# Phase Change Material Trade Study: a Comparison between Wax and Water for Manned Spacecraft

**Gregory Quinn and Ed Hodgson**
Hamilton Sundstrand
**Ryan Stephan**
NASA Johnson Space Center

## ABSTRACT

Phase change material heat sinks have been recognized as an important tool in optimizing thermal control systems for space exploration vehicles and habitats that must deal with widely varying thermal loads and environments. In order to better focus technology investment in this arena, NASA has supported a trade study with the objective of identifying where the best potential pay-off can be found among identified aqueous and paraffin wax phase change materials and phase change material heat sink design approaches. The study used a representative exploration mission with well understood parameters to support the trade. Additional sensitivity studies were performed to ensure the applicability of study results across varying systems and destinations.

Results from the study indicate that replacing a wax PCM heat sink with a water ice PCM heat sink has the potential to decrease the equivalent system mass of the mission's vehicle through a combination of a smaller heat sink and a slight 5% increase in radiator size or the addition of a lightweight heat pump. An evaluation of existing and emerging PCM heat sink technologies indicates that further mass savings should be achievable through continued development of those technologies. The largest mass savings may be realized by eliminating the melting and freezing pressure of wax and water, respectively.

## INTRODUCTION

Thermal management systems for space vehicles often have to accommodate heat loads and thermal conditions that vary over time. In order to dissipate spikes in heat generation or periodic reductions in thermal dissipation capabilities, these systems can either expel the thermal energy from the vehicle as it is generated or store the energy on-board and expel it over a longer period of 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 a smaller load on the thermal control system or more favorable heat rejection conditions 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. A solid-liquid phase change material (PCM) is an effective way of storing thermal energy without increasing the temperature of vehicle systems 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 to keep food cold in a cooler. Other terrestrial applications include the use of paraffin wax embedded in the walls of buildings (1) and wax modules that clamp to electronics to keep them below their operating temperature limits (2). PCM heat sinks have been used in manned space applications since the Apollo era. The Lunar Rover Vehicle (LRV) used two boxes of wax to absorb heat from the battery and the drive control electronics (3). A more recent example of a space flight-qualified PCM heat sink comes from Energy Science Laboratories (ESLI), which created a carbon composite heat sink with paraffin wax that flew on STS-95 (4).

NASA's present interest in PCM heat sinks focuses on crewed missions beyond Earth orbit. These missions will have active thermal control systems (ATCS) that maintain cabin and equipment temperatures within prescribed limits. Certain mission scenarios, such as orbiting the moon, create large, periodic swings in the amount of heat that an ATCS can reject when only using a radiator. Although a sublimator or evaporator could be used when the radiators are over-taxed, the mass of evaporant expelled to space adds up quickly as the spacecraft orbits the moon multiple times during a mission. In this case a PCM heat sink can be used to provide continuous heat adsorption capability equal to the excess vehicle load and eliminate the need to use a sublimator or evaporator.

Traditionally, space-based PCM heat sinks use a paraffin wax as the phase change material. Paraffin waxes are non-toxic, have a stable chemistry, and can be made with a wide range of melt points. Tetradecane, pentadecane and hexadecane are pure paraffin waxes with melting points of 5 °C, 10 °C and 18 °C, respectively. These melt points fall within the most useful range for controlling the temperature of a manned spacecraft. As an example, pentadecane was baselined for use in the Orion Crew Exploration Vehicle and has two phase transitions. The first one is a solid-solid phase transition at 28 °F, which has a latent heat capacity of 18.6 Btu/lb (43.3 kJ/kg). The second one is a solid-liquid phase transition at 49.9 °F, which has a heat of fusion of 70 Btu/lb (162.8 kJ/kg).

Water has the potential to significantly reduce a heat sink's mass and volume when compared to wax due to its higher heat of fusion and higher density. Water has a latent heat of fusion of 144 Btu/lb (334 kJ/kg) and a density that is 16% higher than pentadecane (0.920 g/cc for solid water vs. 0.774 g/cc for liquid wax). As with many benefits, there are drawbacks associated with using water as the phase change material. First among them is that water has a lower freeze/melt temperature than the paraffin waxes mentioned above. Therefore, the thermal control system must condition the working fluid to a colder temperature during the refreeze portion of the mission phase. This could result in larger vehicle radiators or the need for heat pumping, which may negate the mass benefits associated with using water as the phase change material. Additional challenges in designing water-based PCM heat sinks include potential corrosion issues that limit material choices and structural issues resulting from water's significant volume change on freezing.

