

Advanced Thermal Control of Launcher Equipment Bay using Phase Change Material

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In the frame of ESA's Future Launchers Preparatory Programme (FLPP), attention has been paid to the use of Phase Change Materials (PCM) for thermal control of Launchers. Among various possible applications, the avionics equipment bay of Ariane 5LV has been chosen to assess the performance of a Phase Change Material Heat Storage Device. Generally, the thermal control of the electronic units is passive and simply defined by their thermal inertia. In some specific case, an extra thermal inertia is added by using a spreader (thick Al plate) and the coupling with the platform is optimized. The price to pay is an extra mass for the launcher. A new concept of Phase Change Material device, using organic PCM, has recently been developed to improve the thermal control of spacecraft. This concept has been extended to the specific environment of a Launcher and to inorganic salt hydrates. The main results of this study are presented in this paper.

1. INTRODUCTION

ESA's Future Launchers Preparatory Programme (FLPP) oversees system studies and research activities to increase performance and reliability, altogether with reduced operational costs for the next European Launch System. "Selection and maturation of technologies" is one of the three main elements of this programme. The objective of this element is to mature enabling technology through ground testing and to reach TRL 6 at the LV System PDR. In this frame, attention has been paid to Phase Change Materials (PCM) for Launchers.

The renewed interest in Phase Change Material (PCM) for Space applications has been shown previously (Collette & al, 2011)^[21,23]. A PCM is a material having a high heat of fusion, whose state change at the relevant temperature is able to store and release a large amount of energy. During this change of state, the temperature remains almost constant.

The present activity deals with the Thermal Control of the launcher. Among various possible applications, as an example, the avionics equipment bay has been

chosen to assess the performance of a Phase Change Material - Heat Storage Device (PCM-HSD). The study focuses on dissipative avionics equipment thermal control which operates close to their upper temperature limit, and especially in the vehicle equipment bay (VEB).

Various mathematical models have been built on Mathcad, Excel files, Solidworks and Thermica to help for the sensitivity analyses and define the best figure of merit to be used to choose between numerous solutions and non-homogeneous criteria.

After definition of the environment, the next part of this paper deals with the general thermal equilibrium and design of a classical heat spreader (base case).

A reminder of previous results is given, showing the required cross section of the PCM filler material.

A sensitivity analysis has been performed to optimize up to 5 parameters.

Having developed an effective FEM tool and having pre-selected the more effective designs, the analysis of a few PCM-HSD's has been performed in the rebuilt Ariane environment.

Finally, the conclusions are drawn: the results of this extensive computation lead to the selection of a few

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best effective designs. Their mathematical models will be updated through the whole project. In parallel, single and 3 nodes finite difference models have been proposed for system studies.

2. CHOICE OF PCM MATERIALS

Various classes of phase change materials exist, depending on the operational temperature. Most of them are in the range (-30°C; 100°C), but there are PCM at high temperature (100°C; 800°C) and even for cryogenic applications [4-150K].

The most common phase-change transformations are solid-liquid (melting and freezing), liquid-to-gas (vaporization), solid-to-gas (sublimation), and anhydrous salt transformations. Because of the very large volumetric changes involved in vaporization and sublimation, consideration of these two phase-change transformations for reversible heat storage is generally impractical. Usually vaporization and sublimation are used in an open-loop fashion, where the vaporized or sublimed vapor is vented overboard (expendable cooler).

Water is a very effective expendable coolant and has been used in several space applications, including Gemini, Apollo, and the space shuttle. Water melts at 0°C, absorbing 333 kJ/kg. The amount of heat required to raise the temperature of water from 0°C to 100°C (sensible heat) is 418 kJ/kg. Most other expendable coolants absorb considerably less heat, ammonia (NH₃) being the second-best expendable coolant that is used extensively.

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

- Inorganic salt hydrates, e.g., Na₂SO₄ · 10H₂O (Glauber's salt) and CaCl₂ · 6H₂O
- Organic compounds, e.g., paraffins (C_nH_{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.

Table 1 gives a representative list of candidate PCMs in the temperature range of -5 to +45°C. This temperature range is pertinent to temperature control

of electronic equipment and to environmental control of crewed spacecraft. It has to be pointed out that eutectic mixtures are not taken into account because of the sensibility of these compounds on their chemical composition (well defined by the eutectic). Despite of good thermal properties, long term reliability is not assured, due to subcooling, phase segregation and chemical composition. The type of the PCM (organic/inorganic/etc) is indicated in the last column.

PCMs, despite very good thermal properties, usually show some drawbacks. These drawbacks, as the solutions to solve them, are described here below.

1. Phase separation induced by incongruent melting and semi-congruent melting

The effect of phase separation, also called semicongruent or incongruent melting, is a potential problem with PCM consisting of several components. Phase separation is explained in Figure 1 with a salt hydrate as example.

A salt hydrate consists of two components, the salt (e.g. CaCl₂) and water (e.g. 6H₂O). The single phase of the salt hydrate is first heated up from point 1 (solid) to point 2. At point 3 the liquidus line is crossed and the material would be completely liquid. Upon heating or cooling, between point 2 and 3, 2 phases are formed, the liquid and a small amount of a phase with less water (point 4).

If these phases differ in density, this can lead to macroscopic separation of the phases and therefore concentration differences of the chemicals forming the PCM material (points 5 and Figure 1 right).

