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Phase Change Material Device for Spacecraft Thermal Control

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On board a satellite, the experiments and subsystems 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. Usually, the melting PCM can easily be used in reversible, closed systems. Two advantages of a PCM device are the stability of temperature control and the absence of moving parts. The heat-storage requirement is mainly defined by the duty cycle along the orbital period. A trade-off is presented for typical missions, which takes into account the temperature range, the weight and thermal conductivity of the PCM device together with the specific design of the container. Candidates PCM for space applications are reviewed according to their main characteristics such as latent heat, phase transition temperature, conductivity, density but also corrosion potential, hysteresis and ageing. Potential weight and power gains are finally presented for selected missions.

1. INTRODUCTION

Throughout the various phases of every spacecraft mission, there are significant variations in the internal heat dissipated by components and in the external heating fluxes. Despite of these variations, spacecraft components must be maintained within specified operational / non operational temperature limits.

For this purpose, dissipative components use most of the time passive thermal control systems, which rely on the balance between a high rejection capacity to the cold space and a heating capacity activated when internal dissipation decreases.

Nevertheless, the consumption of compensation heating power may become critical for the spacecraft power supply and battery system. Furthermore, some components are designed to undergo phases of high and low dissipation and are subjected to large variations of temperature. Consequently, they request important capacities of heat rejection and heating power as the components have a low thermal inertia. This is a common problem for miniaturized spacecraft.

A solution consists of increasing the thermal inertia, but at the cost of a weight increase.

A promising solution consists then to involve Phase Change Materials (PCM) which absorbs transient dissipation. Consequently they allow limiting extensive radiator and associated heating power consumption.

A PCM is a material having a high heat of fusion, which the change of state 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.

2. HISTORICAL BACKGROUND

The use of PCM for planetary mission is not new. NASA has already undertaken studies in the 70’s on various Phase Change Materials to yield information pertinent to spacecraft thermal control usage. At this period, three PCMs were identified as acceptable: lithium nitrate with zinc hydroxyl nitrate catalyst, acetamide and myristic acid.

By 1972, Venera 8 was launched by the USSR towards Venus. In this mission, for the first time, a

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phase change material (PCM), lithium nitrate trihydrate, was introduced as an efficient heat sink.

Similarly, Venera 9 and 10 contained large PCM heat absorbers while the Pioneer probes used only heatsinks (Beryllium) to extend the operational lifetime.

Three PCM thermal-control systems were used on the Lunar Roving Vehicle (LRV) during the Apollo 15 mission.

Thermal control systems have made several significant developments since the last missions to Venus. Today, most PCM modules that are used on spacecraft utilize paraffin; nevertheless, in the frame of current projects for exploration, NASA is testing water-ice systems.

3. PCM MATERIALS

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 system, where the vaporized or sublimed vapour is vented overboard.

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 (NH_3) 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,
- organic compounds, e.g., paraffins, alcohols, phenols, aldehydes, and organic acids
- eutectics of organic materials,
- natural inorganic elements, e.g., sulphur.

Typical PCM in the range: - 25 to + 62 °C	Melting point (°C)	Heat of Fusion (kJ/kg)	Type
n-Eicosane ($C_{20}H_{42}$)	37	246	Paraffin
Polyethylene glycol 600 [$H(OCH_2CH_2)_nOH$]	20-25	146	Alcohol
Nitrogen pentoxide (N_20_5)	30	320	Salt
Dibasic sodium phosphate ($Na_2HPO_4.2H_20$)	37	279	Salt hydrate
Sodium sulfate ($Na_2S0_4.10H_20$)	31	215	Salt hydrate
Glycerol ($C_3H_8O_3$)	18	199	Sugar Alcohol
Calcium chloride ($CaCl_2.6H_20$)	29	170	Salt Hydrate
Sodium chromate ($Na_2CrO_4.H_2O$)	23	164	Salt hydrate
n-Undecane ($C_{11}H_{24}$)	-25	141	Paraffin
n-Dodecane ($C_{12}H_{26}$)	-12	211	Paraffin
n-Tridecane ($C_{13}H_{28}$)	-6	155	Paraffin
n-Tetradecane ($C_{14}H_{30}$)	6	228	Paraffin
n-Hexadecane ($C_{16}H_{34}$)	17	237	Paraffin
n-Heptadecane ($C_{17}H_{36}$)	22	213	Paraffin
n-Octadecane ($C_{18}H_{38}$)	28	244	Paraffin
n-Nonadecane ($C_{19}H_{40}$)	32	187	Paraffin
n-Octacosane ($C_{28}H_{58}$)	62	253	Paraffin
1-Tetradecanol [$CH_3(CH_2)_{12}(CH_2)$ OH]	38	230	Alcohol
Acetic acid (CH_3COOH)	17	187	Organic Acid
Water	0	333	Inorganic

Table 1 : Candidates PCM for medium temperature

Table 1 gives a representative list of candidate PCMs in the temperature range - 25 to + 62°C; the melting-point temperature of most materials listed is near room temperature. This temperature range is pertinent to temperature control of electronic equipment and to environmental control of crewed spacecraft.

