Passive Thermal Storage of Small Satellites for SWaP Improvements Over Thousands of Operational Cycles

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ABSTRACT

Satellite manufacturers and customers continue to trend toward higher power, duty cycle-driven components (high powered amplifiers) to get the most capability out of each small/CubeSat put in orbit. The result is more waste heat to manage, requiring engineers to develop a means of transferring or storing the energy without causing a substantial increase in thermal management system mass. Phase Change Material (PCM) heat sinks are being utilized by the industry as a solution to this challenge due to their fully passive operation and ability to reduce the mass of the thermal management system. PCM heat sinks for duty cycle applications are intended to absorb waste heat during operation, then utilize the dormant period of the orbit to fully dissipate the energy stored. This time-averaged dissipation allows the radiator panel to be designed for the average heat load rather than the peak value, resulting in significant surface area reduction in most applications. PCM heat sinks can also reduce the magnitude of temperature cycles, which can also reduce the severity of solder/bond line stresses that may accumulate as fatigue damage during cyclic operation. The construction of PCM heat sinks typically employ an aluminum enclosure with an internal conductivity enhancing (fin/foam/lattice) structure with the PCM encapsulated within. The internal conductivity-enhancing structure design of the heat sink and PCM selection must be optimized together to enable high performance, as the PCM material has relatively low thermal conductivity. Furthermore, because the PCM is chosen specifically for its material properties, it is imperative that the PCM retains these properties throughout the repeated melt/solidify cycles that it will experience during use. This is especially true for satellite and space applications where the PCM may see thousands of cycles due to orbital operational profiles. As such, designers in these markets must also focus on qualification of the design across long time periods with many cycles. Long term stability of common paraffin wax (or alkanes PCMs have been verified experimentally) through thousands of operational cycles. Two common hydrocarbon PCMs, Octadecane and Eicosane, have been subjected to over 10,000 phase change cycles and the results are presented here.

INTRODUCTION

Phase Change Materials (PCMs) are widely used for thermal management of electronics [1]. The technology utilizes the materials' high latent heat of fusion to store thermal energy and maintain stable temperature without the use of an outside power source. Just as water stays at a constant temperature when boiling or freezing, PCMs maintain a constant temperature when changing phase; and, it takes a relatively high amount of energy to complete that phase transition. The primary focus in PCM technology for electronics thermal management is the solid to liquid or liquid to solid transition. –Whether acting as a heat sink, or a heat source, PCM technology is analogous to an electrical capacitor, storing or discharging thermal energy during the phase change just as capacitors store and discharge energy in the form of electrical charge.

With the increase in use of PCM technology, a corresponding rise in commercially available PCMs followed. Ranging from pure paraffin waxes, to proprietary blends of waxes and hydrated salts, to low melting temperature metal alloys, nearly any material can be used as a PCM provided it can sustain repeatable melting and solidifying. Numerous applications for PCMs exist where large amounts of heat are generated in a short amount of time, ranging from simple computer processor overclock cooling to satellite thermal control. Consequently, the composition of the PCM needs to be selected, or tailored, taking into account key properties such as: latent heat of fusion (kJ/kg), melting temperature (°C), density (kg/m^3), and thermal conductivity (W/m-K).

When designing a PCM heat sink, PCM material selection is often the first step and all of the physical properties of the PCM need to be taken into account simultaneously. Secondly, because PCMs inherently have low thermal conductivities, the internal design of the container needs to be optimized to maximize the amount of PCM, as well as decrease the temperature difference between the bulk of the PCM and the component to be thermally controlled. Finally, because PCM containers can become pressure vessels, the container filling (charging) process needs to be performed with precision in terms of fill volume and fill temperature to prevent container failure during operation. If any of these design aspects are overlooked, the PCM solution may not provide the energy storage required resulting in drastic over or under-temperature conditions, or, in some cases, structural failure. Proper construction and understanding of the various and competing requirements of the design is crucial to a system that operates as expected.