This paper documents a trade study between water ice and paraffin wax as PCM's for manned missions beyond earth orbit. The purpose of the study was to support NASA's selection of PCM heat sink technology development objectives and ultimately of a phase change material thermal sink design concept for future manned missions. The study had two primary goals. The first goal was to show a comparison of water ice and appropriate paraffin wax phase change materials within a representative spacecraft active thermal control system. The comparison included system and component level mass estimates and showed how a water ice PCM heat sink can replace a paraffin wax PCM heat sink and reduce the overall ATCS mass. The second goal was to develop preliminary design level definition of thermal sink configurations for both paraffin and water, taking into account the numerous heat transport / material management matrices and configurations that may be used.

## TRADE STUDY SCOPE

The scope of the trade study encompasses the sizing, system impacts, and key design parameters for a PCM heat sink on a manned spacecraft orbiting the moon. General applicability of the results to other manned missions and systems are also discussed. The study considers the following items.

- Water and pentadecane paraffin wax
- Active thermal control system based on Orion Lunar configuration
- Lunar orbit with 2644 Watt heat load as a sample mission
- Major ATCS level impacts, including photovoltaic cell mass, radiator mass, coolant accumulator mass, and PCM heat sink mass
- Equivalent System Mass (ESM) of each trade option
- Sensitivity analysis of ESM to changes in major trade factors
- Heat sink materials compatibility with water ice
- Launch and vibration loads on heat sink designs
- Maturity of heat sink design options

## SYSTEM MODELING

This trade study sought to determine if a water ice PCM heat sink could be used on a manned spacecraft, and if it would trade favorably compared with a more traditional paraffin wax PCM heat sink. A transient Matlab/Simulink model of a vehicle ATCS was chosen for this task, with a simplified schematic shown in Figure 1. Control of the ATCS is set by the cabin inlet temperature of 47 °F to 51 °F and the minimum internal loop temperature of 20 °F. These are maintained by the cabin and external control valves, respectively.

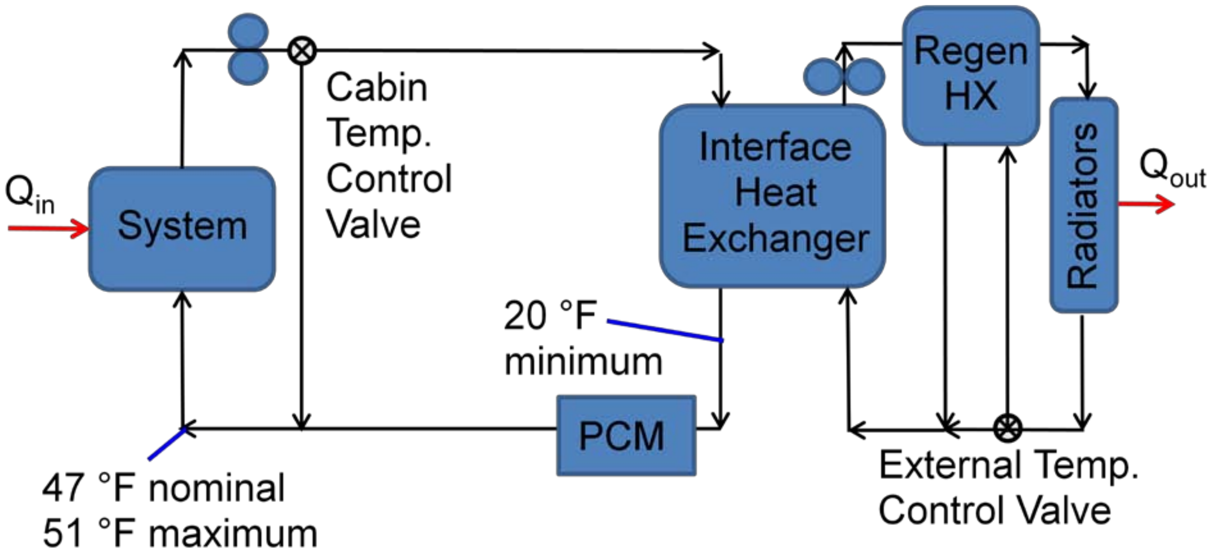

Figure 1: System interactions for the PCM heat sink were evaluated in the context of an active thermal control system modeled on the Orion capsule system design

The heat load, $Q_{in}$, was set at a constant 2644 Watts, and the radiator sink temperature profile was modeled after a lunar orbit profile. These represent a possible mission phase where the vehicle loiters in Lunar orbit while the crew is on the surface. When the vehicle is on the sunny side of the moon it cannot reject all of its 2644 Watts of thermal energy using only the radiators. When it flies into the shadow of the moon, the temperature drops rapidly, giving the radiators excess cooling capacity.