When selecting a PCM for a specific application, a good PCM should possess the characteristics presented in Table 2.

Property or Characteristic	Desirable Value or Tendency
Heat of fusion	High
Thermal conductivity	High
Specific heat	High
Density	High
Volume change during melting	Low
Vapour pressure	Low
Melting and freezing behaviour	Dependable and reversible
Availability	Readily available
Cost	Low
Compatibility	Compatible with container and filler materials
Reversible Solid-to-Liquid Transition	High
Long Term Reliability During Repeated Cycling	High
Toxicity	Nontoxic
Hazardous behaviour	Not exhibited
Property data	Readily available and well documented
Flash Point	High
Coefficient of thermal expansion	Low
Surface tension	Low

Table 2: Best characteristics for PCM

Attention should be addressed to some critical points:

- Abnormalities in solidification behaviour: shift of the solidification temperature or multiple solidification steps have been observed for a number of substances. For some ones, the shift or separation of solidification temperature as compared to melting point is in the range of 5~10°C.
- Stability of the properties. It is known that some PCM can be affected by “thermal fatigue”, namely their properties get downgraded. This is frequently observed for organic based PCM; some salts exhibit the same problems. While this problem is critical, it is not easy to detect if producers, especially of new compounds, either are not aware of the problem yet or simply do not publish. This important aspect calls for preferred choice of well documented solutions.
- Compatibility with container: priority will be given to substances that are not aggressive for containers and heat ducts. For instance, even if hydrofluoric acid had outstanding PCM properties, it would not be the right candidate.
- Availability and product stability. It will be checked that products can be supplied on a reliable basis.

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

- *Hydrated-salts* have been discarded. Indeed, even if we could find PCM in the specified temperature range, these PCM show major drawbacks: corrosion of metallic containment, subcooling and phase segregation.

- *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* were discarded too.

- *Fatty acids* have good thermal properties and working temperature included in the operating range. However, due to the fact that they are concentrated, corrosion problems may arise. Consequently, they were discarded.

- *Sugar alcohols* were discarded from the selection because of melting temperatures out of the operating temperature range (90 to 200°C).

We finally decided to focus only on organic (paraffins $CH_3(CH_2)_nCH_3$) or eutectics of organic materials PCMs. The organic PCMs selected are all made of paraffinic compounds which should not corrode metallic or silicone container.

4. SELECTION OF ORGANIC PCM

According to the small temperature range of working temperature of the selected mission, described in part 7, the most important parameter for initial selection is the melting temperature.

Examples of PCM which present melting temperature between 27 and 32 °C are reported in Table 3. For comparison, the energy stored by water by sensible heat is also considered.

As can be seen in Table 3, the choice of the best PCM for its latent heat is quite straightforward. Indeed n-octadecane has the highest value (water is not shown because we postulate that during the mission, water is not frozen). N-nonadecane has a lower value. Rubitherm RT27 and Rubitherm RT31 follow.

PCM	T_m (°C)	Specific energy density 0-40°C (kJ/m^3)	Latent Energy density (kJ/m^3)	Total energy stored (kJ/m^3)
n-nonadecane	32	70 183	188 784	258 967
n-octadecane	28	67 039	**205 870**	272 909
Rubitherm RT27	27	66 480	161 920	228 400
Rubitherm RT31	31	65 520	148 720	214 240
Water	0	164 800	–	164 800

Table 3: Specific energy and latent energy stored by selected PCM between 0 and 40°C

Beside energy stored in the form of latent heat, PCM can store energy as specific heat. On the basis of this table, it can be seen that, if we consider the whole energy stored from 0 to 40 °C, all the four organic PCM have large values. Due to the fact that we do not consider freezing at 0 °C, water has a lower value.

Thermal diffusivity

The thermal diffusivity is an important parameter for PCM charge and discharge, as it can limit the amount of energy that would be stored during the orbital period. The Table 4 and 5 show the thermal diffusivity, K/Cp*ρ, in liquid and solid state for the selected PCM [1,2,7,9,4,5,6,8].

