45th International Conference on Environmental Systems
12-16 July 2015, Bellevue, Washington
ICES-2015-167

# Phase Change Material Heat Sink for an ISS Flight Experiment

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**A flight experiment is being constructed to utilize the persistent microgravity environment of the International Space Station (ISS) to prove out operation of a microgravity compatible phase change material (PCM) heat sink. A PCM heat sink can help to reduce the overall mass and volume of future exploration spacecraft thermal control systems (TCS). The program is characterizing a new PCM heat sink that incorporates a novel phase management approach to prevent high pressures and structural deformation that often occur with PCM heat sinks undergoing cyclic operation in microgravity.**

**The PCM unit was made using brazed aluminum construction with paraffin wax as the fusible material. It is designed to be installed into a propylene glycol and water cooling loop, with scaling consistent with the conceptual designs for the Orion Multipurpose Crew Vehicle. This paper reports on the construction of the PCM heat sink and on initial ground test results conducted at UTC Aerospace Systems prior to delivery to NASA. The prototype will be tested later on the ground and in orbit via a self-contained experiment package developed by NASA Johnson Space Center to operate in an ISS EXPRESS rack.**

## Nomenclature

| | |
|---|---|
| *EXPRESS* | Expedite the Processing of Experiments to the Space Station |
| *ISS* | International Space Station |
| *ORU* | Orbital Replacement Unit |
| *PCM* | Phase Change Material |
| *TCS* | Thermal Control System |
| *UTAS* | UTC Aerospace Systems |

## I. Introduction

Thermal control systems (TCS) for space vehicles often have to accommodate heat loads and environmental conditions that vary over time. In order to accommodate spikes in heat generation or periodic reductions in radiator capacity, these systems can either expel the thermal energy from the vehicle as it is generated or store the energy on-board and dissipate it at a later time. Rejecting energy as it is generated can require prohibitively large radiators, supplemental heat pumping, or expendables for a sublimator or evaporator. Temporarily storing the energy on-board and rejecting it during times when there is excess TCS capacity can save a substantial amount of mass and volume because the balance of the system can be designed to typical rather than worst case conditions[1]. A solid-liquid

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phase change material is an effective way of accomplishing this within a vehicle TCS without increasing the temperature of mating components above their operating limits.

There are many examples where the latent heat of fusion absorbed during the melting of materials is used to keep a system cool. A common example of a solid-liquid PCM heat sink is the ice used in a cooler. Other applications include the use of paraffin wax embedded in the walls of buildings and wax modules that clamp to aircraft electronics to keep them below their operating temperature limits. PCM heat sinks have been used in manned space applications since the Apollo era. The Lunar Rover Vehicle used two boxes of wax to absorb heat from the battery and the drive control electronics[2], while Skylab used paraffin wax embedded in an aluminum honeycomb heat exchanger[3]. A more recent example of a PCM heat sink designed for space comes from Energy Science Laboratories (ESLI), which created a heat sink with paraffin wax and high conductivity graphite that flew as an experiment on STS-95[4].

Despite the few examples of use in prior crewed spacecraft, PCM heat sink technology has had shortcomings that have resulted in significant risks for inclusion in a broader range of vehicle's TCS. These shortcomings stem from density changes that occur during the phase change. When a sealed container of wax is solidified from one surface, the void space that occurs due to contraction is located at the opposite end of the container from the cold surface. When the cold surface is then heated, as happens in a PCM heat sink with active coolant channels, the wax begins to melt from that point, but is trapped by the rest of the solid wax. If the solid wax prevents the melting wax from expanding, locally high pressures and structural failure occur. Some previous spaceflight PCM heat sinks, such as the Apollo battery heat sink[2] and the Extravehicular Mobility Unit (EMU) headlamps[5], have avoided this issue by ensuring that melting and freezing are initiated at different surfaces. In this way, the void space created during the freezing cycle is at the same location where the wax begins to expand during the melt cycle. A flow-through PCM heat sink used in Skylab solved the problem by hermetically sealing paraffin wax within an aluminum honeycomb cavity, thus limiting the amount of pressure needed to push liquid wax into each cavity's ullage space[3]. However, its ability to maintain temperature control in a TCS was relatively low and would be inadequate for today's vehicles. Another solution to hydraulically locked wax was demonstrated in an STS-95 PCM heat sink flight experiment[4]. The experiment used carbon graphite fibers to shape stabilize the liquid paraffin, which prevented melt-induced pressure spikes due to the even dispersion of micro-voids throughout the solidified wax. The manufacturing technology of graphite composite PCM heat sinks presently relies on epoxy bonding the units together. Designing a large scale TCS heat sink using such construction techniques creates a structural issue that requires significant secondary mass to meet high launch vibration requirements.