However, a properly designed PCM heat sink is capable of enabling satellite capabilities without a significant corresponding mass increase. One of the most common uses of PCM heat sinks are to absorb energy from a high powered, duty-cycled component like a power amplifier; in this scenario, the phase change allows the PCM to receive the waste heat from the power amplifier without a drastic increase in temperature. By placing the PCM between the source and sink, the energy can then be dissipated as a time-averaged value over the duration of the orbit, providing significant reduction to the surface area required to dissipate the energy. PCM heat sinks can also be utilized to minimize temperature swings for critical components – maintaining batteries in a tight temperature band and prolonging bond lines via solder fatigue; the phase change material can be tuned to a point in the temperature range the batteries are being controlled to, dampening the magnitude of temperature swings. Lastly, PCM heat sinks can be used to prevent thermal runaway or decay in a system with applications in survival and sample collection.

Depending on use, PCMs need to provide predictable and stable performance from a single operational cycle to tens of thousands of phase change cycles. Useful life varies depending on the type of PCM to be used. This paper serves to provide some data to support the claim that PCM heat sinks that utilize paraffin wax can perform, repeatably and without detrimental degradation, over tens of thousands of operational cycles.

DESIGN CONSIDERATIONS

PCM Selection

In terms of the first design step of material selection, the desired melt temperature and application dictate the type of PCM that should be used. For most electronics applications, paraffin waxes and non-paraffin organics are a good choice because they are relatively inexpensive and known to be stable through many phase change cycles. For higher temperature applications, metals may be used; these solutions may come with a higher mass penalty that would need evaluated. Additional options such as hydrated salts or salts (non-hydrated) are known to be corrosive and tend to be avoided for electronic applications; therefore, are not discusses any further in this work.

Table 1. Common PCM Types

Property or Characteristic	Paraffin Wax	Non-Paraffin Organics	Metals
Heat of Fusion	High	High	Med.
Thermal Conductivity (W/m-K)	~ 0.2	~ 0.2	Very High
Volumetric Storage Capacity (MJ/m^3)	~ 190	~150	~840
Melt Temperature (°C)	-20 to 100+	5 to 120+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	90 to 250	25 to 300
Corrosive	Non-Corrosive	Mildly Corrosive	Varies
Economics	$$	$$$ to $$$$	$$ to $$$
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Stable
Weight	Medium	Medium	Heavy

Paraffin wax PCMs, or alkanes, are of particular interest for electronics cooling in both terrestrial and space applications. Paraffins provide several attractive attributes for PCM heat sinks including relatively high latent heat of fusion (142 kJ/kg for Undecane to 251 kJ/kg for Triacontane, compared to 334 kJ/kg for water), wide melting temperature ranges (-26°C for Undecane to 65°C for Triacontane), compatibility with metals (containment vessel), and low toxicity.

Because the PCM is chosen specifically for its material properties, it is imperative that the PCM retains these properties throughout the repeated melt/solidify cycles it will experience during use. Therefore, PCM life must not be overlooked as an important design consideration. This is especially crucial for satellite and space applications where the PCM may see thousands of cycles due to orbital operational profiles. Consequently, designers in these markets must also focus on qualification of the design across long time periods with many cycles.

Construction/Anatomy of a PCM Heat Sink

A PCM heat sink is generally made up of 3 components: the enclosure, the conduction enhancing structure, and the PCM. An exploded view of a simple PCM heat sink showing these components is shown in Figure 1. The enclosure of a PCM heat sink is made of a base metal best-suited for the application – typically aluminum due to its relatively high thermal conductivity and low weight for space applications. Several approaches have been used to fabricate PCM heat sinks. More commonly, aluminum vacuum brazing is used with 3D-printing (Direct Metal Laser Sintering, DMLS) gaining traction as a means of rapid-prototyping for brassboard or lab testing of Engineering Demonstration Units (EDU). The former involves the enclosure being machined in two parts: the base and the lid. The conduction-enhancing structure can be machined integrally to the enclosure, but is more commonly a separately fabricated item introduced to the assembly with folded fins and porous metal foam being common. The enclosure and conduction-enhancing structure components are then joined through the vacuum brazing process. Lastly, the system is charged with PCM and hermetically sealed.