PCM	Solid			
	Density (kg/m^3)	Cp (J/kg°K)	K (W/m°K)	Thermal Diffusivity (m^2/s)
n-nonadecane	912	1920	0.14	8.0E-08
n-octadecane	865	1910	0.358	**2.2E-07**
Rubitherm RT27	880	1800	0.2	1.3E-07
Rubitherm RT31	880	1800	0.2	1.3E-07
Water	/	/	/	/

Table 4: Thermal diffusivity in the solid state

PCM	Liquid			
	Density (kg/m^3)	Cp (J/kg°K)	K (W/m°K)	Thermal Diffusivity (m^2/s)
n-nonadecane	769	2300	0.23	1.3E-07
n-octadecane	780	2220	0.148	8.5E-08
Rubitherm RT27	760	2400	0.2	1.1E-07
Rubitherm RT31	760	2400	0.2	1.1E-07
Water	1000	4120	0.6	**1.5E-07**

Table 5: Thermal diffusivity in the liquid state

The Table 4 shows that in the solid state, n-octadecane has the highest thermal diffusivity. In Table 5, liquid water has a good thermal diffusivity.

If the thermal conductivity is the most important parameter, water should be used because of its good thermal diffusivity properties. Nevertheless, in all cases, thermal conductivity can be improved by the use of a metallic filler. The fact that we can be sure that the thermal properties of water will not change during the whole life of the satellite is a strong argument in favour of water. So, water in liquid state could constitute a good balance between thermal properties and lifetime.

Volume change

The volume changes during phase change of the selected PCM are shown on Table 6 [7,5,6].

PCM	Density solid (kg/m^3)	Density liquid (kg/m^3)	Volume change (%)
n-nonadecane	912	769	19
n-octadecane	865	780	11
Rubitherm RT27	880	760	16
Rubitherm RT31	880	760	16
Water	920	1000	-9

Table 6: Volume change during melting

This Table indicates that the four selected PCM exhibit large volume change when melting. The worst is n-nonadecane, with 19% volume change. However, in the case of water, the volume increase occurs when the water solidifies. This could be an issue because the mobility of a liquid is always higher than the mobility of a solid. So a PCM container could accommodate more easily a volume increase for a melting than for a solidification[19].

Melting behaviour of selected PCM components

The thermal behaviour of the selected paraffins are reported in literature. Ziehe and al.[10] reported the DSC (Differential Scanning Calorimetry) measurement of Rubitherm RT31 and Rubitherm RT 27.

Rubitherm RT31 exhibits an extended melting range, from 25°C to 38°C. This aspect must be then considered for the selection.

Rubitherm RT27 has an extended melting range, from 25°C to 35°C.

Similarly, n-nonadecane also presents an extended range of melting. A two phase transformation, namely solid/solid and solid/liquid can be seen. The solid/solid transformation occurs from 22 to 26°C while the solid/liquid occurs from 30 to 35°C. This PCM shows a supercooling behaviour. Indeed, its solidifying temperature is lower than its melting temperature.

For pure octadecane, Zhang and al.[12] reported that, due to supercooling, the solidifying temperature is shifted towards lower temperatures after few thermal cycling.

PCM thermal properties: Conclusions

The melting behaviour constitutes a good criterion to select a PCM. Indeed, as previously reported, Rubitherm RT 31 presents a wide melting range shifted to high temperature. This fact should lead us to discard this PCM. Indeed, if the temperature of the electronics does not reach the highest temperatures, the PCM could be only partially melted. So the total energy stored could be overestimated.

Rubitherm RT 27 presents also a wide melting range but it is less problematic. Indeed, the melting range is from 25 to 35°C. As the maximum operating temperature is 40 °C, the PCM could totally melt. N-nonadecane and n-octadecane melting range are included into the whole operating temperature. Water is not concerned by these problems, due to the fact that we would not consider phase change, i.e. work only with its specific heat.

So, only Rubitherm RT27, n-nonadecane, n-octadecane and water are still considered as potential PCM for the mission.

Among them, n-nonadecane would have the highest volume change during phase transformation. This PCM is therefore discarded

If the temperature does not decrease below 0°C, water will not exhibit large volume change during the whole operating temperature. But, if the water freezes, the volume increase during solidifying could be problematic because the mobility of a liquid is always higher than a solid. N-octadecane has the lowest volume change of the three remaining PCM.

Thus, only water, n-octadecane and Rubitherm RT27 would remain in the final selection. The ultimate choice would be harder because water has a higher thermal diffusivity than Rubitherm RT27 and n-octadecane but a lower amount of stored energy.

Considering the lifetime of the PCM, water is the best option. Because its melting temperature does not change with time and the molecule of water does not show degradation of its properties.

Except for water, the corrosion of the container is not a problem because organic compounds are selected. The flash point of all the organic compounds is high and not problematic (>150°C).