Typical PCM's	Melting point (°C)	Heat of Fusion (kJ/kg)	Density (kg/m ³)	Type
Calcium chloride	29	170	1530	Salt hydrate
Lithium nitrate trihydrate (LiNO ₃ ·3H ₂ O)	30	296	1550	
Sodium sulfate (Na ₂ SO ₄ ·10H ₂ O)	31	250	1485	
Calcium dibromate hexahydrate (CaBr ₂ ·6H ₂ O)	34	115	1956	
Sodium sulfate (Na ₂ SO ₄ ·12H ₂ O)	35	265	1522	
Zinc nitrate hexahydrate (Zn(NO ₃) ₂ ·6H ₂ O)	36	147	1828	
Dibasic sodium phosphate (Na ₂ HPO ₄ ·12H ₂ O)	37	279	1522	
Water	0	333	998	Inorganic
Glycerol (C ₃ H ₈ O ₃)	18	199	1261	Sugar alcohol
Caprylic acid	16	149	901	Fatty acid
Acetic acid (CH ₃ COOH)	17	187	1049	
Capric acid	32	153	878	
n-Tetradecane (C ₁₄ H ₃₀)	6	228	760	Organic
n-Hexadecane (C ₁₆ H ₃₄)	17	237	760	
Polyethylene glycol 600 (HO(CH ₂ CH ₂) _n H)	20-25	146	1126	
n-Heptadecane (C ₁₇ H ₃₆)	22	213	776	
Polyglycol E600	22	127	1126	
n-Octadecane (C ₁₈ H ₃₈)	28	244	774	
n-Nonadecane (C ₁₉ H ₄₀)	32	187	786	
n-Eicosane (C ₂₀ H ₄₂)	37	246	779	
1-Tetradecanol (CH ₃ (CH ₂) ₁₂ (CH ₂)OH)	38	230	824	

Table 1: List of PCM candidates

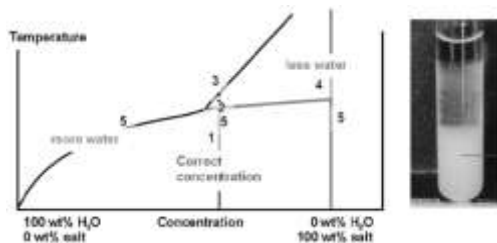


Figure 1 : Phase separation of a salt hydrate (e.g. CaCl₂·6H₂O) into three distinct phases with different water concentration and density (right) and corresponding phase diagram (left)

When the temperature of the sample is reduced to below the melting point, the latent heat of solidification can usually not be released. This would require the correct concentration of the chemical components throughout the whole sample to form the solid PCM again. When the sample is heated up to a temperature where the phase point of the whole sample is in the liquid region (point 3) the different

phases should mix again by molecular diffusion. If the sample is not mixed artificially, this can however take many hours or even days.

In most cases phase separation can be overcome using a gelling additive. A gelling additive forms a fine network within the PCM and thereby builds small compartments which restrict phases with different density to separate on a macroscopic level. If the sample is then heated to a temperature somewhat above the melting point, molecular diffusion can homogenize the PCM material again.

In some cases, phase separation can also be overcome by adding other chemicals to the original PCM and thus changing the phase diagram in a way that phase separation is prevented completely.

2. Subcooling

Ideally, the PCM should melt and solidify at the same temperature. However, many PCM do not get solid right away if the temperature of the PCM is below the melting temperature. This effect is shown on the Figure 2.

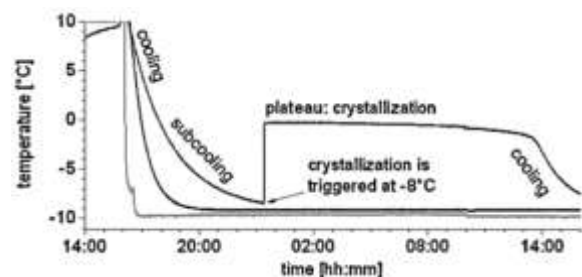


Figure 2 : subcooling of water.

This effect is called subcooling or supercooling. During subcooling, the PCM gets in a metastable state, which means it is not in thermodynamic equilibrium. Subcooling is typical for many inorganic PCM. The main consequence of this effect is that the temperature is not kept constant as expected and that lower temperatures are required to regenerate the PCM. To reduce or suppress subcooling, a nucleator has to be added to the PCM to ensure that the solid phase is formed with little subcooling. Potential nucleators are:

- **Intrinsic nucleators:** particles of solid PCM. They have to be kept separately from the PCM as they would otherwise melt with the PCM and thereby become inactive.
- **Extrinsic nucleators:** often chemicals that show very similar crystal structure as the solid PCM. This usually means that they

have similar melting temperatures as the PCM itself and thus become deactivated at temperatures very close to the melting point of the PCM itself.

Nucleators have been developed for many, but not all, well investigated PCM. For a new PCM however, the search for a nucleator is usually time consuming and often not successful, as there is still no reliable theoretical approach for the search for a nucleator.

3. Poor thermal conductivity

The low thermal conductivity of PCM is an intrinsic property of non-metallic liquids in general. It poses a problem, because PCM store a large amount of heat in a small volume and this heat has to be transferred through the surface of this volume to the outside. As a consequence this can induce charge and discharge problems and to slow down the transformation.

