INNOVATIONS IN ACTION
The Thermal Management Experts

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

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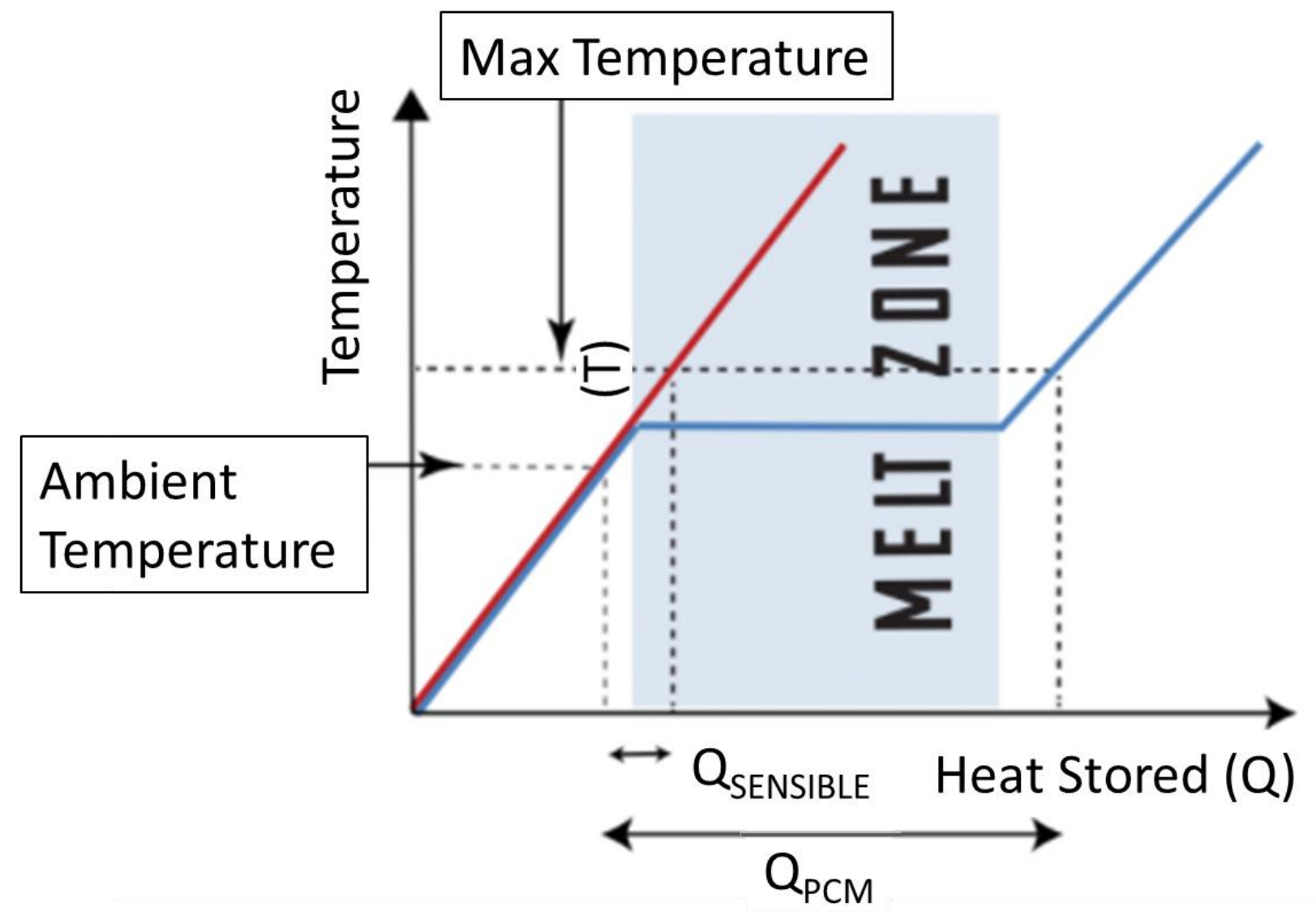
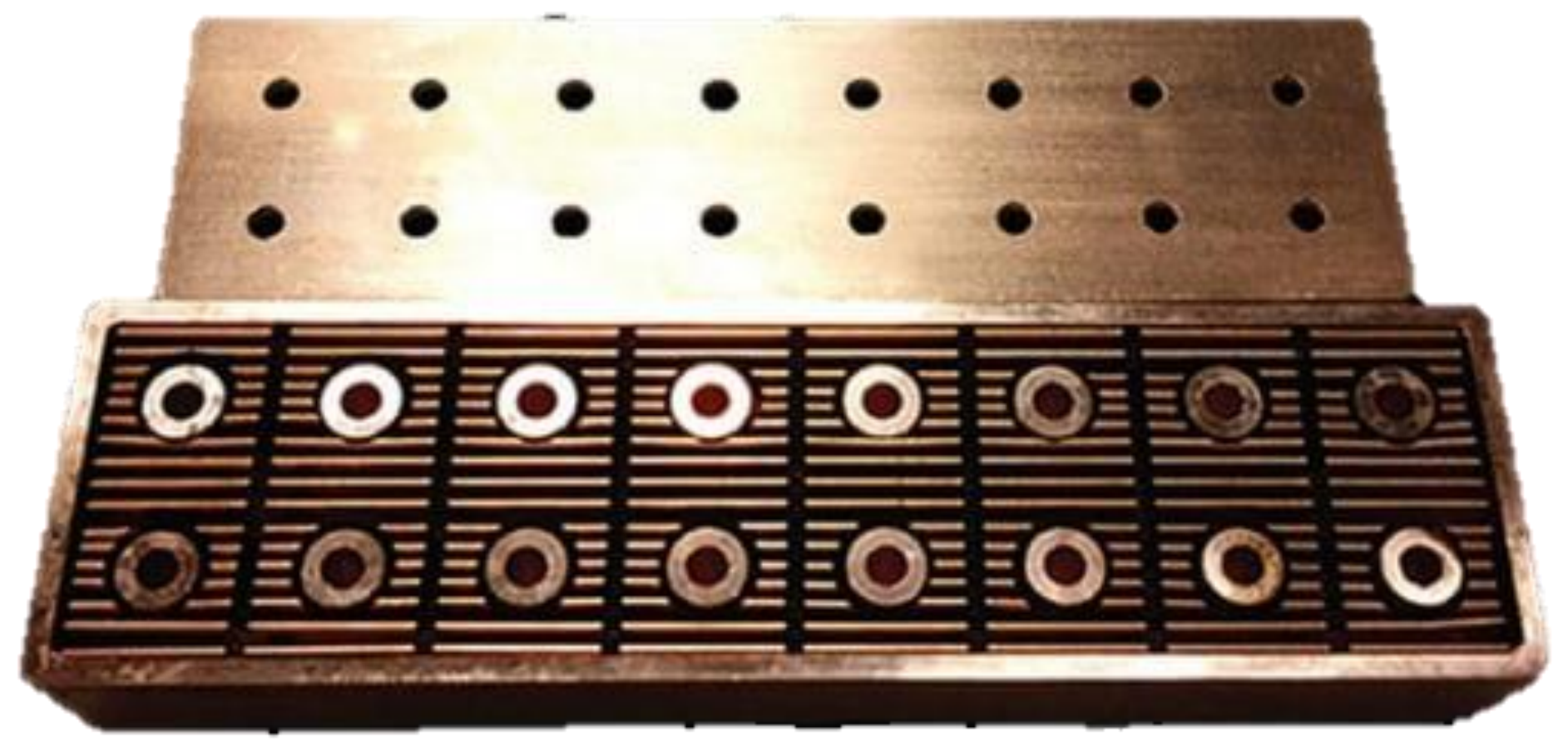
Introduction