5. IMPLEMENTATION

In general, a PCM system can be implemented in various manners. The following scheme shows the parameters to take into account when a PCM is coupled to an electronic box.

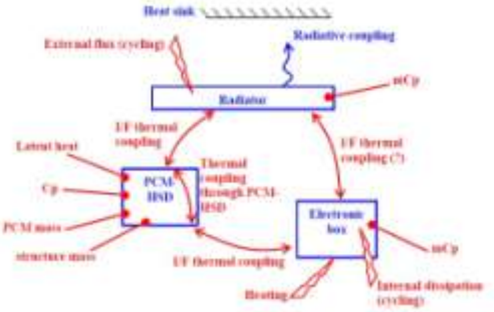

Figure 1: General implementation of a PCM

6. METHODOLOGY

In designing PCM thermal-control systems for specific applications, a number of factors other than heat of fusion must be considered. These include thermodynamics, heat transfer, combined thermodynamics and heat transfer, the function of fillers and containment.

A step by step approach is presented hereafter, to optimize a PCM implementation.

Step 1 General thermal-weight balance

A set of thermodynamic conservation equations are generated to describe the system[14]. It allows estimation of the energy-storage requirements of the PCM, the required mass of PCM, and the size of the radiator to be defined.

The ideal radiator will normally operate very close to the PCM melting-point temperature at all times and have nearly constant radiant-heat rejection to the external environment. If the component heat generation and radiation to space are the only energy exchanges to which the package is subject, the radiator is sized so that the total energy dissipated by the component during one cycle equals the total energy radiated by the radiator over that same time period. This is expressed mathematically as:

$$\varepsilon.A_{rad}.\sigma T_m^4.\Delta T_c = Q.\ \Delta Tp$$

ΔT_c : the cycle duration
ΔTp : the heat pulse duration
T_m: the melting temperature of the PCM

assuming an absolute-zero thermal-radiation sink and no solar or planetary radiation incident upon the radiator surface.

Although the thermodynamic considerations are simple and straightforward, the heat-transfer problems are perhaps the largest obstacles in the design of PCM systems. 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 component to a PCM. This temperature gradient can result in a large temperature rise of the component during the melting process.

Therefore, the thermal diffusivity is a critical parameter.

Step 2 The optimization of fillers

Up to now, a number of different fillers have been tested for use in PCMs, including carbon fibers, copper foam, alumina foam and powder, honeycomb, fins and nanoparticles doping [15,16].

For example, the Russian modules to Venus probably had an aluminum casing with aluminum fins for increasing heat transfer into the PCM. Aluminum honeycomb filler was also found to offer increase in system thermal diffusivity. For the Pioneer Venus mission, few significant advances in PCM module technology were made, except the use of carbon foams as filler materials. This application can provide increased thermal conductivity into the PCM over aluminum fins and reduces mass.

The function of filler materials is to provide low-thermal-resistance paths through the PCM, thus raising its equivalent thermal conductivity. Various test results reported with different PCMs indicate that aluminum honeycomb, aluminum fins, and carbon fibers offer the most system improvement. The data indicate that aluminum honeycomb offers the most improvement in thermal diffusivity compared to the others tested. However, other types of fillers conceivably could offer at least as much improvement. Aluminum fins are currently being used by some investigators in preference to honeycomb because of the problems encountered with obtaining good contact between honeycomb and the cold plate. Heat pipes as fillers also could offer system improvement since they have nearly infinite thermal conductivity. Addition of nanoparticles in the PCM has also received attention[20].

The problem can be expressed in the form of 5 equations:

1. The maximum energy that must be stored by the PCM package is

$$E_{max} = \rho_{PCM}.A_{PCM}.L.h_f + (\rho_f.A_F.Cp_f + \rho_{PCM}.A_{PCM}.Cp_{PCM}).L/2.(T_{compmax}-T_{melt})$$

With:

ρ_{PCM}	PCM density
A_{PCM}	PCM cross section
h_f	latent heat of PCM melting
ρ_f	filler density
A_F	filler cross section
Cp_f	filler specific heat
Cp_{PCM}	PCM specific heat
L	PCM thickness

And assuming

$Tmin = T_{melt}$

2. Temperature constraint

Any resistance in the heat-transfer path between the component and the PCM will cause the component temperature to rise above the PCM melt temperature. This temperature rise must be limited so that the component does not exceed its maximum allowable operating temperature.

$$Q = k_T.A_T(T_{compmax}-T_{melt})/L$$

3. Total equivalent conductance

$$k_T.A_T = k_{PCM}.A_{PCM} + k_F.A_F$$

index T: Total
index F: Filler

4. Conservation of Mass

$$W_T = (\rho_{PCM}.A_{PCM} + \rho_F.A_F).L + \rho_c[2A_T + (4\sqrt{A_T}).L].L_c$$

The c index defines the container.