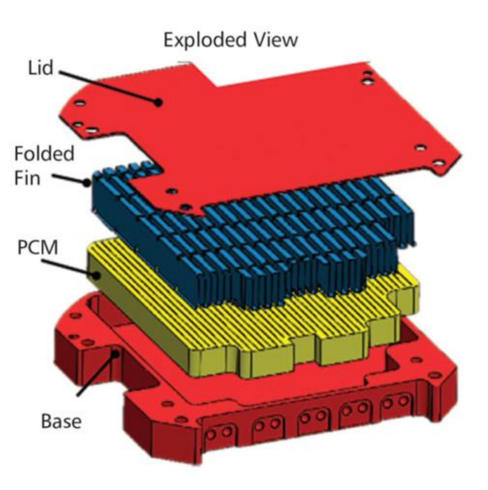

Figure 1. PCM Heat Sink Schematic

While appearing quite simple, each component of a PCM heat sink must address specific challenges. The enclosure must be designed to sustain pressure differentials between the internal cavity and the external environment. In a terrestrial application, this is typically a net positive pressure external to the system. However, in a vacuum environment, the system becomes a pressure vessel and must satisfy common industry requirements such as designing to provide positive margin at 4x Maximum Expected Operating Pressure (MEOP) [2]. The conduction-enhancing structure serves to improve the thermal performance of the system because PCM excels in thermal storage but has a relatively low thermal conductivity. Typical paraffins used for PCM heat sinks are in the 0.1 to 0.2 W/m-K range [3]. Figure 2 shows the thermal resistance network a finned PCM heat sink., Specific to the design of fin conductivity-enhancing structure, the fin spacing and thickness can be optimized to determine an appropriate solution. This is typically a tradeoff between lower temperature difference from the heat source to the PCM volume (high fin volume) vs. storage capacity of the assembly (high PCM volume). Additionally, stresses induced on the conductivity-enhancing structure by pressure differentials must be considered to maintain the integrity of the structure.

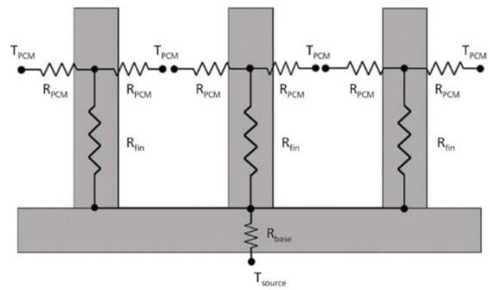

Figure 2. Simplified PCM Thermal Resistance Network

Case Study

Consider a conceptual small satellite for a LEO application that needs to effectively manage a waste heat load of approximately 350W at the payload for a repeated, duty-cycled duration each orbit. With an approximately 11 minutes power-on state per orbit, with each orbit taking approximately 100 minutes (11% duty cycle) and a maximum radiator panel surface area of 900 cm^2. Scoping calculations, neglecting thermal mass of the various structures and assuming this waste heat was uniformly distributed across a radiator panel, determined a significant and unfeasible radiator panel surface area would be needed to fully dissipate the load. Depending on sink temperature a radiator area of over 4000 cm^2 is required to reject the peak heat load, which was significantly over the radiator panel surface area budget. Figure 3 shows radiator area requirements for the stated case.