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, causing engineers to determine a means of transferring or storing the energy without causing a substantial impact to mass of the system. 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 system. PCM heat sinks are designed to absorb waste heat during operation, and 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 (order of magnitude) in most applications.



PCM heat sinks also reduce the magnitude of temperature cycles, which can also reduce the severity of solder/bond line fatigue over each operational cycle. The construction of PCM heat sinks typically employ an aluminum enclosure with an internal fin structure and the PCM encapsulated within. The PCM then captures and stores the heat through the latent heat of fusion in a solid to liquid phase transition. While latent heat is an important material property in selecting a PCM, the internal fin design of the heat sink and PCM selection need to optimized together to enable high performance, as the PCM material has relatively low thermal conductivity. Consequently, designing a PCM heat sink becomes a matter of both selecting the PCM with the right material properties such as latent heat of fusion, thermal conductivity, density, melting point, etc. as well as the internal fin design. Furthermore, because the PCM is chosen specifically for its material properties, it is imperative that the PCM retains these properties throughout the multiple melt/solidify cycles that it will experience during use. Despite this, PCM life is often overlooked as a key design consideration in addition to those described above. 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 the PCM has been verified experimentally for common paraffin wax (or alkanes) 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 presented.



Internal Folded Fin Stack Example: Distributes heat throughout the PCM

Design Considerations and Pure Paraffins

Designing a PCM heat sink quickly becomes a fairly involved process with the amount of variables and tradeoffs the designer must consider. Some main design variables are listed below, each having their own branches and ultimately effecting the thermal design and performance. Furthermore, many of these are interdependent, making the design process a delicate balancing act. There is a multitude of materials that can be used as PCMs. From paraffin waxes to proprietary, commercial blends, each has their own benefits, be it latent heat content or material compatibility/toxicity. Pure paraffin wax PCMs are particularly attractive in spacecraft applications due to the relatively high latent heats (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.

PCM Material

Latent Heat Of Fusion
How much energy can the PCM store per kg of mass?

Thermal Conductivity
What kind of thermal gradients can I expect? Will it effect the PCM melting?

Melting Point
My expected temperature range is X to Y, will this PCM work?

Density
Can I fit enough PCM mass in my constrained volume?

PCM Life
Will the PCM retain its properties throughout 10,000 cycles?

Mechanical Design

Fin Thickness
Structurally sound? Allows enough PCM? Yields desired thermal gradients?

Material
Structurally sound? Yields desired thermal gradients Compatible with PCM?

Fin Spacing
Structurally sound? Allows enough PCM? Yields desired thermal gradients?