5. Additive Area Relation

The total area is the sum of the cross-sectional areas of the PCM and filler:

$$A_{PCM} + A_F = A_T$$

The solving of these equations gives a graph which can look as this one:

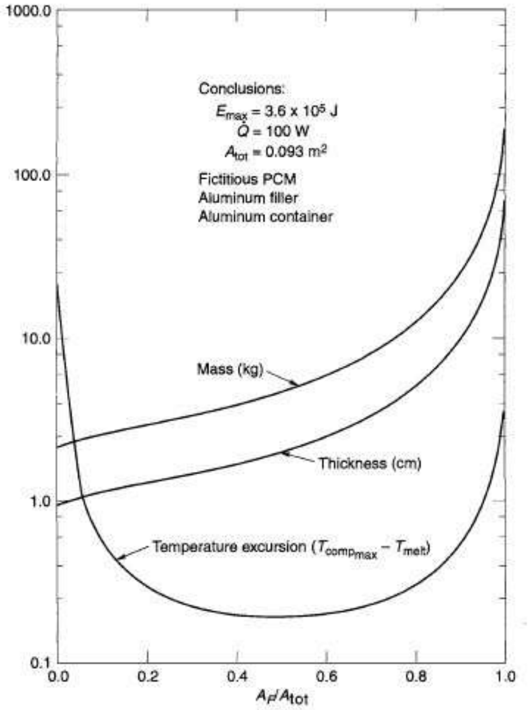

Figure 2: Filler optimization [14]

The more filler is placed, the heavier the design is, but the lower the temperature excursion.

Generally, the optimization leads to a fin/total cross section ratio of about 5-10 %.

Step 3 The transient behavior

The previous equations were all based on a thermodynamics approach and did not take into account the transient behaviour, except to some extent, for an estimation of the maximum temperature overshoot of the component to be regulated. The transient behaviour of a PCM device is nevertheless critical and needs to be detailed in another mathematical model.

The numerical model we have built is based on the resolution of the Laplace equation by finite difference on a pre-defined number of nodes. The transient behaviour is solved by an explicit scheme.

Differing from other computer codes just describing the phase change phase, the code which has been developed here takes also into account the precedent and following phases where only the heat capacity is involved. Furthermore, it is difficult to estimate the added value of a PCM-HSD without checking its behaviour in practical cases. That means that the whole environment has to be modelled as well. As two missions have been selected, two configurations, which are essentially different, had to be analysed. For this reason, it has been decided to write two specific codes, each one dedicated to each mission configuration.

The model includes an electronic box with a heat generator, a PCM device, a base plate and a radiator. The PCM is conductively coupled to the base plate and the electronic box. The electronic box and base plate can be radiatively coupled to the radiator. All surfaces can vary. In fact, numerous couplings can be used for various implementations.

The conductive thermal resistances can be adjusted together with the emissivity and view factor between the various surfaces.

The phase change medium is described as a thermal capacity which accumulates heat only if the temperature is greater than the change phase temperature (in fact inside an adjustable interval). Once the capacity is completely filled, the PCM behaves as a traditional conductance with its own specific heat. Of course, no convection can happen.

Separate properties can be used for both solid and liquid phases

Accessible variables (in function of the time) are:

- Heat generation
- Heat flux from electronic boxes to PCM
- Heat flux from PCM to base plate
- Heat flux from base plate to radiator

- Heat flux from electronic boxes to radiator
- Heat flux to cold space
- Accumulated energy in electronic boxes
- Accumulated energy in PCM
- Accumulated energy in base plate
- Electronic boxes temperature
- PCM temperature at TBD nodes
- Plate temperature at TBD nodes
- Liquid/solid ratio in PCM at TBD nodes

7. CASE STUDIES

In the frame of an ESA study, an investigation has been performed to select the best promising implementations and mission scenarios where a PCM could give an advantage on a traditional Thermal Control System.

Two kinds of missions have been taken into consideration:

- The first one is a Science Mission in an HEO (Highly Elliptical Orbit) with a ~20 h period similar to PROBA 3 mission.
- The second one is a LEO (Low Earth Orbit) mission dedicated to visible and near infra-red observation of the Earth, with a period of around 100 minutes, similar to SENTINEL-2

HEO mission (ex: PROBA 3)

For the HEO mission, PROBA 3 simplified preliminary design is taken as reference case. The concerned equipments are the Coronograph electronic, CLS and SIPOD as illustrated in the following figure:

