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Phase Change Material Heat Accumulator for the HEXAFLY-INT Hypersonic glider

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From the launchers to the spacecrafts, various on-board systems have to be maintained within specified temperature limits. Phase Change Materials (PCM) offer the possibility to store thermal energy directly as latent heat of fusion. Among the advantages of a PCM device are the stability of temperature control, the absence of moving parts and a reduced mass. The HEXAFLY-INTERNATIONAL project aims to flight test an experimental vehicle above Mach 7 to verify its potential for a high aerodynamic efficiency during a free-flight. European Major Research Centers and Industries are collaborating on this challenge. The presented activity focus on the use of a Phase Change Material device already developed under ESA projects up to TRL 6. Two efficient heat accumulators using PCM will allow avoiding overheating of electronic units such as telemetry & telecommand receivers, transmitters and data acquisition units for the hypersonic flight. The paper presents the complete cycle of design and environmental testing for the two PCM Heat Accumulators selected for the flight. The conclusions will show the benefit of adopting a Phase Change Material Heat Accumulator.

I. Introduction

Under the auspices of the European Space Agency, a study is running to include an experimental Phase Change Material-Heat Storage Device (PCM-HSD) on-board a hypersonic glider. This experimental payload is the result of a deep development of the technology since 2013 under EC co-funded projects such as LAPCAT I & II, ATLLAS I & II. These studies resulted into technologies mature enough to experimentally test them out during a hypersonic flight mission, which was further supported by the EC under the HEXAFLY and HEXAFLY-INT projects. The overall objective of HEXAFLY is to create a generic high-speed platform enabling in-flight testing of several breakthrough technologies. To mature this idea, a scientific mission profile was worked out based upon a preliminary design of a high-speed flight test vehicle along with the identification of the most promising flight platform, e.g. sounding rocket.

The Experimental Flight Test Vehicle (EFTV), for testing the cruise performance as a non-propelled glider at high-speed, will be launched by a sounding rocket (the Brazilian VS43 launcher based upon an 8-ton solid rocket motor) in a suborbital trajectory having an apogee at about 90 km. After the release from the launcher, the EFTV will perform the first part of the descent docked to the Experimental Service Module (ESM), which controls the vehicle attitude. As soon as the EFTV features full aerodynamic control authority, it undocks from the ESM and pulls out from its descent to perform a hypersonic cruise at approximately Mach 7. In this experimental phase, the EFTV aims to demonstrate as a glider a high aerodynamic efficiency ($L/D \geq 4$), a positive aerodynamic balance at controlled cruise Mach numbers (7÷8) and an optimal use of advanced high-temperature materials and structures. The overall mission requirements are listed in Table 1.

The vehicle design, manufacturing, assembly and verification are the main drivers and challenges in this project in combination with a sounding rocket tuned for the mission. Both the glider and the propelled options of the HEXAFLY-INT high-speed vehicle are characterized from the aerodynamic and aerothermodynamic points of view. The EFTV, see Figure 2, is a hypersonic glider of 3.29m length and having a span of about 1.23m. During ascent and first part of the re-entry phase after release from the rocket at the 90km apogee, the EFTV starts its pull-out manoeuvre to bring the EFTV to a hypersonic levelled flight above Mach 7 and executes its overall mission objectives starting from a 30km altitude. A typical trajectory is given in Figure 1.