A new aluminum and wax PCM heat sink has been constructed as part of an ISS flight experiment being built by NASA to prove out fusible heat sink performance in microgravity. The aluminum wax prototype, shown in Figure 1, addresses the historical issues described above, and is an iteration on a concept that has successfully undergone over a hundred freeze/thaw cycles on the ground by using a novel phase management approach that eliminates the pressure spikes seen in previous units. This paper describes the design, construction, and early testing of the PCM heat sink unit.

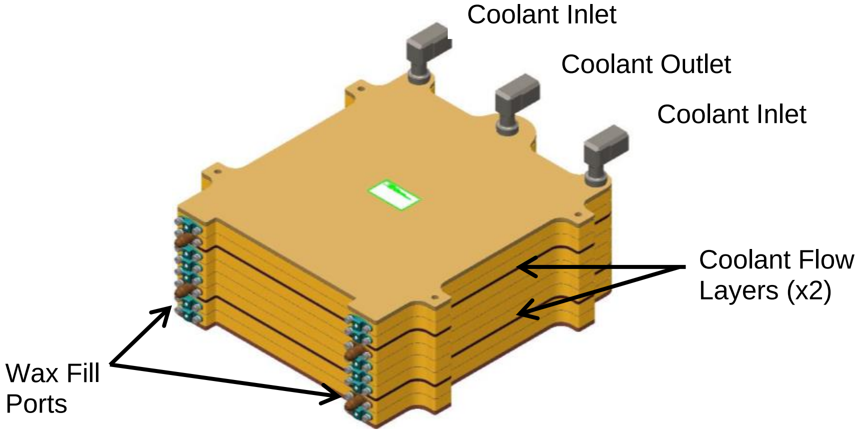

**Figure 1. PCM Flight Experiment Wax Prototype**

## II. Analysis and Design Description

The aluminum and wax PCM heat sink was designed to be the first test article for NASA's ISS PCM experiment. That experiment will occupy a double EXPRESS rack, with room for the heat sink orbital replacement unit (ORU). Due to the limited size of the rack, and the limited power available to it, the test article was scaled to fit, while still allowing essential microgravity issues to be tested. Table 1 shows the sizing requirements for the heat sink. A full scale vehicle heat sink is anticipated to have a similar width relative to coolant flow, but with a greater length and additional coolant and wax layers.

**Table 1: PCM Heat Sink Design Requirements**

| | |
|---|---|
| Maximum envelope: L x W x H | 14.3" x 13.6 " x 7.6" |
| Coolant | 50/50 PGW |
| Nominal Coolant Flow Rate | 94 lbm/hr |
| Wax Melt Point | 10 °C |
| Heat Storage Rate | 300 to 742 Watts |
| Heat Storage Capacity | >710 kJ (Latent heat capacity is 856 kJ) |
| Max. allowable coolant outlet temperature during melt | 11.2 °C |
| Maximum Coolant Pressure | 120 psig |
| Allowable Coolant Pressure Drop | 5.0 psid at 93.6 lbm/hr and -10 °C |
| Leakage | < 1 x $10^{-5}$scc/s Helium at maximum pressure |
| Melt Cycle Life | 17,390 freeze/thaw cycles |
| Vibration Loads | Consistent with soft-stowed cargo |

The test arical is made up of two coolant layers, each sandwiched between four wax layers. There are a total of eight wax layers, each of which is sealed off from the adjoining layers. Coolant flows in a two-pass arrangement with internal headers that are in formed as part of the heat sink stack. The two coolant layers shown in Figure 1 flow in parallel, which is an essential feature to test in microgravity. Full scale heat sinks can have four or mor coolant layers flowing in parallel. Aluminum fins are used in all of the layers for heat conduction and for strength.