The PCM heat sink was modeled within Simulink using ten nodes. Each node represented one tenth of the coolant flow plate area coupled to one tenth of the PCM cavity volume and mass. A film coefficient was calculated for the coolant based on a notional flow plate, and resistance into the PCM cavity was estimated based on dimensions and conductivities of a notional heat sink made using Laminate Core interstitial material (aluminum and graphite composite manufactured by ESLI). In a real system, the thermal response of a heat sink will vary with dimensions and interstitial materials. Optional heat pump evaporator and condenser models were programmed into the model. The model accounts for thermal capacitance in the major components and transport fluids. Five orbits were run for each experiment, which allowed the system to establish repeatable cyclic operation as defined by negligible change in the temperature profiles from one orbit to the next.

**HEAT PUMP STUDY**

A heat pump model was incorporated into the overall ATCS model as a way of addressing the low melting temperature of water ice. The model consisted of a condenser, an evaporator and a controller. The evaporator temperature could be adjusted and the evaporator and condenser effectiveness were set at 90% each. The overall heat pump efficiency was set as a percentage of the Carnot efficiency. This trade study looked at efficiencies varying between 30 % and 60 % of the ideal Carnot efficiency for the required heat pump evaporator and condenser temperatures for each analysis case.

There were several ways that the heat pump could be arranged to accommodate the difference between the water ice melt point of 32 °F and the cabin inlet set point of 47 °F. Figures 2 through 5 show four arrangements that were tested with the system model. The first two configurations used the heat pump to regenerate the PCM heat sink while the last two configurations used the heat pump to maintain the cabin inlet temperature after the ice PCM was exhausted. In all of the cases the radiator remained at the baseline size. Arrangement # 4 proved to be the most efficient combination of heat pump and PCM heat sink location. Results from each arrangement are shown in Table 1.

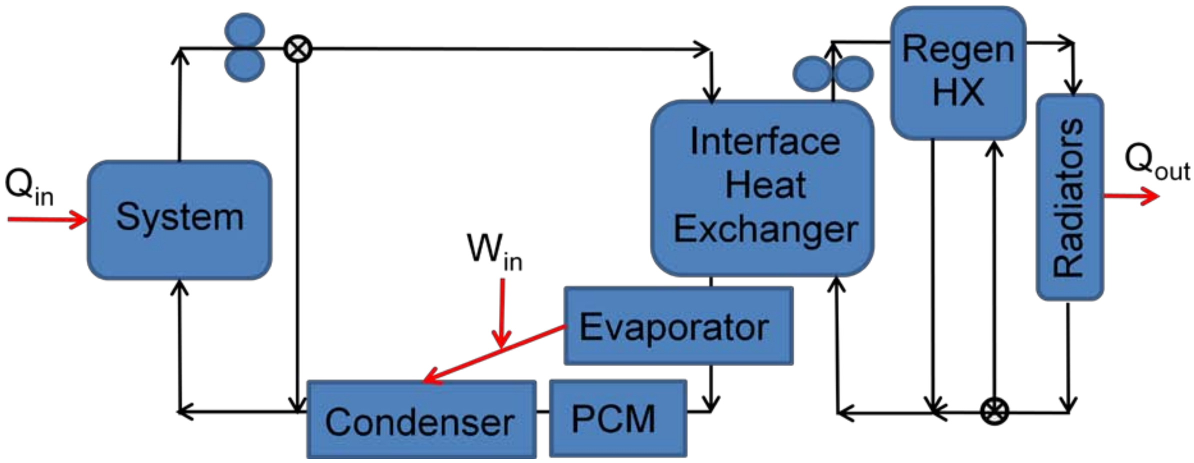

Figure 2: Heat Pump Arrangement # 1, Regenerates ice PCM and keeps energy in internal loop