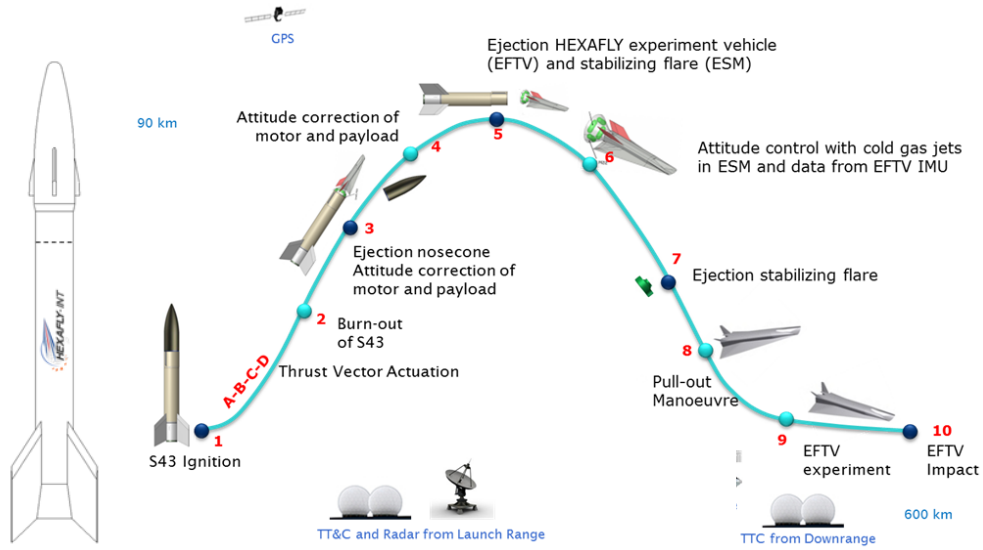


Figure 1 HEXAFLY-INT VBS-43 launch vehicle (left) and overall mission profile (right).

Table 1 Basic mission requirements for EFTV

Requirement	Target Value	Min. Value	Max. Value	Comment
Phase I: insertion into level flight: Mach number [-]	7.4	7	8	Phase I: addressing aerodynamic balance after pull-out manoeuvre
Phase II: Gliding Phase: → Flight Mach number [-]	5 to 7.4	2	8	Phase II: Mach number gradually dropping during gliding phase potentially including manoeuvres.
Flight altitude [km]	30	27	33	Optimal: level flight
Flight path angle [o] Phase I	0 (level)	0	10 to 15	Accuracy: 0.1 (measured) Accuracy: +/-5 (TBD) for insertion
Test time (Phase II) [s]	Max. possible	150	Till impact	Gliding Phase duration defined by aero-stability range

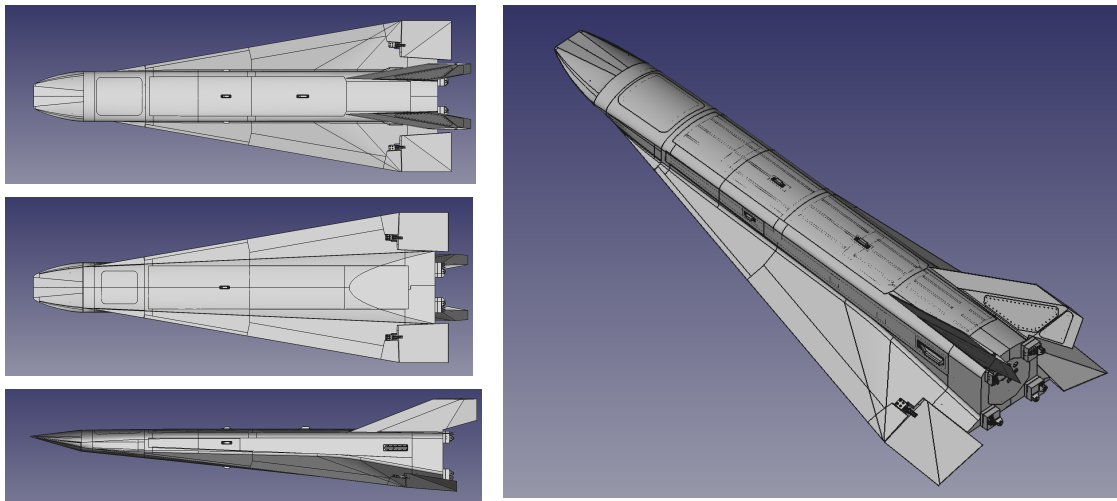


Figure 2 Layout of the EFTV

As a low cost demonstrator, the main structure of Hexafly-Int vehicle is almost metallic. The chosen material is a titanium alloy which is able to withstand 700°C along the reference trajectory. Almost all equipment is fixed on the internal frames of the main structure. So as to slow conductive heat transfer coming from the structure, nuts and bolts of the fixations are based on the low thermal conductivity (≈ 0.29 W/m/K) Vespel® material able to withstand 260°C in continuous operation.