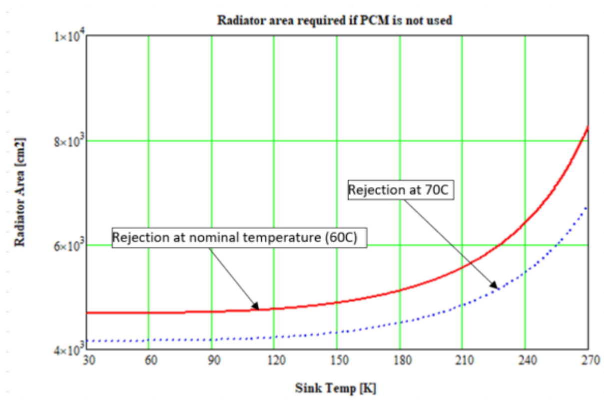

Figure 3. Required Radiator Panel Surface Area for Waste Heat Dissipation - Without PCM

Now consider the use of a PCM volume being introduced to first *store* the waste heat then rejected throughout the duration of the orbit. The radiator can now be sized to reject the time-averaged heat dissipation in lieu of the peak value that was initially investigated, which reduces the waste heat required for dissipation to a constant

38.5W. Figure 4 shows radiator area sizing with PCM for several PCM options.

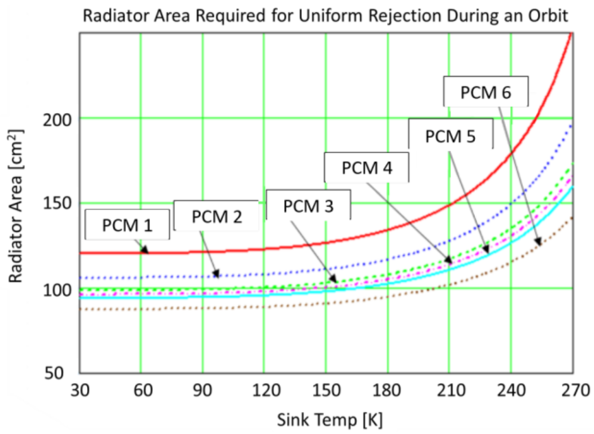

Figure 4. Required Radiator Panel Surface Area for Waste Heat Dissipation - With PCM

By introducing PCM to the system, the required radiator panel surface area reduced from over 4000 cm^2 to 100 to 300 cm^2. The radiator panel surface area required was reduced over 90%. This reduction in size corresponds to a significant reduction in mass of the system. For example, a typical aluminum honeycomb core has a density between 1.5 and 12 lb/ft^3 and is sandwiched between two aluminum face sheets each of approximately 0.02" to 0.03" thickness. Factoring in additional structure for securing the large radiator to the satellite, the heat pipes or other mechanisms for transporting the heat to and spreading across the radiator panel, the radiator panel can easily exceed 10 kg. The thermal control system utilizing PCM was estimated at under 2.5 kg, which includes the mechanisms to transport the heat from the components to the radiator panel, the heat pipes that would spread the heat across the radiator, the radiator panel, and the PCM heat sink.

For satellites that are restricted in mass and available radiator surface area, it is evident PCM can provide a passive means of significantly reducing panel area required in a lower mass package than more common thermal control solution.

PCM RELIABILITY

Methods

Advanced Cooling Technologies, Inc. (ACT) is a premier thermal management solutions company and has years of experience in utilizing both proprietary commercial and pure paraffin wax PCMs in novel thermal management solutions for many defense and aerospace applications. Furthermore, ACT has the capabilities to not only design and analyze, but also rigorously test and verify compliance to the design requirements. As stated previously, PCM life (stability over time while experiencing melt-solidify cycles) is key to long term application success. As such, ACT has investigated the correlation between melt-solidify cycles and the physical properties of two common paraffin wax PCMs: Eicosane and Octadecane which have melting temperatures of 37°C and 28°C respectively. First, the differential scanning calorimeter (DSC) shown in Figure 5 was used to determine the 0-day latent heat of fusion of small samples of the PCM. The samples were then exposed to thousands of melt-solidify cycles using a thermoelectric heat/cooled test stand shown in . DSC latent heat of fusion characterizations were performed at several cumulative cycle counts to determine any changes with accumulated cycles.

