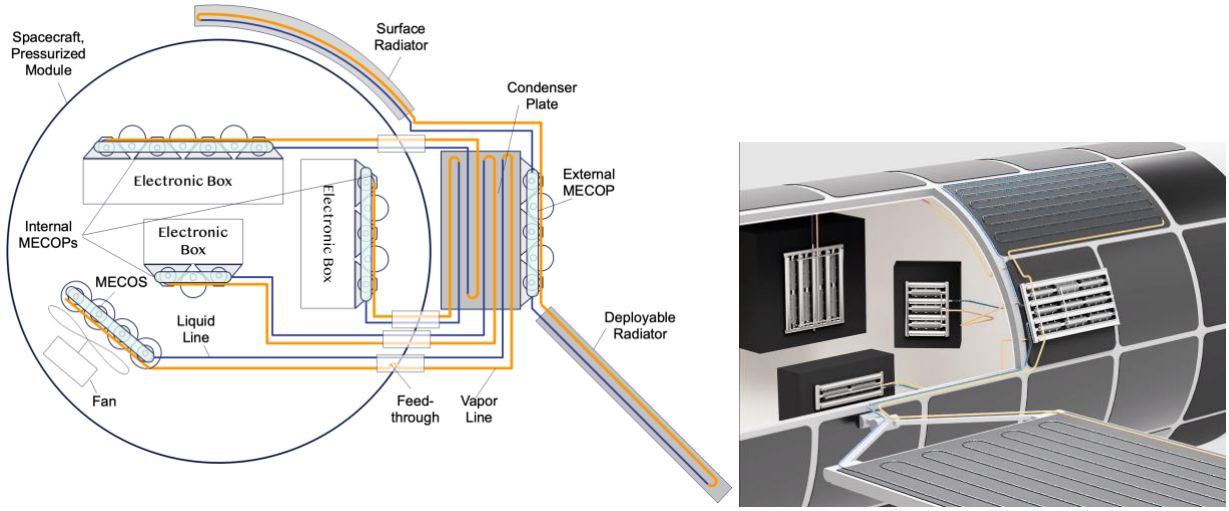


Figure 15. MECOP/MECOS-based cascaded TCS: schematic (left), rendering (right).

VII. MECOP in Thermal Architectures for Pressurized Modules

It has been shown that a number of applications can benefit from the proposed technology. Among others, it really opens new perspectives on the thermal control of pressurized infrastructures: a specific insight into the matter is given in the current section.

The main objectives of the TCS of a pressurized infrastructure consist of managing the heat dissipated by onboard avionics (equipment and payload) and controlling the temperature of the cabin air, with significant variations depending on the type of module and mission. The avionics reject heat either through their baseplate, directly into the cabin air, or through both methods. In habitats, which are typically characterized by high levels of dissipation and the presence of a true ECLSS, the most common approach is to collect this heat through an ATCS, using cold plates and air/coolant exchangers: this is the solution adopted, for example, on Columbus (ISS) and I-HAB (Gateway).

The possibilities offered by the new modular technology (especially the ease of integrating the circuit through the pressurized shell during the system integration of the module and the ability to collect heat from extended surfaces) allow conceiving a similar architecture using a set of LHPs instead of a mechanically pumped loop. The simplicity, reliability, and cost-effectiveness of the solution makes it advantageous compared to an ATCS up to a certain level of dissipation. Dedicated trade-offs based on the current performance of the MECOP-LHP indicate a limit around 2 kW, beyond which the number of LHPs and their associated interfaces start making the ATCS more competitive (also taking into account its greater flexibility in controlling temperature).

The reference thermal architecture is the one presented in the following pictures. The unit to be controlled (or a group of units that share similar temperature limits, installed on a common panel/doubler inside the cabin) is mounted at the MECOP evaporator, which acts as a two-phase cold plate. The transport lines, through fluidic feedthrough, connect MECOP with its condenser, which, in turn, is coupled to the external radiator panel. The radiator is essentially a suitably adapted MDPS (Micrometeoroid and Debris Protection System) panel, thus with quite limited additional mass and design effort vs. the original design of passively controlled modules. The condenser/radiator concept is similar, though in a slightly more complex implementation, to the one already flight-proven onboard Cygnus.