Internal equipment is switched on nearly 20 min before the booster ignition. During these pre-flight operations and then during all the flight, equipment is heated up because of its own Joule effect. This energy is poorly evacuated into the internal structure due to the insulating bolts, washers, nuts at the fixation points (see previous section) and free convection is also very limited due to the low pressure into the vehicle at high altitudes.

So, a high emissivity paint is recommended for dissipating the energy. If not efficient enough, a metallic heat sink could be introduced between the equipment and the fixation frame. ONERA performed nodal thermal simulations of the equipment alone. A high emissivity paint is sufficient to dissipate the heat for most of equipment except for telemetry boxes. Sizing of an adequate aluminum heat sink leads to a prohibitive increase of mass and occupied volume. A light and compact solution consists in using two rectangular aluminum boxes containing phase change material. These boxes are designed by WALOPT firm and manufactured by CRM in Belgium.

The PCM technology will offer an unprecedented gain of mass to the thermal control of the on-board electronics of a vehicle flying up to Mach 8. A study has been started with preliminary results showing this mass gain. The onboard electronic units have been grouped in two systems to optimize their thermal control. Instead of managing independently each unit, 9 units have been assembled on a single PCM-HSD. The last massive electronic unit has its own thermal control. The challenge is to maintain the electronic units in their operational thermal range from 20 to 50 °C, in a harsh external environment.

II. Equipment to control

The equipment that needs a specific thermal management is:

- 1 telemetry & telecontrol electronic unit (TM/TC E-Box)
- 4 telemetry transmitters (TM&TV-TX)
- 2 telemetry couplers (TM&TV-Coupler)
- 2 telecommand receivers (TC-RX)
- 1 global positioning system (GPS)

Two PCM-HSD's are planned:

- the first one is dedicated only to the TM/TC E-Box
- the second one is dedicated to the TM&TV-TX, TM&TV- Couplers, TC-RX and GPS

The implementation of this equipment is given in Figure 3.