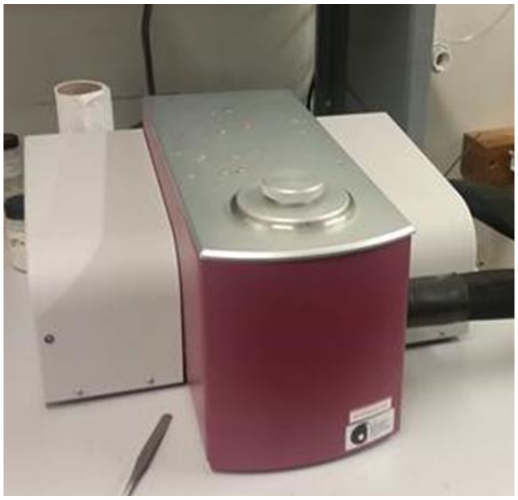

Figure 5: Differential Scanning Calorimeter

Figure 6. Thermoelectric Test Stand for DSC Sample Cycling

Results

Tables 2 and 3 below tabulate the latent heat of fusion determined by the DSC test for samples after various number of cycles, while Figure 7 shows the data in graphical form.

Table 2: Latent Heat vs. Cycles - Eicosane

Eicosane		
Total Number of Cycles	**Latent Heat (kJ/kg)**	**% Change**
Published	**246**	
0	288	-
5302	277	-3.8%
10604	272	-1.7%
15868	274	0.7%
21167	275	0.3%

Table 3: Latent Heat vs. Cycles - Octadecane

Octadecane		
Total Number of Cycles	**Latent Heat (kJ/kg)**	**% Change**
Published	**244**	
0	329	-
7944	322	-2.9%
13246	317	-2.0%

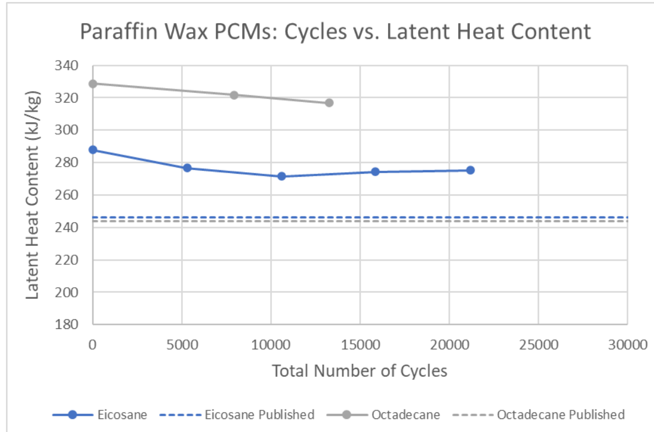

Figure 7: Cycles vs. Latent Heat

Both the tables and graphs illustrate that the paraffins show little to no degradation in latent heat of fusion after roughly 10,000-20,000 melt-solidify cycles. All changes in the latent heat content were well within the approximate 2-6% measurement uncertainty of the DSC [4]. These results align with many commercial PCM manufacturers, which advertise stability over thousands of cycles. One such manufacturer, PureTemp™, performed life tests similar ACT's for their biobased, vegetable oil derivative, PCMs. In their studies, the PCMs also showed long term stability exceeding 10,000 cycles [5].

CONCLUSIONS

In summary, phase change materials (PCMs) of interest for electronics thermal management applications are materials with high latent heat of fusion content that are used to store and release thermal energy. Because the phase change happens without an associated increase or decrease in temperature, their application stabilizes and decreases the temperature range of the electronics during cyclical power loading. PCMs are becoming increasingly important for thermal control in many fields ranging from computer electronics to space satellites. The specific choice of PCM is based on its important material properties including melting point, latent heat of fusion, density, and stability over cycles, but must be carefully evaluated in tandem with the PCM enclosure design. Pure paraffin PCMs have been shown to meet the demanding requirements of the defense and aerospace industry, primarily because of their relatively high latent heat of fusion and their non-reactive, stable nature. The mass savings by including PCM in a representative satellite thermal control system is strong evidence supporting the consideration of PCM use in appropriate applications. ACT's cyclic testing of two pure paraffin PCMs, Eicosane and Octadecane, demonstrated long term stable properties through 10,000 cycles, agreeing with similar life tests performed by commercial PCM manufacturers.

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