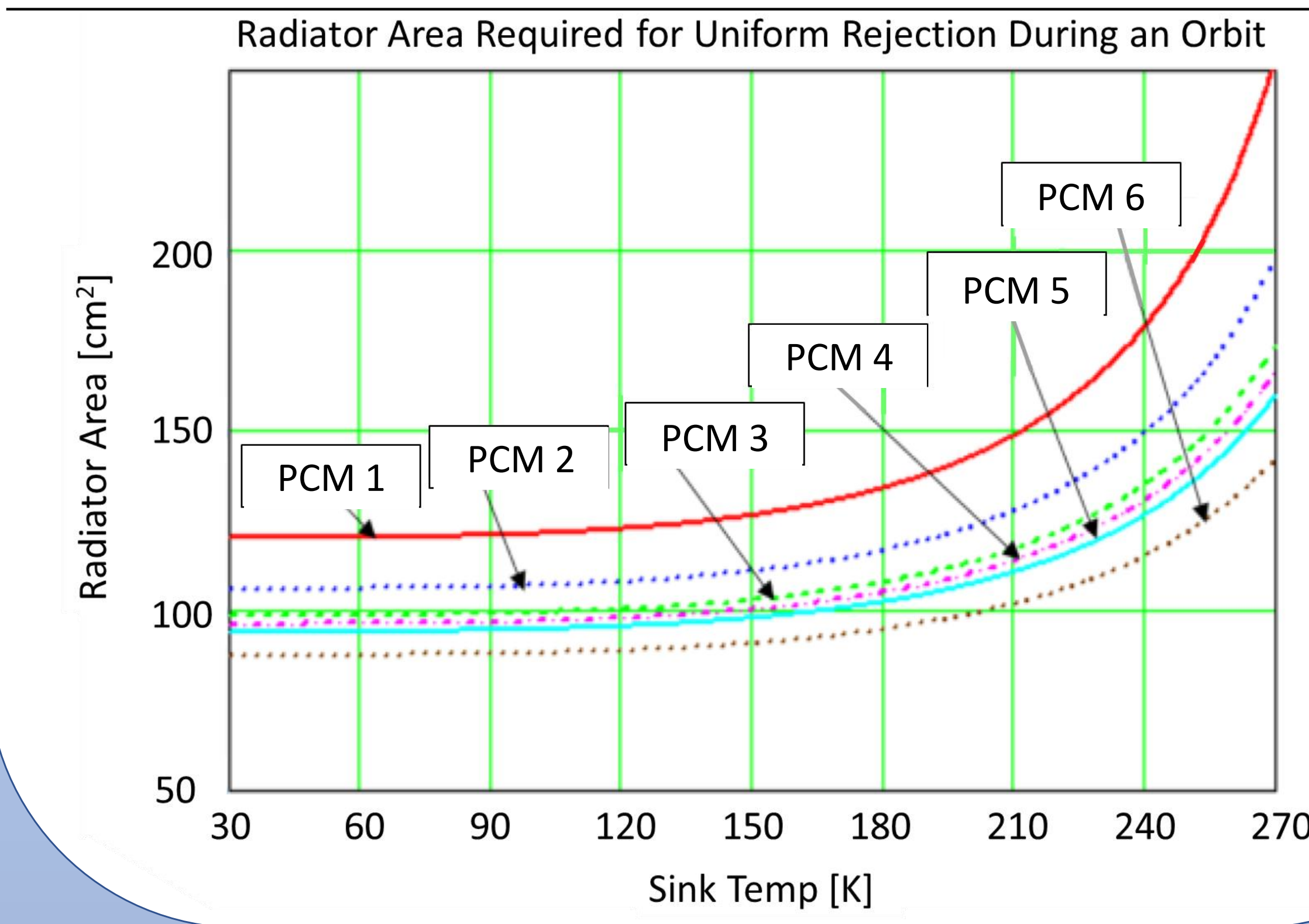
Fill Temperature
How does the filling temperature relate to end use? Does it affect heat sink performance?

Wall Thickness
Structurally sound? Allows enough PCM? Yields desired thermal gradients?

Void %
If the PCM heat sink reaches X°C, will it burst? With X % void volume, will I still get the thermal storage required?

Example Case Study

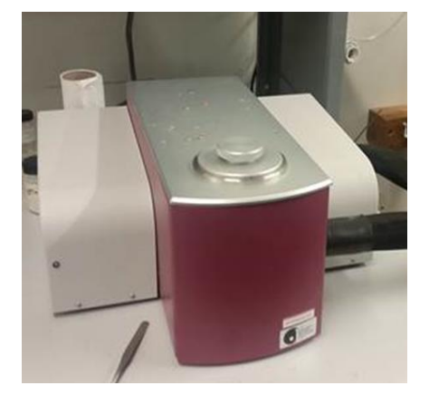
The following example demonstrates the effectiveness of PCM in reducing the necessary radiator size. A small satellite designed for a LEO application has the following properties: 350W payload, 11% duty cycle, 100 minutes per orbit, and an allowable radiator size of 900cm^2. Preliminary calculations for this application showed necessary radiator areas above 4000 cm^2, far greater than the 900cm^2 budget. The system was then evaluated with a PCM to first store the waste heat. This allowed the radiator to be sized for an time-averaged constant dissipation of 38.5W, opposed to the 350W value. The plot below shows the required radiator size vs. sink temperature after a PCM solution was implemented using different PCMs. **The PCMs allowed for over 90% size reduction!** Furthermore, mass estimates show that a PCM solution could **reduce overall thermal control mass by greater than 70%!**