Several models were used to aid the design effort. A well-correlated heat exchanger model was used to select the coolant fin configuration, ensuring that they met thermal and pressure drop performance requirements. That model was supplemented with a computational fluid dynamics model to help predict coolant flow distribution within each of the two coolant layers. The phase change material performance was predicted using a two-dimensional nodal model which was correlated to previous test data. It uses an explicit scheme that treats the phase change in each node by holding it at the melt temperature until it absorbs enough energy to fully melt. Coolant flow and sensible heat are also incorporated into the model. Structural and pressure loads were analyzed using a finite element analysis (FEA) of the heat sink. The unit is designed to meet the transportation, launch, environment, and pressure loads identified in the requirements.

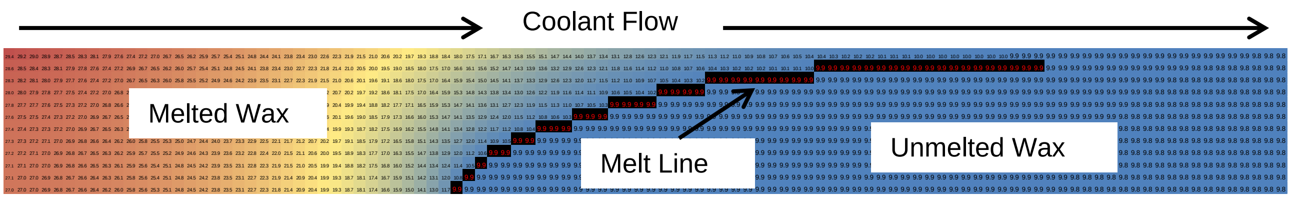


**Figure 2. PCM nodal model output**

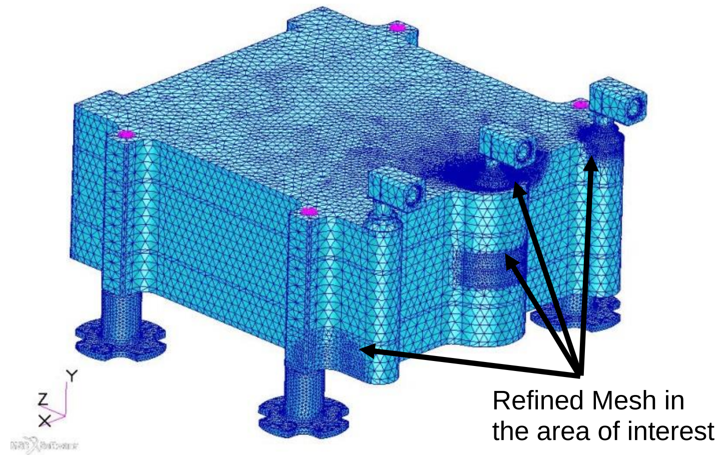


**Figure 3. Finite element model mesh**

## III. Manufacturing

Construction of the PCM heat sink was accomplished using vacuum brazing, welding, and final machining. Heat sink closure bars, fin, parting sheets, and end sheets were precision cleaned, then stacked onto a custom fixture and weighted. The assembly was then vacuum brazed in UTAS's aluminum braze ovens. Coolant ports were welded onto the top afterwards. A series of leak checks and pressure tests ensured that the unit met the $< 1 \times 10^{-5}$scc/s helium leakage requirement after exposure to proof pressure. Each wax layer was then filled and plugged independently. Temporary insulation and instrumentation will be added for a first round of performance testing at UTAS, followed by permanent insulation and instrumentation prior to its integration with the ISS experiment at NASA Johnson Space Center.

## IV. Performance Test Plan

Three sets of performance tests are to take place on the heat sink. The first will be check-out testing at UTAS prior to delivery to NASA. These tests will include thermal performance and gravity orientation sensitivity with regard to PCM cavity pressure. Thermal testing will encompass the heating and cooling power envelope of the ISS experiment as well as higher power melting tests that scale directly to full sized vehicle heat sinks. Gravity orientation testing will monitor pressure transducers coupled to the wax layers to ensure that the melting wax does not become hydraulically locked, and that the phase management features are working as expected.

The second set of tests will take place at NASA with the heat sink integrated into the full ISS experiment. These will help to check out the experiment as a whole and to set baseline performance data on the heat sink. The final set of tests will be conducted on the ISS and will include a repeat of the performance tests as well as life cycle tests. Figure 4 shows the matrix of thermal performance tests that will be conducted on the ground and on the ISS. Test points using powers above 450 watts will only be conducted on the ground due to ISS power limitations.