There are generally two ways to improve heat transfer:

- Improvement of heat transfer using mass transfer, which is convection. Convection only occurs in the liquid phase and therefore only acts when heat is transferred to the PCM. When heat is extracted, the solid phase forms at the heat exchanging surface.
- Improvement of heat transfer through increasing the thermal conductivity. This can be achieved by the addition of objects with larger thermal conductivity to the PCM (aluminium honeycomb, metallic foams, metallic fillers, fins, etc.).

In our case, we will focus on the second solution.

4. Compatibility with other materials

The compatibility of PCM with other materials is important with respect to lifetime of the encapsulation (or vessel) that contains the PCM, and the potential damage to the close environment of the encapsulation within the system, in case of leakage of the encapsulation.

Common problems in materials compatibility with PCM are:

- Corrosion of metals in contact with inorganic PCM.
- Stability loss of plastics in contact with organic PCM.
- Migration of liquid or gas through plastics that affect the performance of a contained

organic or inorganic PCM and outside environment.

To avoid compatibility problems, compatibility tests under conditions typical for the planned application are performed. From their results, suitable material combinations are selected.

5. Leakage and volume change

In almost all cases a PCM has to be encapsulated for technical use, as otherwise the liquid phase would be able to flow away from the location where it is applied. Two solutions are available :

- Macro encapsulation, which is encapsulation in containments usually larger than 1 cm in diameter. Besides holding the liquid PCM and preventing changes of its composition through contact with the environment, macro encapsulation also :
 - Improves material compatibility with the surrounding, through building a barrier.
 - Reduces external volume changes, which is usually also a positive effect for an application.
- Micro encapsulation, which is encapsulation in containments smaller than 1 mm in diameter. It can currently only be applied to water repelling PCM. Micro encapsulation serves the same purpose as mentioned above for macro encapsulation, but additionally :
 - Improves heat transfer to the surrounding through its large surface to volume ratio.
 - Improves cycling.

In our case, we will mainly focus on macro encapsulation, due to its proven efficiency. Moreover we plan to use volume compensating systems in order to prevent destruction of the PCM heat storage device.

A preliminary selection, regarding to the PCM type has been realized:

- *Pure salts* were discarded because they have operating temperatures higher than expected ones and show strong corrosion problems.
- Due to corrosion problems linked with the metallic container, *pure metals* as well as *alloys* were discarded too. Moreover these compounds, despite high densities show low latent heat. Finally, there is not much compounds in the working range.
- *Sugar alcohols* ($\text{HOCH}_2(\text{CH}(\text{OH}))_n\text{CH}_2\text{OH}$) were discarded from the selection because of melting temperatures out of the operating

temperature range (90 to 200°C). However, the literature survey indicated that these compounds show large melting enthalpy and density. These compounds should be considered for higher transformation temperatures.

Among all the PCM cited, we decided to focus on:

- Organic (paraffins $\text{CH}_3(\text{CH}_2)_n\text{CH}_3$) or eutectics of organic materials PCMs,
- Fatty acids ($\text{CH}_3(\text{CH}_2)_{2n}\text{COOH}$),
- Hydrated salts.

According to the small temperature range of working temperature, we decided that the most important parameter for initial selection would be the melting temperature. The optimal working temperature is 40°C. This value was extended to the range 35-50°C.

Considering all these remarks, we started the review of the literature and the databases concerning PCM.

6. PCMs selection

After review of the literature dedicated to thermal energy storage, the following PCM were selected for detail review:

- Paraffin (straight chain alkanes) :
 - n-eicosane ($\text{CH}_3(\text{CH}_2)_{18}\text{CH}_3$),
 - n-heneicosane ($\text{CH}_3(\text{CH}_2)_{19}\text{CH}_3$),
 - n-docosane ($\text{CH}_3(\text{CH}_2)_{20}\text{CH}_3$),
 - n-tricosane ($\text{CH}_3(\text{CH}_2)_{21}\text{CH}_3$).
- Fatty acids :
 - Lauric acid ($\text{CH}_3(\text{CH}_2)_{10}\text{COOH}$),
 - Elaidic acid ($\text{C}_8\text{H}_7\text{C}_9\text{H}_{16}\text{COOH}$),
- Hydrated-salts :
 - $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$,
 - $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$,
 - $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$,
 - $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$.
- PCM with solid/solid transformation :
 - Neopentyl glycol ($(\text{CH}_3)_2\text{C}(\text{CH}_2\text{OH})_2$)

PCM	T _m (°C)	Density solid (kg/m ³)	Heat of fusion (kJ/kg)	Latent Energy density (kJ/m ³)
n-eicosane	37	790	247	195130
n-docosane	44	780	248	193440
Lauric acid	41-43 (42)	930	180	167400
Neopentyl glycol	40-50 (45)	1060-1190	116-139	143437
$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	37	1820	223	405860
$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$	35-44 (39)	1520	280	425600
$\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	36-45 (40)	1940-2060	134-147	281000
$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$	47	1680	155-190	289800
water	0	1000	333	

Table 2: Latent energy density of selected PCMs

The table 2 shows the melting temperature, density in solid state, heat of fusion and latent energy density, calculated as $\rho \cdot \Delta H$, of the selected PCMs. The values indicated between brackets concerning melting temperature are values used to calculate the amount of heat stored under the form of specific heat. Indeed, depending on the reference, the given melting temperatures fluctuate, as indicated in Table 2.