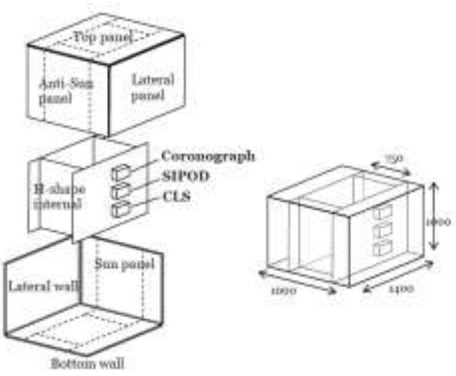

Figure 3: Proba 3 General View

The dissipation profile is the following:

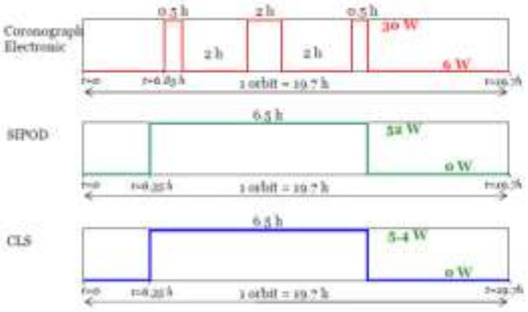

Figure 4: Proba 3 dissipation profile

The operational temperature objectives are the following:

	Toper min	Toper max
Coronograph electronic	0°C	40°C
SIPOD	0°C	40°C
CLS	0°C	40°C

Table 7: Temperature objectives

The purpose is to verify if a PCM device can reduce the total weight of the thermal control system by decreasing the size of the radiator. If not, we will check if it can be useful to decrease the temperature range and relax the constraints on the thermal control system.

Step 1

A direct comparison of the mass of a radiator for a PCM based design, with its mass for a non-PCM based design can be made. We can safely say that the radiator size and mass may be reduced through the use of thermal storage. The first question to answer, however, is whether the added mass of the thermal-storage system is less than the mass saved by reducing the radiator size.

The first step in the trade-off is to define the limits of thermal-storage benefits by determining the maximum potential mass savings of a thermal system with a PCM versus one without.

If thermal storage is not considered, the control of a payload component to its desired temperature requires sizing the radiator for peak dissipation.

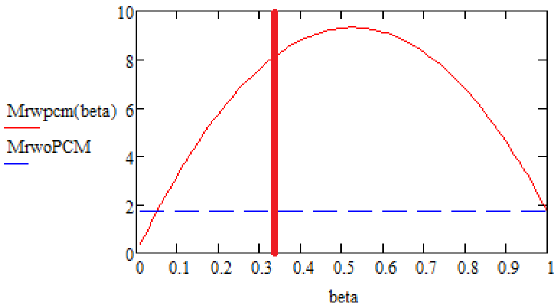

Figure 5: Weight trade-off

The figure 5 shows the mass of a reduced size radiator + an additional PCM device (Mrwpcm) in function of the duty cycle (Beta = Peak dissipation period/total cycle period). The comparison is made with the weight of the original radiator (MrwoPCM) without a PCM.

The red vertical line shows the Proba 3 duty cycle (33%). Simulations with various PCM materials have been made. For sure, higher capacity PCM allows higher duty cycle. Nevertheless, the very large amount of energy generated during the peak power of Proba 3 (1 602 432 J) does not allow to satisfy the mass criterion.

Latent heat (Wh/kg)	**Radiator Temperature (K)**	**Attractive duty cycle**
40	243	< 5.1 %
66	243	< 8.5 %
80	243	< 10.3 %

Table 8: Attractive duty cycle for Proba 3

Another benefit can nevertheless be found in the damping of the temperature range of the electronic boxes. This will save heaters and power during the mission.

Step 2

The solving of the 5 simultaneous equations shows that the temperature overshoot is largely limited from 5 % of filler material (in cross section). This small amount of Aluminium will not penalize too much the overall weight of the PCM device. Higher quantities of filler material are unfavourable.

Step 3

First, a simplified modeling of the PROBA 3 electronics has been made without PCM.

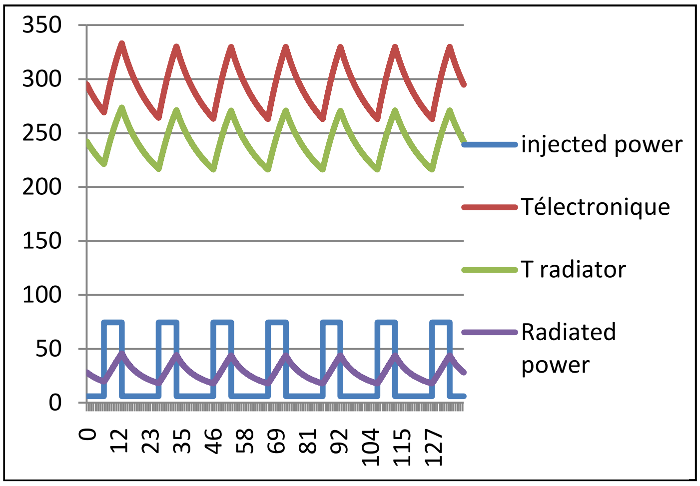

Figure 6: Proba 3 electronics without PCM

The range of temperature is pretty high, between 263 and 333 K, that is a 70 K range, out of specification.