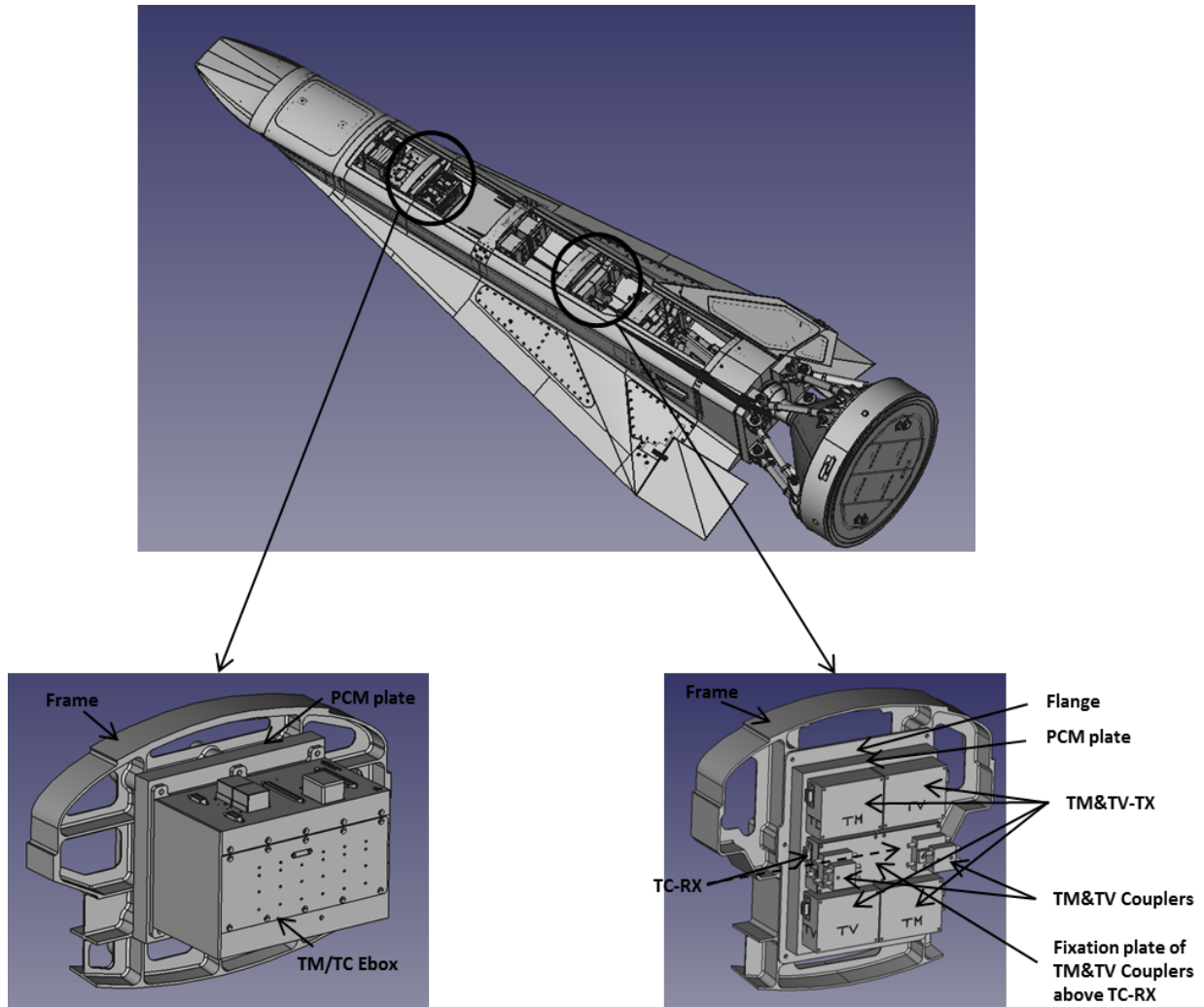


Figure 3 Integration of the electronic units and their associated PCM HSD into the EFTV

III. Environment

Equipment is switched ON during all pre-flight operations and the flight. It is submitted to its own thermal dissipation, the thermal radiation with the structure, the thermal conduction from the fixations to the structure, the thermal free convection with the internal air.

Each PCM-HSD and its equipment are submitted to quasi static and sinusoidal g-loads, vibrations loads, shock loads during the boosted phase of the flight. They are submitted only to quasi static g-loads during the other phases of the flight.

Air cooling between the fairing and the vehicle is planned during the pre-flight operations so as to prevent heating from the sun. A conservative value for the initial temperature of the equipment when they are switched ON is 20°C.

Thermal control includes both the pre-flight operations and the flight itself. The duration of the pre-flight operations is 20 minutes (i.e. 1200 s) and the duration of the flight is nearly equal to 13 minutes (i.e. 840 s). So, the duration of the complete controlled mission is 2040 s.

IV. Choice of a PCM material

A number of classes of materials have been previously investigated for use in phase-change devices (ref 9). Some of the more important are:

- Inorganic salt hydrates, e.g., $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ (Glauber's salt) and $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$
- Organic compounds, e.g., paraffins ($\text{C}_n\text{H}_{2n+2}$), alcohols, phenols, aldehydes, and organic acids
- Eutectics of organic materials, e.g., 88-mole% acetic acid + 12-mole% benzoic acid
- Natural inorganic elements, e.g., sulphur (S).
- Pure metal, e.g. lithium (Li) and tin (Sn).

Salt hydrates show unusual melting behaviour. Indeed, contrary to the other compounds, they store energy during hydration and dehydration.

PCMs, despite very good thermal properties, usually show some drawbacks. These drawbacks are reminded here below.