As can be seen in table 2, the choice of the best PCM in the point of view of latent energy density is quite simple. Indeed salt hydrates have the highest value, due to high density in solid state. Among them, $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ seem to be the most promising. Water has a quite high value but its melting temperature is out of range.

On the basis of Table 3, it can be observed that, if we consider both types of energy, all the hydrated salts have huge values of total energy stored (even if specific energy is not taken into account for $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ and $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$, due to lack of data.

Organic compounds and water are a level below the hydrated salts. However, the values are close for these two kinds of compounds.

PCM	Specific energy density (20-70°C) (kJ/m ³)	Latent Energy density (kJ/m ³)	Total energy stored (kJ/m ³)
n-eicosane	76344	195130	271474
n-docosane	83452	193440	276892
Lauric acid	98563	167400	265963
Neopentyl glycol	99640	143437	243077
FeCl ₃ .6H ₂ O		405860	405860
Na ₂ HPO ₄ .12H ₂ O	135593	425600	561193
Zn(NO ₃) ₂ .6H ₂ O	134172	281000	415172
Fe(NO ₃) ₃ .9H ₂ O		289800	289800
water	210000	/	210000

Table 3: Specific energy and latent energy stored by selected PCMs between 20-70°C

If we had to sort the PCMs according to the total energy stored, Na₂HPO₄.12H₂O and Zn(NO₃)₂.6H₂O would be the most promising PCM. If the data of FeCl₃.6H₂O and Fe(NO₃)₃.9H₂O could be completed, these PCM would be promising. The remaining organic PCM would then be chosen. Water would be the last choice.

Thanks to our experience, we can expect the paraffin to have a limited melting and solidifying range (max ~5°C).

The type of thermal behaviour of Lauric acid obtained by DSC measurement is illustrated on the Figure 3.

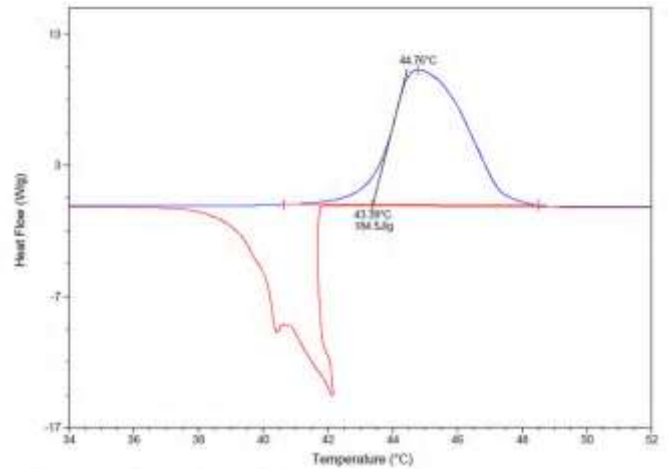


Figure 3 : DSC measurement of lauric acid

It can be seen that Lauric acid presents an extended melting range, from 38°C to 48°C. It is expected that the PCM would be completely melted within the operating temperature of the VEB. This figure indicates that the solidifying temperature is not the same as the melting temperature. This kind of behaviour is called subcooling.

The thermal behaviour of neopentyl glycol is illustrated on the Figure 4.

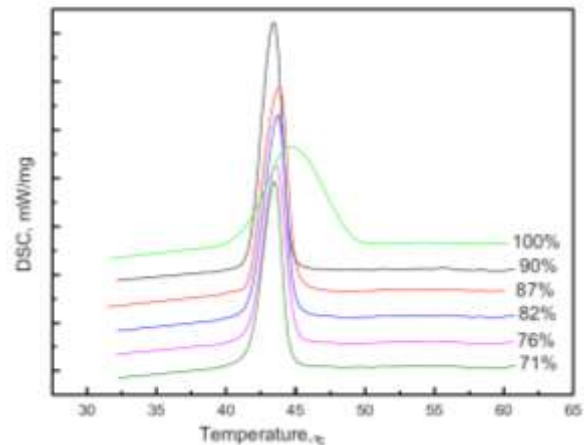


Figure 4: DSC measurement of neopentyl glycol (green curve)

Neopentyl glycol has extended melting range, from 40°C to 50°C. This melting range fits the operating temperature of the VEB.

The melting and solidifying DSC curves of FeCl₃.6H₂O, Fe(NO₃)₃.9H₂O and Zn(NO₃)₂.6H₂O have not been found in the literature but are expected to be quite wide.

The DSC of $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ is shown here below on the Figure 5.

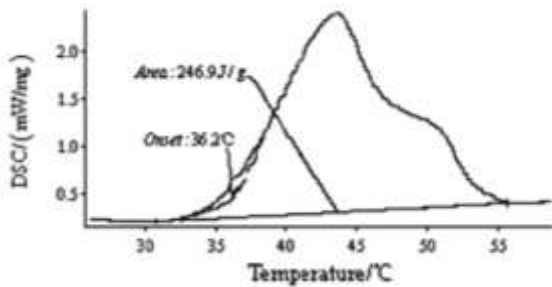


Figure 5 : melting DSC measurement of $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$.

$\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ has an extended range of melting. The solid/liquid transformation occurs from 30 to 55°C. This will not induce problems because, in this case, the range of VEB component temperature covers the whole transformation temperature of the PCM.