The solution comes very easily with the use of a 0.5 cm thick PCM:

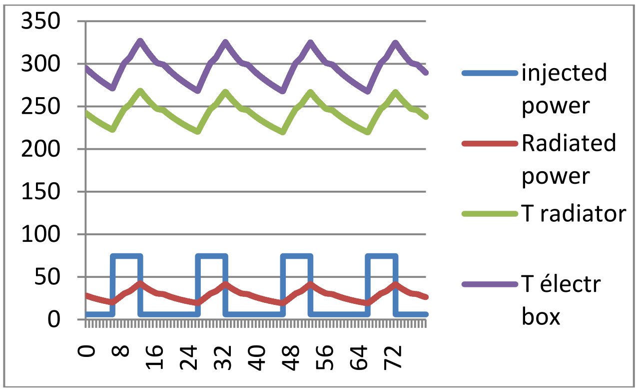

Figure 7: Proba 3 electronics with PCM

The range of the temperature is reduced to 59.7 K with an additional mass of only 0.7 kg. In this case, the Figure 11 shows that the melting of the PCM is fully reached and that it completely solidifies in the cooling period.

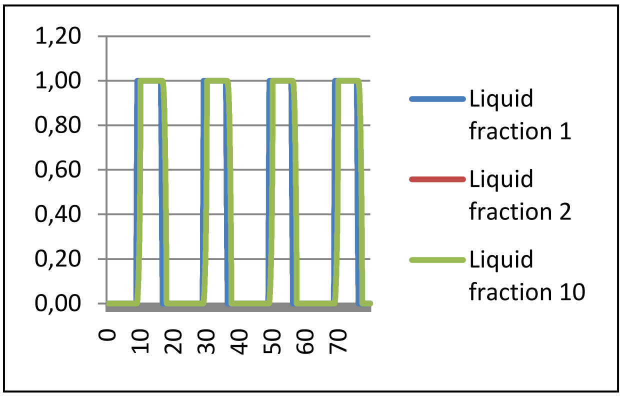

Figure 8: loading/unloading of PCM

Nevertheless, such unloading of the PCM is not trivial. A thermal ratcheting can appear and lead to a particular behavior.

If the capacity of a PCM is lower than the total energy to be stored, two behaviours can happen:

- after a few cycles when the temperature is really damped by partial fusion of the PCM, a secondary increase of the temperature happen when the PCM is fully melted and stays in the liquid phase.

- If the unloading is fully effective, the temperature increase will be stopped for a certain time (during the melting to 100 %) and then start again during each cycle.

These considerations show that the most important parameter is not the full capacity of the PCM versus the total heat load but its unloading capacity. The following example illustrates the thermal ratcheting.

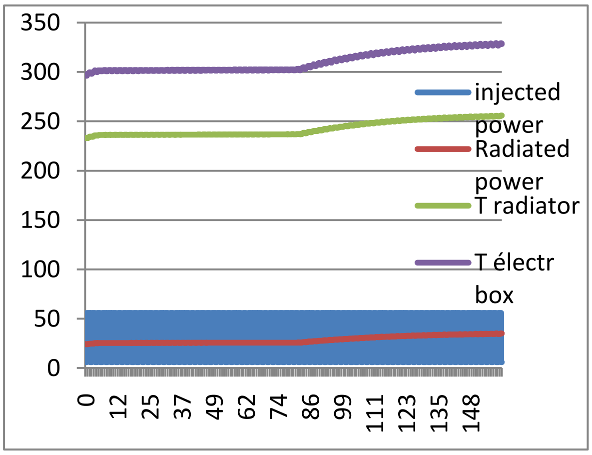

Figure 9: Illustration of thermal ratcheting

The figure 12 shows the electronic temperature behaviour during 160 hours. The increase of the temperature up to the fusion temperature of the PCM clearly appears at the most left part of the diagram.

The damping of the electronic temperature is well done by the PCM but after 80 h, the PCM is fully saturated and a temperature increase comes back.

The radiated power which was not in equilibrium with the injected power increases towards a stabilized level.