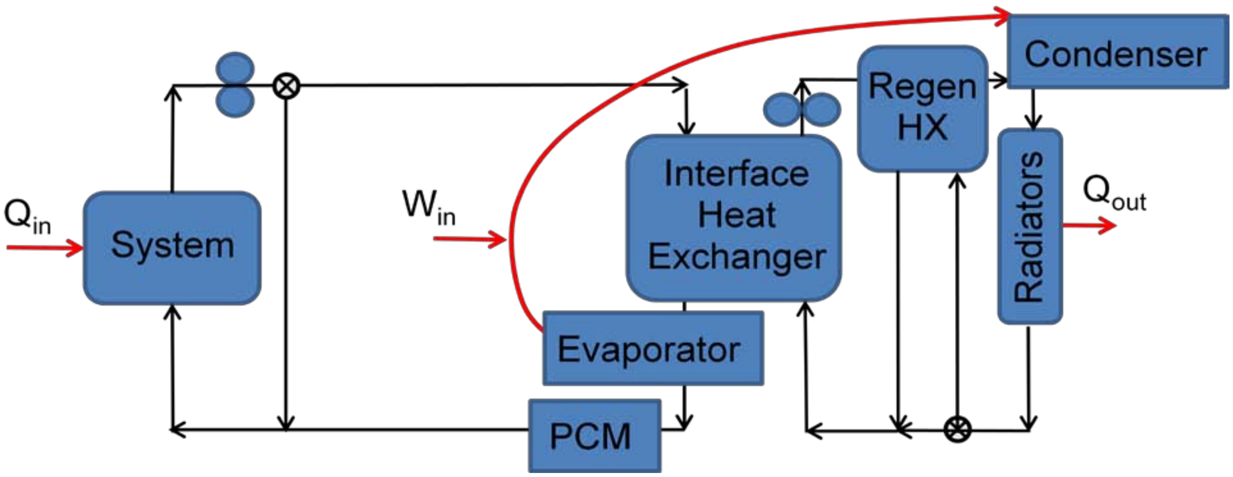

Figure 3: Heat Pump Arrangement # 2, Regenerates ice PCM and puts energy into radiators

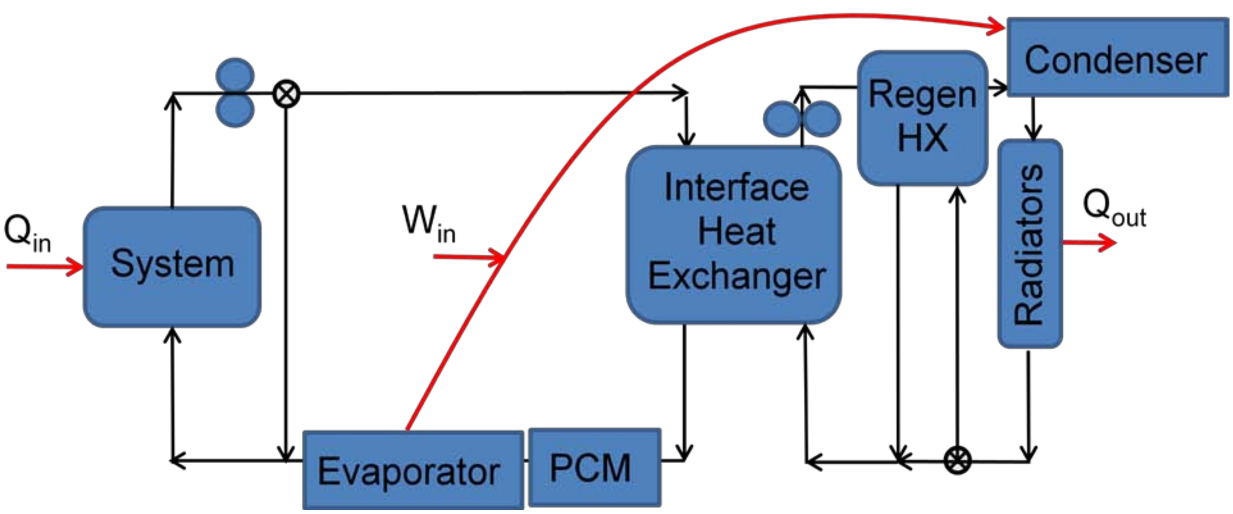

Figure 4: Heat Pump Arrangement # 3, Heat pump as topper with ice PCM in internal loop