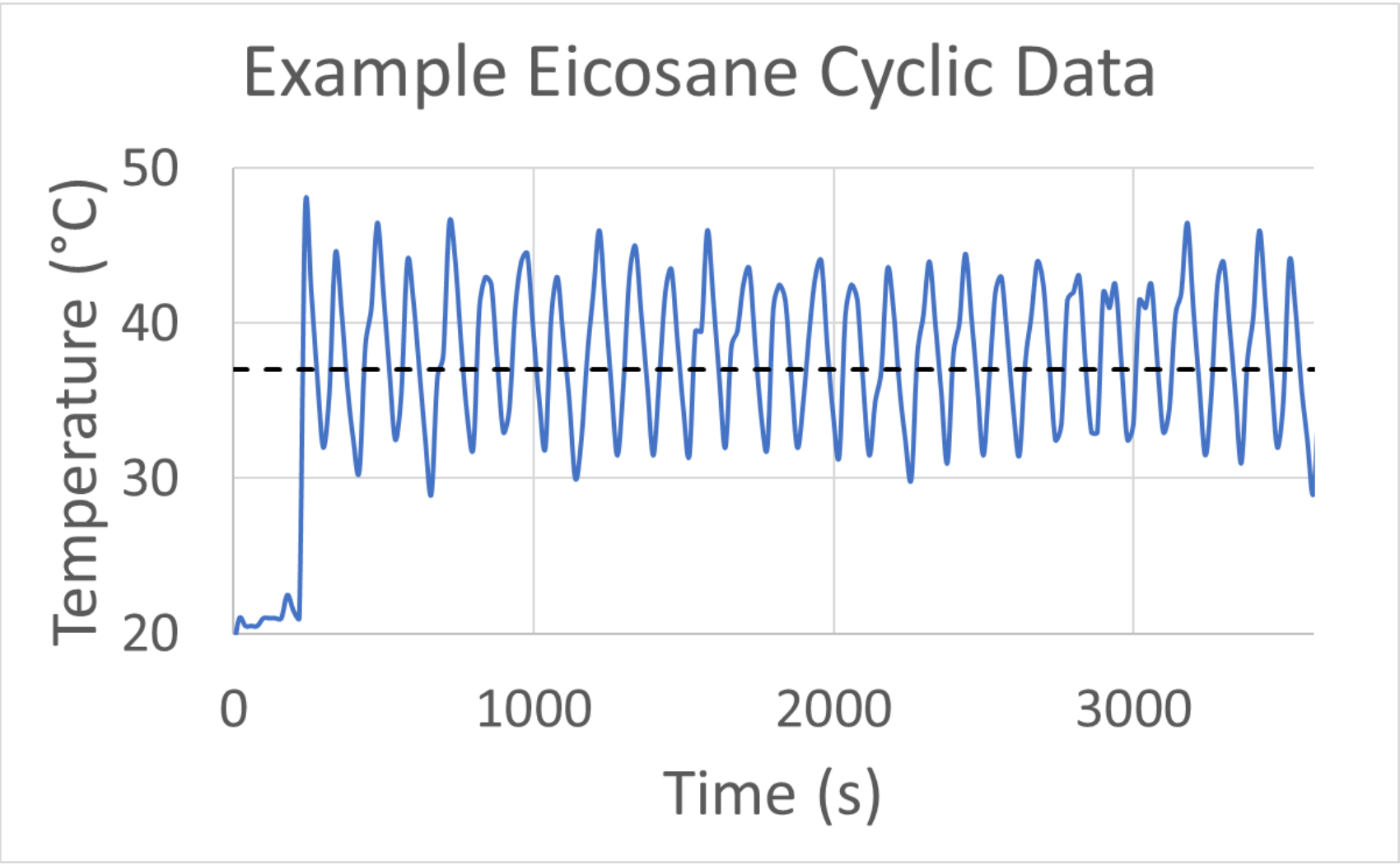
Methodology

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 pictured below was used to calculate the 0-day latent heat of fusion of small samples of the PCM. Then, the samples were exposed to thousands of melt-solidify cycles. DSC characterizations were performed at several cumulative cycle counts to determine any changes in the latent heat of fusion.