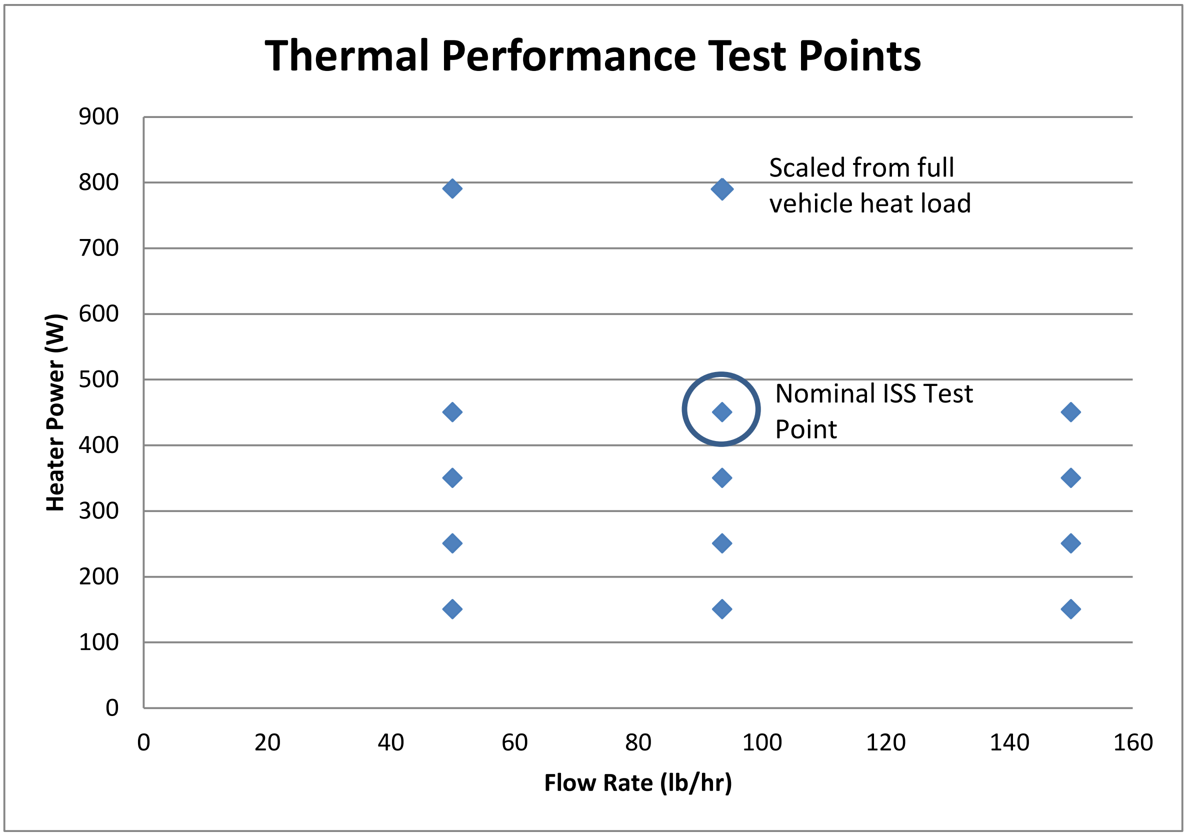


**Figure 4. PCM Heat Sink Thermal Performance Test Points**

## V. Conclusions

A solid/liquid paraffin wax phase change material heat sink was sized, designed and manufactured as part of a flight experiment. The heat sink will be incorporated into an experiment built into an EXPRESS rack for long duration microgravity testing on the ISS. This testing will determine if a novel phase management approach for a coolant driven PCM heat sink will keep the wax from becoming hydraulically locked, and allow the technology to be used in future space vehicles.

The heat sink was sized to fit inside of the EXPRESS rack, but maintains features such as a full scale coolant flow width and parallel coolant flow passages that are essential for testing the technology's viability in microgravity. The item was made using standard vacuum braze methods for aluminum, which provides sufficient thermal performance and strength to withstand launch loads. It is presently undergoing check-out testing at UTAS prior to shipment to NASA Johnson Space Center for integration into the ISS experiment.

## Acknowledgements

Funding for this work was provided under NASA contract NNJ14-4GA01C. The authors would like to acknowledge the NASA for providing the funding and NASA Johnson Space Crew and Thermal Systems Division for their ongoing collaboration to create the PCM flight experiment for the ISS.

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