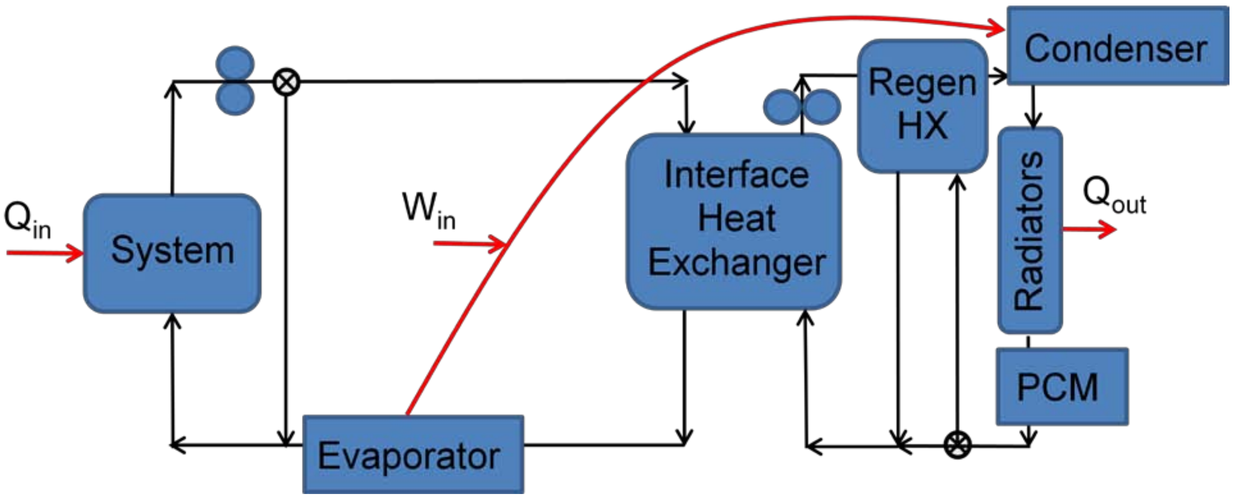

Figure 5: Heat Pump Arrangement # 4, Heat pump as topper with ice PCM in external loop

Table 1: Heat Pump Results

| Arrangement | Cabin Temperature Controlled? | Peak Heat Pump Power (W) | Average Heat Pump Power (W) | Ice PCM Size (lb) |
|---|---|---|---|---|
| 1 | No | N/A | N/A | 34 |
| 2 | Yes | 7100 | 1300 | 34 |
| 3 | Yes | 3000 | 533 | 34 |
| 4 | Yes | 567 | 55 | 34 |

Heat Pump Arrangement # 4 (fig 5) required the lowest heat pump power and smallest PCM heat sink of all the arrangements. This configuration put the PCM heat sink at the outlet of the radiators, where it could be completely regenerated without having to decrease the minimum temperature of the inner cooling loop. The PCM heat sink also gets full flow while being regenerated at the outlet of the radiator, rather than receiving a decreased flow in the inner loop as a result of the need to maintain the cabin inlet temperature at 47 °F. In this arrangement with a 34 lb PCM heat sink, the heat pump moved a maximum of 3939 watts of thermal energy at a peak cost of 567 watts of additional power. The heat pump would require an average of 55 Watts over the entire orbit.

One drawback of having the PCM heat sink at the outlet of the radiator is that it begins to melt when the radiator outlet temperature is below the cabin inlet control temperature. In order to prevent this, a bypass around the heat sink was created, and all subsequent analyses used the bypass arrangement. A simple valve and temperature sensor are all that would be needed to implement this type of bypass, so that the impact on the system would be low. Using a bypass reduces the necessary water mass by about one pound, and the corresponding structure by one to two pounds per heat sink. These saving would have to be traded against the mass of a bypass system.

**SYSTEM MODEL RESULTS**

The system model was first used to determine how large a pentadecane heat sink would need to be in order to control the cabin inlet temperature to 51 °F or less. Results from the model studies were then used in calculating the equivalent system mass of each option, which is documented in the ESM Trade section of this report.

Running the system model with a pentadecane PCM at the outlet of the interface heat exchanger, as shown in Figure 1, results in an optimized pentadecane PCM mass of 54 lb. This configuration keeps the cabin inlet temperature at or below 51 °F without the need for a sublimator, a heat pump or extra radiator area. For comparison, a water PCM heat sink with the equivalent thermal capacity would have 34 lb. of water.