- Phase separation induced by incongruent melting and semi-congruent melting (salt hydrate as example).
- Subcooling
- Poor thermal conductivity
- Compatibility with other materials
- Leakage and volume change

The various criteria have been presented previously (ref 9). The choice among the different available PCM was made according to different PCM important characteristics, among which :

- Abnormalities in solidification behavior;
- Stability of the properties upon cycling;
- Chemical compatibility with the container;
- Availability;
- Thermal properties:
 - Thermal diffusivity;
 - Volume change during phase change;
 - Melting behavior;
 - Latent heat;
 - Specific heat;

The final choice has been made on n-octadecane for its latent heat and transition temperature: ~213 kJ/kg and 26 to 28°C. The main octadecane characteristics are presented in Table 2.

Table 2 PCM characteristics

	n-octadecane
Melting temperature (°C)	28
Melting energy density (J/g)	213
Volume change during phase change (%)	9.8
Density in solid state (g/cm ³)	0.865
Density in liquid state (g/cm ³)	0.774
Thermal diffusivity in solid state (m ² /s)	$2.2 \cdot 10^{-7}$
Specific heat in solid state (kJ/kg°K)	1.91

V. Design of the PCM-HSD's

The design of the two PCM-HSD's has been made according to the generated heat of the electronic units and space available. The general overview of the in-board electronic units is presented in Figure 4.

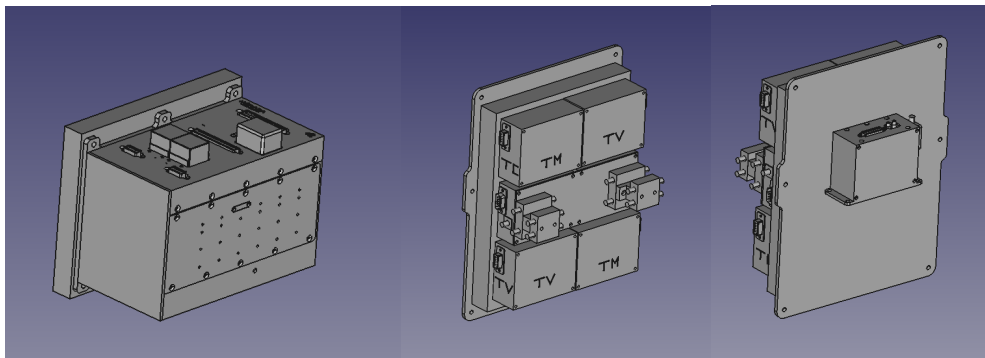


Figure 4 Electronic units and their PCM HSD's

The main problems of the PCM are the high volume change during phase change and low thermal conductivity. Indeed, as the PCM is chosen for its particular thermal properties, no problems are issued from its melting temperature or enthalpy.

So, two critical parameters arise from the characterisation tests: high volume change during phase change and low thermal conductivity.

1. Volume change during phase change

N-octododecane undergoes a melting with a high phase volume change, namely 9.8 %. This high volume change during phase change can induce critical problems of mechanical stability to the PCM-HSD. So, a specific design has been chosen from our previous developments.

2. Thermal conductivity

In a general way, organic PCMs show low thermal conductivity in solid and liquid states. As a consequence, fillers have to be added to the PCM-HSD in order to improve heat transfer through the PCM. The filler chosen was the one developed and qualified in previous projects. This filler was designed (nominal density, shape, etc.) to

ensure sufficient heat transfer among the PCM during phase change. It has to be noted that, for thermal testing, the PCM-HSD are filled using a well defined procedure to ensure >99% filling of the available volume. The effect of gravity has already been studied (ref 10) and the filling is a proprietary process.

Three specimens of PCM-HSD's have already been manufactured to qualify their design on ground. They are presented in Figure 5.