DSC



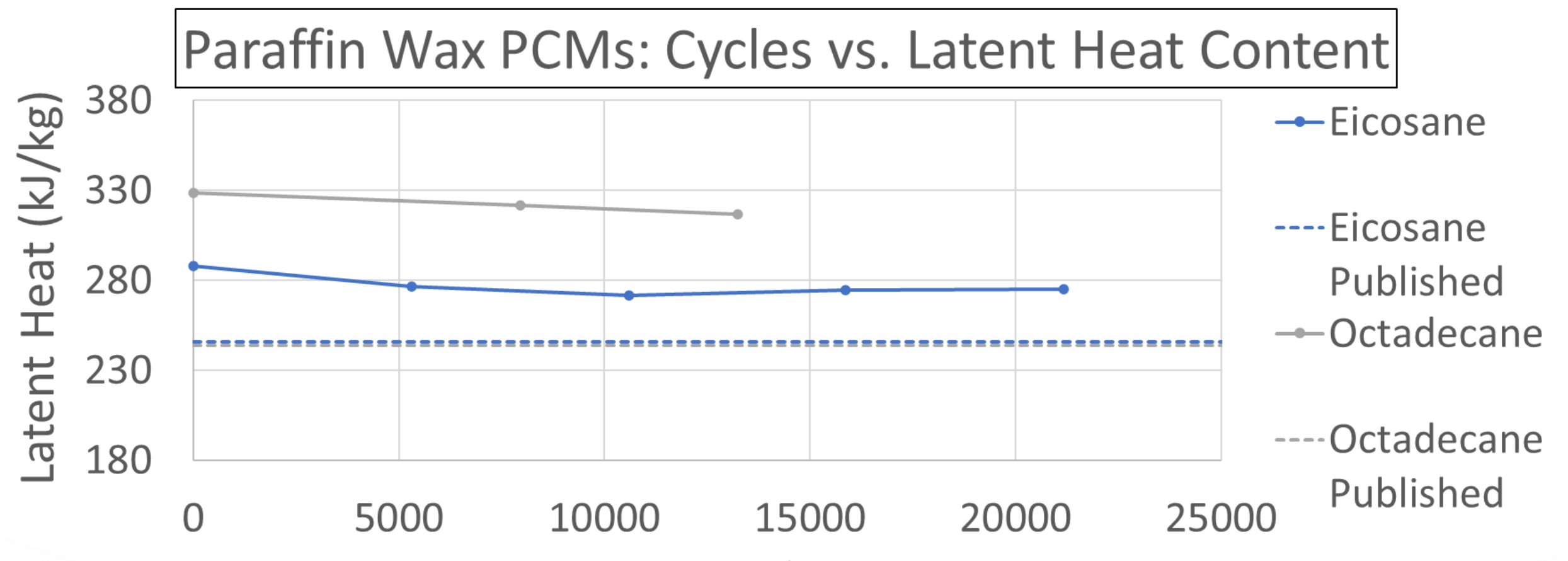
Environmental Chamber



Results

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%

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



Summary

- Phase change materials (PCMs) are materials with high latent heat of fusion content that are used to store and release thermal energy.
- The phase change happens at a constant temperature, therefore PCMs stabilize and decreases the temperature range of electronics during cyclical power loading.
- PCMs are becoming increasingly important for thermal control in many fields, especially small satellites where PCM heat sinks
  1. Allow designers to greatly reduce radiator size by designing for the average heat load rather than the peak value
  2. Provide the same thermal storage with far less mass than a strictly sensible heating thermal solution.
- The design process for a PCM heat sink includes many variables and tradeoffs including not just the PCM material properties, but also the critical internal fin and housing structure and filling procedure.
- An often overlooked PCM material in design is stability over cycles.
- Pure paraffin PCMs have proved 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.
- ACT's cyclical testing of two pure paraffin PCMs, Eicosane and Octadecane, demonstrated long term stable properties through 10,000 cycles.