As a first attempt to use water as the phase change material in the model, the wax was replaced with an equivalent mass of water. If 54 lb of water could not maintain the cabin inlet temperature, it would demonstrate that heat pumps or extra radiator area were needed. When the pentadecane heat sink was replaced with a 54 lb water heat sink without any other changes to the schematic or system, only 24% of the heat sink could be regenerated and the cabin inlet temperature spiked to 74 °F. The reason for this is that the water PCM heat sink is located in the inner coolant loop. When a pentadecane wax heat sink is used and the radiator outlet temperature drops below 49 °F, the heat sink immediately begins to freeze. In addition, the cabin inlet temperature controller maintains the full flow of coolant through the wax PCM heat sink during freezing, allowing it to regenerate as quickly as possible. When water ice is used in the same location, the heat sink does not begin to regenerate until the radiator outlet temperature drops below 32 °F. The conditions for regenerating the ice PCM become even worse, because the cabin inlet temperature controller reduces flow to the heat sink in order to mix the 32 °F PCM outlet temperature with a hot fluid stream to create 47 °F into the cabin.

Due to the issues stated above, a more effective location for a water PCM heat sink is at the outlet of the radiators, where the coolant temperature is allowed to drop below 20 °F and the heat sink can receive the full flow rate while it's being regenerated. The drawback to locating the PCM heat sink at the outlet of the radiator was that it begins melting before the radiator outlet temperature is higher than the cabin control temperature. When a 54 lb water ice PCM heat sink is located at the outlet of the radiator, 70% of the heat sink can be regenerated, and the maximum cabin inlet temperature is reduced by 15.8 °F to 58.2 °F. This is still higher than the maximum allowable cabin inlet temperature of 51 °F, so either a heat pump must be added as in Figure 5, or additional radiator area must be added to allow the heat sink to fully regenerate in each orbit.

The most efficient configuration found in this study for using a heat pump with an ice PCM is shown in Figure 5, where the heat pump is used to maintain the cabin inlet temperature at 51 °F when the PCM heat sink is exhausted. Any sized heat sink can be used with a heat pump to maintain the cabin inlet temperature, but as Figure 6 shows, the heat pump capacity is a function of PCM heat sink mass. Water ice heat sink masses of 20 lb to 54 lb were considered, along with heat pump efficiencies of 30% of Carnot up to 60% of Carnot, as defined in Equation 1.

(1)