It has to be pointed out that the hydrated salts usually show overcooling problems that can induce cycling problems. As a consequence they will have to be deeply characterised.

7. PCM's induced corrosion

Based on previous experience, the PCM-HSD will probably be made of aluminium. Therefore, the corrosive behaviour of the selected PCM on aluminium must be considered.

Straight chain alkanes like n-eicosane and n-docosane should not show any corrosive behaviour on aluminium.

Lauric acid can be quite corrosive if it catches water from the air. No data were found about neopentyl glycol, but as an alcohol, no major effects are expected.

Important corrosion is expected from hydrated salts.

Moreover, it has to be pointed out that in the case of aluminium, a high concentration of alloying elements means a poor corrosion resistance. So, in the case of alloy 6061-T651, quite important corrosion problems may arise.

Of course, protective coatings can be performed on the PCM-HSD. For instance, in the case of aluminium PCM-HSD, anodisation can be realized to improve corrosion resistance.

3. PRELIMINARY DESIGN

First of all, a typical mission has been chosen: it assumes a continuously dissipative VEB unit. Ariane's VEB is located above the cryogenic upper stage.

The whole VEB is in a low Earth sun-synchronous orbit.

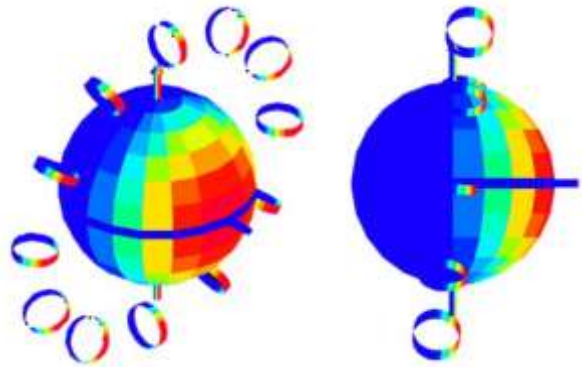


Figure 6: LEO model

The dissipation profile of the three chosen units is the following:

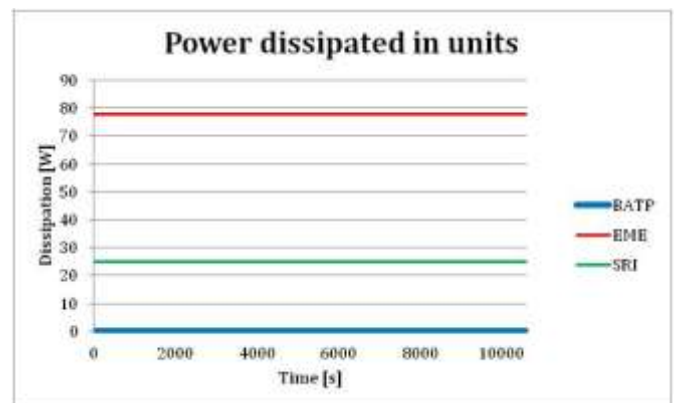


Figure 7: Power dissipation in some VEB units (Case 1)

The dissipations in hot case are applied continuously: 78 [W] for the emitter, 25 [W] for the SRI and 0 [W] for the BATP.

The results in terms of temperature are presented on Figure 8.

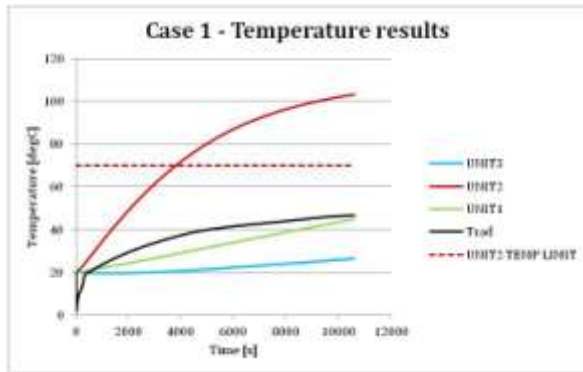


Figure 8 : Case 1 - Temperature profiles from Thermica study (source: ESA)

The unit 2 goes upper than its temperature limit (70 °C); this is why a PCM could be used for this unit to delay this temperature overtaking.

It is useful to remind here the main justification of studying PCM as a possible thermal control mean. The PCM is one of several potential thermal-design approaches. In most space applications, criteria for design selection boil down to which one has the lowest mass and power requirements. Competing thermal-control approaches include using a solid heat sink made from a high-specific-heat material such as Aluminium (but also beryllium), relaxing temperature stability requirements. In the trade-off with a solid heat sink, an efficiently packaged PCM will usually show a mass advantage over the solid heat sink. Two kinds of advantages can be reached when using a PCM heat storage:

- mass gain by sizing down or suppressing the thermal spreaders
- decrease of the qualification temperature of the electronic equipment by limiting the temperature range.

Anyway, attention should be paid to the PCM container thickness, which can constraint the good conductance through the PCM. Volume of the PCM container should also be addressed carefully when analyzing its implementation.

We can focus the use of a PCM on one of these targets or mixing both. For designs where the goal is to reduce temperature cycle ranges, the trade between temperature stability and thermal-design mass and cost must be made on a case-by-case.