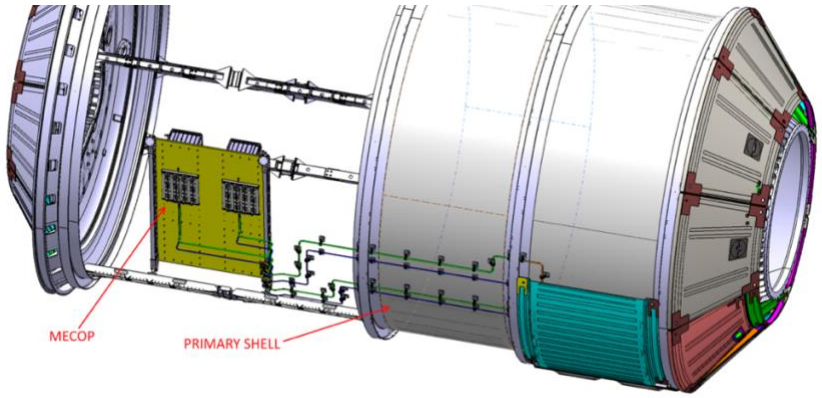


Figure 16. ESPRIT RM WIT with MECOP LHP thermal management for avionics pallet.

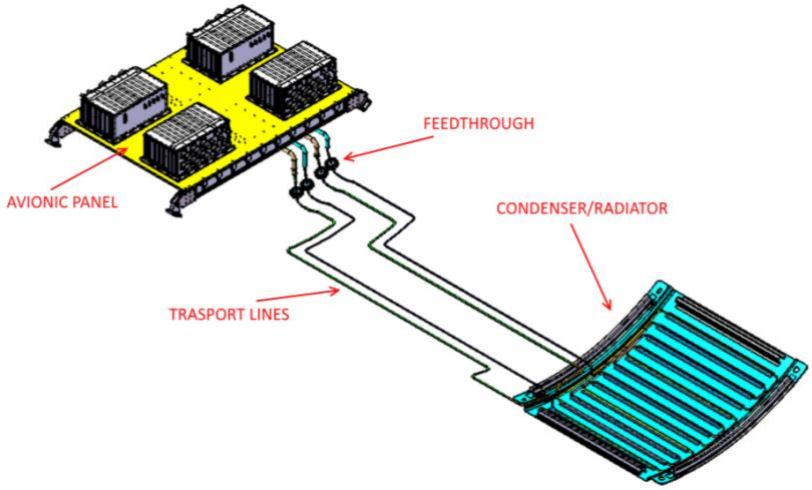


Figure 17. Two MECOP under pallet connected to a serpentine condenser.

The exploitation of the modular-LHP technology extends beyond the thermal management of "conductive" avionics. Its ability to extract heat from extensive areas facilitates the integration of a multi-module evaporator within an air-to-loop heat exchanger, enabling effective heat capture from cabin air. This feature can be implemented in a straightforward manner by coupling MECOP, in its current configuration described above, with the air loop, as established in the ESPRIT RM WIT baseline. Alternatively, a more efficient approach entails adapting the design to transform the evaporator itself into the heat exchanger. This adaptation is referred to as MECOS, briefly introduced in previous sections. The capacity to directly extract heat from an airflow represents a further novel advancement for Loop Heat Pipes, paving the way for new applications of these (otherwise) established devices.

VIII. Conclusion

Novel technologies for two-phase capillary loops were developed by Allatherm[10] with the goal of promoting modularity and standardization while overcoming the typical limitations of traditional designs. In collaboration with Thales Alenia Space Italia[12] and as part of two research projects funded by the European Space Agency, a modular loop heat pipe evaporator was created, featuring a grid of interconnected CPs and CCs. This device, named the MultiEvaporator COld Plate (MECOP), was specifically designed to collect heat from large flat surfaces, like a cold plate.

MECOP has undergone extensive testing at both the breadboard and engineering model levels, achieving TRL6.

The unique features of the evaporator, along with additional modularity aspects at the overall LHP level, facilitating assembly and filling processes at large integrator facilities during spacecraft integration, have supported the development of innovative thermal-control architectures for pressurized space infrastructures. These advanced technologies enable the efficient collection of waste heat from cabin air and avionics, transporting it to external radiators through transport lines that pass through the pressurized shell. This approach offers a simpler, more reliable, and cost-effective alternative to mechanically-pumped loops for missions in the 0.5÷2 kW power range (and, potentially, beyond with multi-loop "cascade" architectures).

The results achieved thus far open new avenues for broader and easier utilization of two-phase capillary pumping systems across a wider range of applications. Following the successful outcomes of extensive thermal and mechanical performance testing at the R&D level, this technology is set to be qualified within the ESPRIT-WIT project, marking its first planned flight opportunity.

Acknowledgments

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