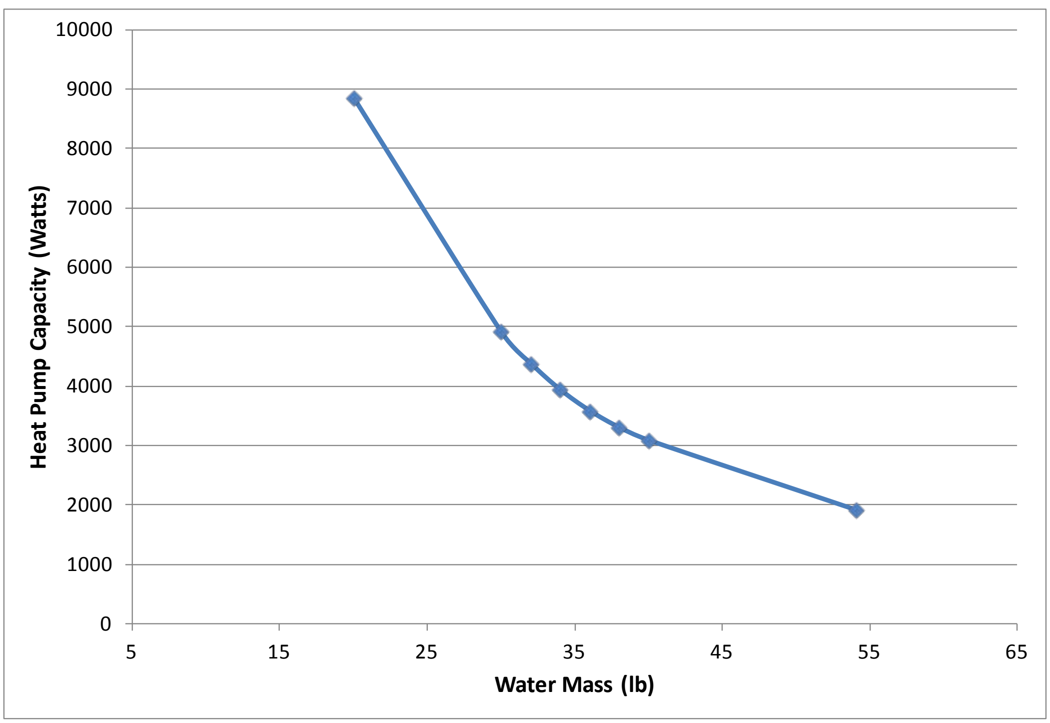


Figure 6: Heat pump capacity as a function of Water mass in the heat sink. Heat pump efficiency set at 50% of Carnot.

Results show that increasing the PCM heat sink size decreases the power needed for the heat pump. However, Figure 6 shows that even if an ice heat sink contains the same amount of mass as a pentadecane heat sink (54 lb), it still requires a heat pump in the sample mission and system configuration used for this study.

The second approach to getting a water ice PCM heat sink to maintain the cabin inlet temperature is to increase the radiator area, which would allow more energy to be radiated to space and may allow more of the heat sink to freeze. The baseline radiator for the sample mission had 218 $ft^2$ of total area. The model was run with up to 20% additional area. Table 2 and Figure 7 show how increasing the radiator area helped the system to meet the cabin inlet temperature and allowed for the use of smaller ice PCM heat sinks. A similar set of experiments were run with the model and a pentadecane wax heat sink. Those results are also shown in Table 2 and reveal that the wax PCM cannot be made much smaller, even with significantly larger radiators.

Table 2: Effect of radiator size on PCM mass

| PCM Material | Radiator Size | PCM mass (no structure) | Maximum Cabin Inlet Temperature |
|---|---|---|---|
| | | lb | °F |
| **Wax (Baseline)** | **100%** | **54** | **51** |
| Wax | 102% | 50 | 52.0 |
| Wax | 105% | 50 | 51.6 |
| Wax | 110% | 50 | 51.3 |
| **Wax** | **115%** | **50** | **51.0** |
| Water | 102% | 54 | 48 |
| **Water** | **102%** | **50** | **50** |
| Water | 102% | 42 | 56 |
| **Water** | **105%** | **42** | **50** |
| Water | 105% | 40 | 52 |
| Water | 105% | 38 | 55 |
| **Water** | **110%** | **40** | **49** |
| Water | 110% | 38 | 52 |
| Water | 120% | 54 | 48 |
| Water | 120% | 40 | 48 |
| **Water** | **120%** | **38** | **49** |
| Water | 120% | 36 | 52 |