A direct comparison of the mass for a PCM based design, with mass for a non-PCM design can be

made. The first question to answer is whether the added mass of the thermal-storage system is less than the mass saved by reducing/suppressing the spreader, with launch cost around 25 000 €/kg. We can safely say that the spreader size and mass may be reduced through the use of thermal storage. We have examined the case of unit 2 of the vehicle equipment bay, which is the Emitter.

Aluminium plates are one of the common heat spreaders for military and commercial electronics applications. Embedding heat pipes into traditional aluminium heat sink and spreader plates can increase the conductivity by up to six times and are commercially available.

For applications needing further weight reductions, Magnesium plates can be used. Magnesium has a density of 1.74 g/cm³ which is 65% the density of Aluminium. Magnesium is not often used as a heat spreader due to its low thermal conductivity but can be found in some military applications (UAV). Thermal conductivities of Mg plates with heat pipe range from 450 - 800 W/m.K.

Material	Weight (% is vs Al plate)	k (W/m.K)	Electronics Max Temp (°C)
Aluminum 6061	1,85 kg	180	91
Aluminum + heat pipe	124 %	700	61
Magnesium + heat pipe	98 %	575	67

Table 4: Respective performance of commercial heat spreaders

Table 4 shows the properties of different thermal spreaders that have been tested in a specific application. The spreader plates were designed for a high power electronics board. They are made as follows: an Aluminum 6061 plate, an Aluminum + heat pipe plate, and a Magnesium + heat pipe plate.

It is clear from this benchmark that the use of integrated heat pipes lowers the maximum temperature.

But the weight is increased (except with Mg) and the structural stability is lowered. The complexity and cost of manufacturing are also a serious drawback. Furthermore, the behaviour of the heat pipes can be disturbed by the acceleration during the ascent phase: as long as the wick's capillary force is greater than the pressure drops and the acceleration loading, the heat pipe will perform properly under various

acceleration loadings. However, large adverse acceleration loadings may overwhelm the wick's capillary capability, de-priming the wick or eventually causing the wick to dry out.

Dynamic effects are also to be taken into account:

- ✓ the instantaneous energy which is transmitted into the PPE structure is greater with the spreader than with a PCM-HSD: on one side, with a spreader, the equipment will quicker reach a higher operating temperature than with a PCM; this will lead to a higher heat flow to the launcher structure. On the other side, the PCM will maintain the operational temperature near its melting temperature.
- ✓ the heat flow into the PCM is not immediate. The thermal diffusivity through the PCM-HSD is of prime importance.

A more detailed analysis has then to be done. But first, the effect of the filler material inside the PCM-HSD will be reminded in the following chapter.

Effectively, the heat-transfer problems are perhaps the largest obstacles in the design of PCM systems.

4. ROLE OF FILLER MATERIAL

As a general rule, materials with relatively large heats of fusion have relatively low thermal conductivities. Therefore, for significant heat fluxes, a very large temperature difference may be required to transfer the heat from a face to the other one. This temperature gradient can result in a large temperature rise of the component during the melting process.

According to the previous study (ref [21]), a thermodynamical model has shown the main features to be considered when designing a PCM Heat Storage Device. The thermal diffusivity is a critical parameter; it is defined by the relationship $a = k/\rho.C_p$ where a is the thermal diffusivity, k is the thermal conductivity, ρ the density, and C_p the specific heat. This model has been written in Mathcad and has shown that a filler cross section between 5 % and 10 % is the optimum. Various publications analysing the use of PCM in numerous applications converge towards this mean value of filler cross section.

5. SENSITIVITY ANALYSIS

The main target in analyzing various PCM-HSD designs is to find a solution, giving all together:

- ✓ Good thermal transfer
- ✓ Low mass
- ✓ Manufacturing easiness

As far as the thermal transfer is concerned, it has been shown that the thermal conductivity of the PCM is generally low. Without filler, the heat flow has a trend to "short-circuit" the PCM, especially when the sides of the container are in a good conductive material such as Aluminum (more realistic choice to be able to weld the covers all together and get a tight assembly)

Nevertheless, a trade off should be made as the more numerous fins, the more massive structure (the specific mass of Aluminum is larger than the PCM's).

Various fin designs have been under investigation in the precedent study.

Optimization of various parameters has been addressed. One of the possible methods to perform optimization is a sensitivity analysis.

The parameters under study are the following:

- Length of fins
- Number of fin rows
- Thickness of fins
- Shape of fins
- Material (Al alloy, Ti alloy, A 304 or mild steel)

The performance has been measured in two conditions: first a steady state environment to estimate the thermal gradient between the hot and cold faces, giving an equivalent thermal conductivity. In a second stage, a transient environment has then been applied to compute the maximum temperature reached by the hot face.

The PCM used in these simulations is the Lauric acid and the container is in Aluminum.

The load cases are the same for every model and defined as follows:

Steady State:

- Hot face heating: power = 25W.
- Radiative cooling of the cold face:
 - T° environment = 77K

- Emissivity = 0,85
- View Factor = 1

Transient:

- Hot face heating: power = 50 W from 0 to 900s.
- Radiative cooling of the cold face from 0 to 2700s:
 - T° environment = 77K
 - Emissivity = 0,85
 - View Factor = 1
- Initial Temperature = 300K

Various materials have been addressed during the study. The first choice was Al 6061 T6 which is a current alloy used for flight equipment. The reason is a very good figure of merit (see table further). Nevertheless, corrosion tests with salt hydrates have shown the unfavorable evolution of this Al alloy. A coating could be used to protect this alloy against the salt hydrates. But another type of alloy, offering a better resistance could also be envisaged. For this reason, some computations have been made with Ti alloy, A 304 and mild steel.