When considering the liquid fraction inside the PCM, this behaviour is clearly explained: three nodes have been used to model the PCM. The Figure 10 shows the liquid fraction of these nodes, starting to cycle when the temperature reaches the fusion temperature but not coming back to 100 % solid at the end of the cycle (1 means 100 % liquid fraction). A small delay also appears between the three nodes, showing the melting front propagation speed inside the PCM.

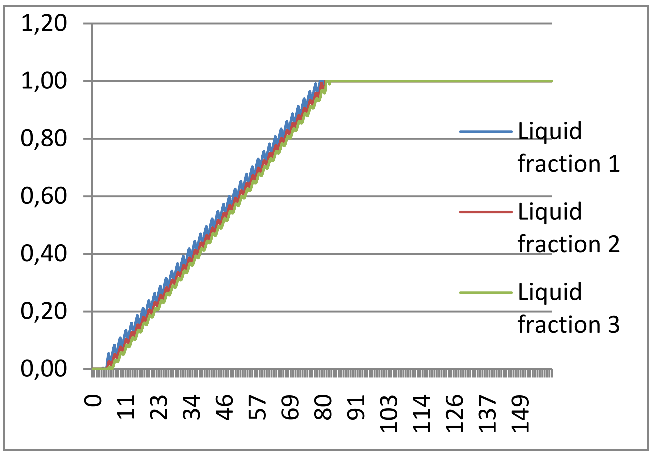

Figure 10: PCM liquid fraction during thermal ratcheting

To unload a PCM, various strategies are possible: increase the cooling period, increase the conductivity, increase the cooling power, … The choice will come from a detailed trade off. In some circumstances, it will be more interesting to increase the performance of the thermal link to the cold source.

Doing so, in the case of Proba 3, a solution has been found to decrease the temperature range to 273 – 302 K with the addition of 0.7 Kg of n-octadecane, which satisfies the specification (273 – 313 K).

LEO mission (ex: VNIR electronics of Sentinel 2)

Another analysis has been made with a reference to the LEO mission Sentinel 2, with a particular focus on the VNIR electronics.

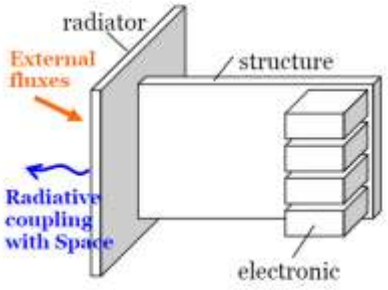

Figure 11: VNIR scheme

The dissipation profile is the following:

Figure 12: VNIR power dissipation

The operational temperature objectives are the following:

	Toper min	Toper max
VNIR electronics	20°C	30°C

Table 9: VNIR operational temperatures

In a demanding configuration (temperature limited to a range of 20/30 °C for noise reduction reason), the PCM could help decreasing the overall weight and gain 4 W in the housekeeping system by comparison to the current design based on a standard aluminum radiator and heating power compensation when the electronics are OFF.

VNIR	+	-
Support weight gain	2 Kg	
Power gain	4 W	
PCM extra weight		0.027 Kg

Table 10: VNIR PCM gains

8. NUMERICAL CONVERGENCE

When computing a transient phase change, an important parameter is the time step used to integrate the Laplace equation in the explicit scheme. Previous NASA studies[18] have shown the necessity to adopt a short time step. In the present study, we have seen the same behaviour in the numerical resolution. At first view, a time step, originally fixed at 10 s for an orbital period of 20 h, seemed to be adequate. Nevertheless, in this case, the heat balance in the PCM was not good. We had to review the integration step to 1 sec and even to 0.05 sec in some cases.

The number of nodes in the model has also an important impact on this choice. Defining numerous nodes means high spatial discretisation. But the time step should be adapted to this spatial increment; it means that a higher number of nodes (and so, a better spatial resolution) necessitates a smaller time step.

9. CONCLUSION

PCM have not often been used for European Space applications, most often because of mass consideration. Improved materials and innovative design could make PCM worth, particularly with regard to micro/nano-satellites, which are particularly demanding in power saving.

In some cases, we have shown that a net mass gain could be reached. But even if a mass gain cannot be reached, it has been also shown that a large power saving and damping of the temperature can be the rewarding result of using a PCM.

Further work is foreseen to build a breadboard that will be used to assess various engineering designs with PCM and test, amongst others, implementation of various fillers. Water instead of PCM is also interesting to consider for lifetime reason.

Finally the test results will be used to correlate and update the mathematical model.

10. ACKNOWLEDGMENT

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11. LIST OF ABBREVIATIONS

ESA	European Space Agency

ESTEC	European Space Research and Technology Centre
HEO	Highly Elliptical Orbit
HSD	Heat Storage Device
LEO	Low Earth Orbit
PCM	Phase Change Material

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