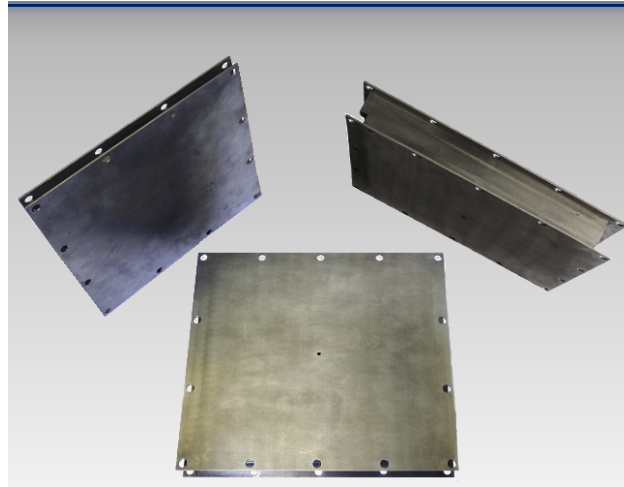


Figure 5 PCM-Heat Storage Devices

VI. 3D thermal analysis

It has been shown that the use of an organic PCM is interesting as this product is stable and inert vs the Al casing. The main drawback is its very large thickness for the proposed application. A way of improving the implementation of such a PCM is to increase the lateral size of the PCM-HSD, making its cross section as large as possible. The upper face, very conductive, will spread the heat to the full cross section of PCM. The design of the container has been adapted to the specific sizes of the electronic units. Furthermore, the thermal resistance between the dissipating electronic units and the heat accumulator is a critical parameter. The planarity of the units will be controlled and a conductive coupler such as Cho-therm® will be used. To take into account the variability of the conductive resistance at the interface a hot and cold case have been analysed: respectively, the thermal resistance is taken as 200 W/m².K or 1000 W/m².K.

In the first configuration, the equivalent heat sink is an Aluminum block weighting more than 13 kg in the hot case. The equivalent PCM-HSD mass is 1.480 kg for the same thermal control.

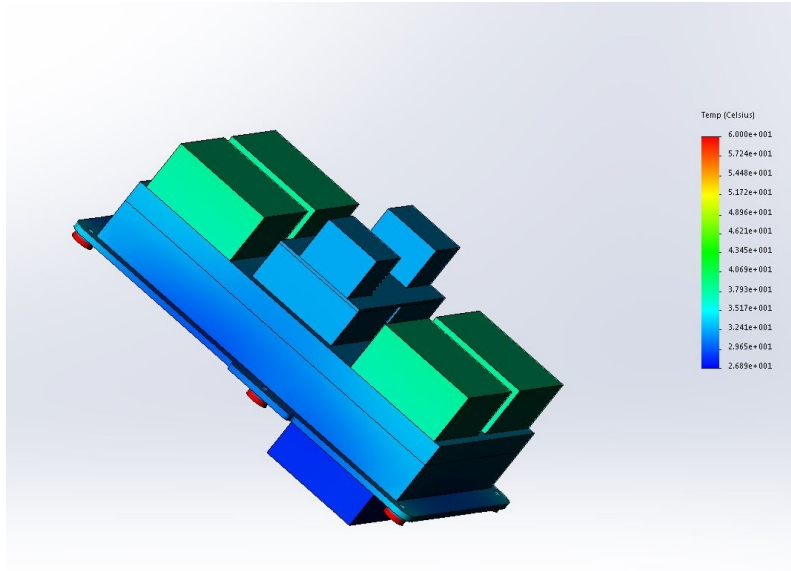


Figure 6 Temperature field at end of mission with a thermal resistance of $1000\text{W}/\text{m}^2\cdot\text{K}$ and the frame at 300°C .