The following table shows the main properties of the candidates.

	Specific mass (kg/m ³)	Conductivity (W/m.K)	Specific heat (J/kg.K)	Diffusivity	Conductivity/specific mass
Al 6061 T6	2700	167	896	6.90E-5	0.0619
Ti 6A 14V	4430	7.3	560	2.94E-6	0.0016
A304	8000	16.2	500	4.05E-6	0.0020
Cu	8940	401	385	1.17E-4	0.0449
Mild steel	7801	43	473	1.17E-5	0.0055

Table 5: Main properties for candidate materials

- The stainless steel has a thermal conductivity lower than the Al 6061 T6 one (16.2 for 167 W/m.K), but still higher than the one of Ti 6A 14V (7.3). The behavior of this steel is therefore better than the expected behavior of the Ti alloy.
- The thermal diffusivity is the best for Cu. Al 6061 T6 is the second best. Ti

6A 14V and A 304 have the lowest diffusivity. A factor of merit conductivity/specific mass has been computed and shows Al 6061 T6 as the best material, followed by Cu. Ti 6A 14V and A 304 are the worst.

6. MATHEMATICAL MODELS

Elementary mathematical models of a PCM device have been first developed. They were based on a thermodynamics approach and did not take into account the transient behaviour. The transient behaviour of a PCM device is nevertheless critical and needs to be detailed in another mathematical model.

Very simplified FEM models have been used in the sensitivity analysis, both in static and transient conditions. These models were made very simple to allow a very large number of computations, analysing the influence of 5 main parameters. To analyse the transient response of a PCM-HSD in real conditions, a more elaborated model is nevertheless needed

Systems models are generally based on a nodal model, such as those in use in Esatan, Thermica, ThermXL, etc Finite Element models have the advantage of defining very accurately the behaviour of the equipment under study. Details can be easily modelled, and most important, the mathematical model can be automatically generated from a CAD model. As an example coming from the previous study, a detailed model of a PCM-HSD has been realised.

These facilities are nevertheless counterbalanced by the huge amount of calculations to be undertaken, especially in transient analysis. But, in the preliminary design phase, it is necessary to assess the results with numerous changes in geometry, materials, etc ... and the correct understanding of the PCM-HSD needs to model it in detail, taking especially care of the filler inside. A simplified model could therefore be very useful to get easily and quickly the answers to the “what if” questions. Only simplified FEM models can easily be handled in transient mode.

The following table summarizes the rough energy balance of a PCM-HSD (or spreader):

Energy to be stored	J
Radiative losses	151 742
EME	141 750
Conductive losses	71 534
Total	365 026

Table 6: Energy to be stored

The methodology is the following:

1. First estimation of the PCM height
2. Assembly of a full PCM-HSD
3. Creation of an equivalent model
4. Insert the equivalent model of the PCM-HSD in the FEM Ariane PPE model

Thermal contacts have been taken into consideration in the FEM model.

The energy to be stored is balanced by the latent energy of the PCM but also its sensitive heat in solid and liquid states.

With the Phosphate Sodium Dibasic, the total mass with an Al box is estimated to **1.47 kg**. The properties are:

- L = 280 000 J/kg
- T_m = 35-44 °C
- C_p solid = 1690 J/kg.K
- C_p liquid = 1940 J/kg.K
- Rho solid = 1520 kg/m³
- Rho liquid = 1440 kg/m³
- Lambda solid = 0.513 W/m.K
- Lambda liquid = 0.437 W/m.K

The results obtained are shown in the following figure:

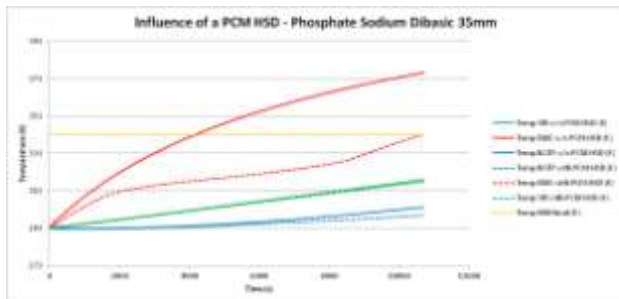


Figure 9: temperature of VEB units with a PCM-HSD 35 mm Phosphate Sodium Dibasic

With the Lauric Acid, the total mass with Al box estimated to **1.87 kg**. The properties of the Lauric acid are:

- L = 180 000 J/kg
- T_m = 41-43°C
- C_p solid = 1950 J/kg.K
- C_p liquid = 2400 J/kg.K
- Rho solid = 930 kg/m³
- Rho liquid = 873 kg/m³
- Lambda solid = 0,150 W/m.K
- Lambda liquid = 0,147 W/m.K

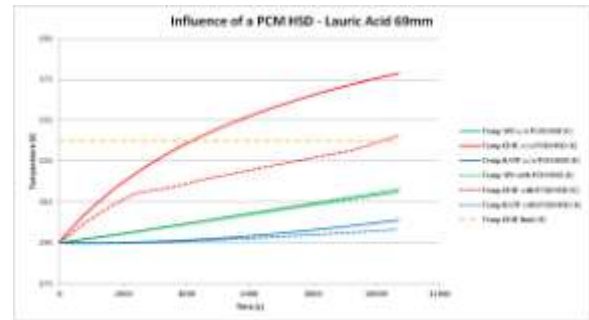


Figure 10: temperature of VEB units with a PCM-HSD 66 mm Lauric Acid

The maximum temperature of the EME is a bit too high and can be further decreased to 343 K by adding a few mm of Lauric Acid. Nevertheless, it is clear that a thickness of about 7 cm is high and that this is the cause of a non flat melting plateau.