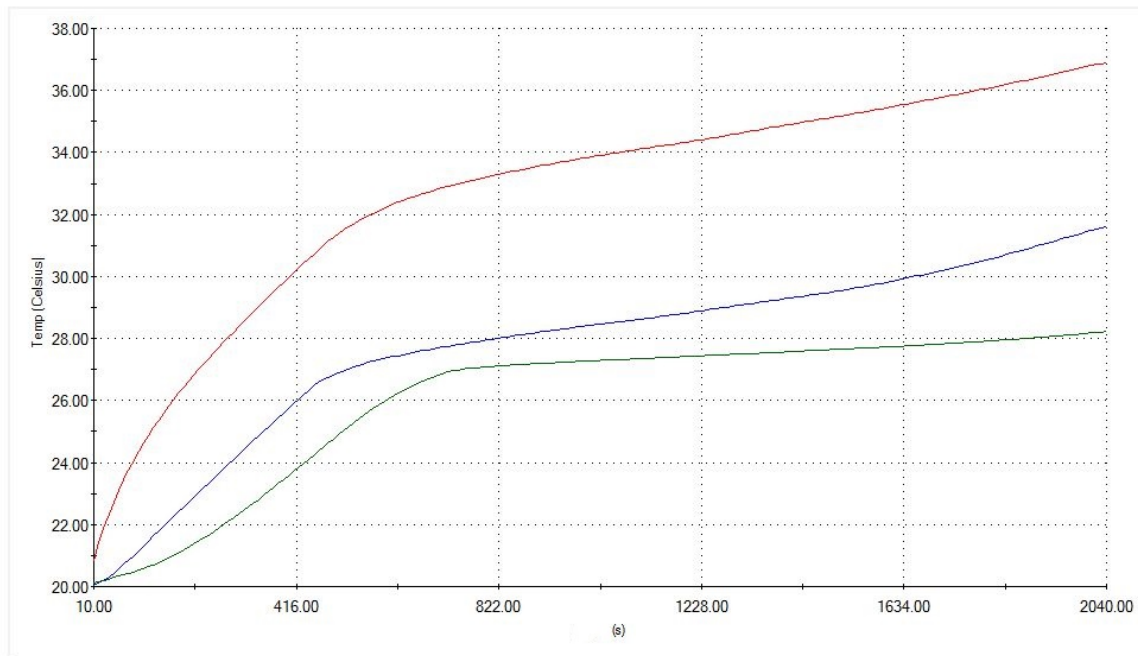


Figure 7 Maximum temperature of the electronic units (red), PCM-HSD (blue), base plate (green) versus time (s)

In the configuration shown in Figure 6, the thermal resistance is $1000 \text{ W/m}^2\cdot\text{K}$ and the maximum temperature reached by the hotter electronic unit is $37 \text{ }^\circ\text{C}$ as shown in Figure 7. For a very high thermal resistance of $200 \text{ W/m}^2\cdot\text{K}$, the maximum electronic unit temperature is $52 \text{ }^\circ\text{C}$.

During the mission, the PCM will change from solid to liquid phase without cycling as it should be the case in an orbital operation. The vehicle and its equipment will not be re-used.

In the second configuration, the equivalent heat sink is an Aluminum block weighing more than 4 kg in the hot case. The PCM-HSD mass is 1.29 kg for the same thermal control. The computed masses do not take into account the accessories (bolts, thermal coupling such as Chotherm, straps, ...).

The main results are presented in Table 3. It can be seen that, for a similar maximum temperature of the electronic units, the mass gain versus a spreader is large:

- 1.483 kg versus 13.116 kg on one side;
- 1.291 kg versus 4.000 kg on the other side.

Table 3 PCM-HSD Performance vs Spreaders

	Full Size PCM-HSD (mm)	Mass (kg)	Tmax (°C)
Spreader 1	220*230*96	13.116	59
PCM-HSD for 9 electronic units assembly	216*281*30	1.483	37
Spreader 2	202*210*35	4.000	45
PCM-HSD for single electronic unit	202*210*22	1.291	36

VII. Tests

A full test campaign will be run and will include verification of the PCM characteristics (density, melting temperature, latent heat, volume change, ...), leak test, vibration test and thermal coupling with the equipment.

VIII. Conclusion

The manufacturing of the PCM-HSD units has started and the tests are foreseen shortly. Thanks to the previously achieved TRL 6, this mission will allow reaching TRL 7 with the first maiden flight foreseen in early 2020.

The overall mass gain is 14.300 kg. This shows the strong interest in using Phase Change Material as a heat accumulator for launchers and/or hypersonic gliders.

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