In summary, the weight of the three solutions are:

	Mass (kg)	Thickness (mm)
Spreader	9.32	140
Lauric Acid	1.87	66
Phosphate sodium dibasic	1.47	35

Table 7: Mass & thickness for various thermal controls

The thickness of the PCM to be used in this configuration (Lauric Acid) is practically too high. The conductivity through the PCM-HSD is an issue and it has been chosen to increase the cross section of the PCM-HSD by a factor of two as shown hereafter.

7. FINAL COMPUTATIONS

In the previous study it has been shown that the maximum allowable temperature of EME is respected. The thickness of 35 mm with the inorganic salt is low and acceptable.

The use of Lauric Acid 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 Lauric Acid is to increase the lateral size of the PCM-HSD, making its cross section twice the section of the EME box. The upper face, very conductive, will spread the heat to the full cross section of PCM. The design of the container should of course be modified to allow fixation of the unit through the PCM-HSD.

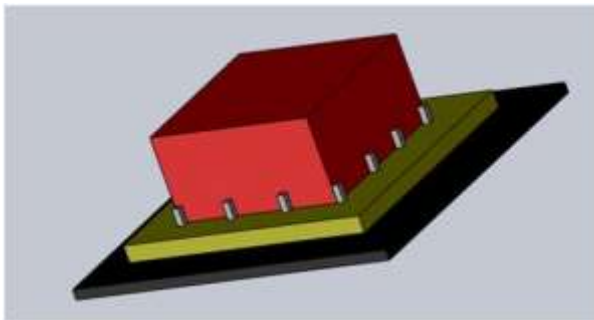


Figure11: Possible assembly for Unit and PCM-HSD on PPE

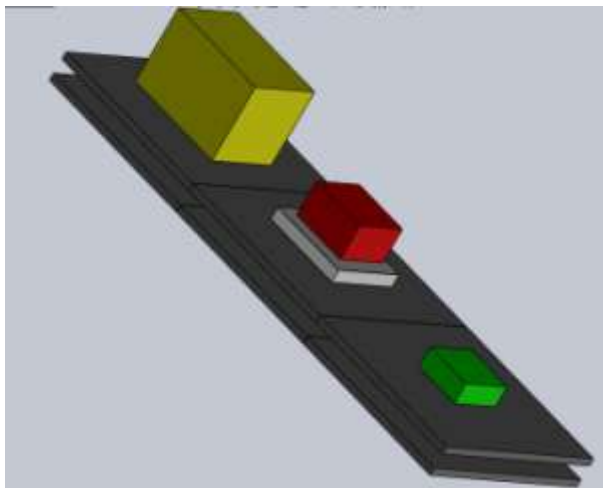


Figure12: Doubled surface PCM-HSD

Various PCM's have been used in the configuration where the surface is doubled. Four PCM's have been selected for this detailed analysis: n-Docosane, Neopentyl glycol, Phosphate Sodium Dibasic, Zn nitrate.

FEM simulations have been run and have led to the following results:

1. All the configurations respect the targeted mission: reduce the maximum temperature of the EME. This is normal as the models are based on the same energy storage capacity. So, at the end of the transient, all the configurations show a similar behaviour.
2. The transient zones are different according to the PCM material in use. The transient zone can be more or less flat: it is flatter for the n-docosane than with the phosphate sodium dibasic.
3. The most interesting configurations are n-Docosane and Phosphate Sodium Dibasic: they have the lower mass.
4. As the n-Docosane is better known and recognised as better for corrosion, toxicity, ... the final choice for the preliminary phase is n-Docosane.
5. In this preliminary phase, the number of stiffeners has not been optimised. The stiffeners are used to make the face as stiff as possible and allow a good thermal contact with the electronic unit and the platform.

8. CONCLUSION

The final result is the following:

Fin density: 5%

Cross section: 240*205 mm²

PCM	PCM thickness (mm)	PCM-HSD mass (kg)
n-docosane	33	1.783
Neopentyl glycol	43	2.801
Hosphate sodiumdibasic	18	1.664
Zinc nitrate	26	2.711

Table8: PCM-HSD Mass

When considering the rough price for launching one kg in orbit (25000 euros), a first financial assessment can be made for the gain reached with a PCM-HSD:

Solution	Gain in total mass (kg)	Financial Gain (€)
PCM-HSD n-docosane	15,074	376 850
PCM-HSD Neopentyl Glycol	13,038	325 950
PCM-HSD Phosphate Sodium Dibasic	15,312	382 800
PCM-HSD Zn Nitrate	13,218	330 450

Table 9: Financial gain

9. ACKNOWLEDGMENT

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10. LIST OF ABBREVIATIONS

DSC	Differential Scanning Calorimetry
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
FEM	Finite Element Method
HSD	Heat Storage Device
PCM	Phase Change Material

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