Note: Bold entries meet cabin inlet temperature requirements

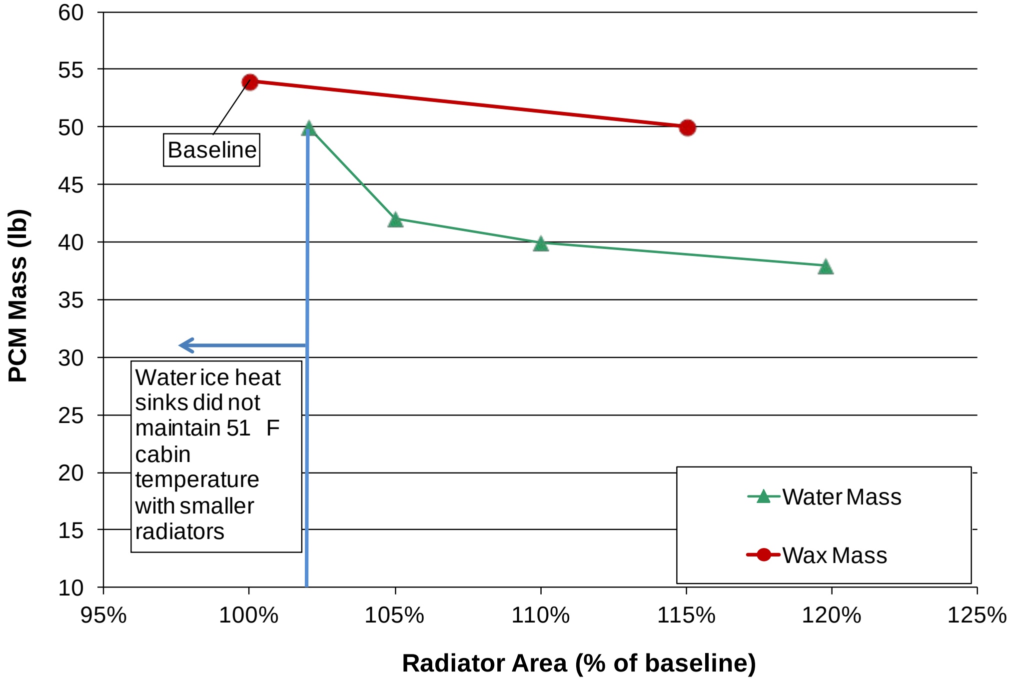


Figure 7: Minimum PCM mass at differing radiator sizes necessary to maintain a 51 °F Cabin inlet temperature

**COMPONENT ANALYSIS**

While the system-level comparison of water and wax as phase change materials showed how much material may be needed in a system and how to effectively modify the system to take advantage of the heat sink, a component-level analysis was required to understand how much structure may be needed to make a practical heat sink. The component-level analysis shows what total heat sink mass may be required for a given thermal capacity, what some of the major driving factors are that affect that metric, and what other issues exist when wax or water are used as the PCM.

In order to be effective, a PCM heat sink must:

- Support complete or nearly complete use of the heat capacity of the PCM
- Provide effective heat transfer between a system heat load interface and the phase change material in melted, thawed, and intermediate conditions.
- Contain and support the PCM and maintain system heat transfer interfaces across the full range of host vehicle operating environments.

Major challenges in meeting these requirements include the modest thermal conductivity of the PCM, which drives the need for large internal extended heat transfer surface areas, and significant changes in PCM density between the frozen and thawed states. Together these factors can drive dramatic increases in heat sink mass for the extended heat transfer surfaces and for structural provisions required to deal with PCM volume change across mission gravity environments, vehicle orientation, and varying thermal cycles. The potential for PCM corrosion of other sink materials can compound these challenges, restricting material choices and driving further increases in heat sink mass, especially with the choice of water as the PCM. Optimum solutions to these challenges in practically manufacturable heat sinks remain a current development objective. Within the scope of this trade study, design alternatives were evaluated based on current knowledge and best estimates of design characteristics of emerging solutions. Uncertainty in the conclusions reached were addressed through parametric consideration of a range of PCM mass fraction values in the heat sink.

Most often, system heat transfer to the PCM heat sink is through a circulating heat transfer fluid. That is the design case specifically addressed in this study.

Phase change material heat sinks can be produced in many different configurations, each of which has its own benefits and drawbacks. The list below shows the most relevant configurations for a spaceflight application after removal of several candidates that have been shown ineffective in past development.

- Compact heat exchanger
  - Aluminum fin
  - Graphite foam
  - Laminate Core Aluminum/graphite composite from ESLI
  - Fiber Core graphite from ESLI
- Shell-in-tube with PCM on the tube side
- Flow through packed bed

The compact heat exchanger alternatives shown reflect varying design approaches that combine attempts to minimize stresses by localizing the phase change material through melt-thaw cycles and structural design to withstand stresses that result from imperfect localization. In general, each of these features multi-functional material, use in which extended heat transfer surface also supports PCM localization, heat sink structural design, or both. At the current state of development, these alternatives present a trade-off between heat sink mass and manufacturability risk over a range of almost 2:1 in mass when design solutions that are robust across gravity environments, orientations, and thermal load patterns are considered. Values presented in Table 3 reflect current design estimates of the range of mass fraction performance that may result as development is completed.

The shell-in-tube heat exchanger is prevalent in industrial applications and may be an effective approach to containing the high melt pressures that have been measured in paraffin PCM heat sinks. By putting the wax into a tube (2 inch diameter), the melt pressure can be contained without breaking it. The pressure inside the tube can be reduced even further by putting it into cross flow, rather than axial flow, so that the melting wax does not act like a piston attempting to extrude solid wax down the length of the tube. At practical design tube diameters, interstitial materials inside the tube are still required for effective heat transfer to the wax. This can be metal fins, aluminum foam or graphite foam.

There is a level of uncertainty regarding the thermal performance and PCM mass percent that can be achieved using a shell-in-tube arrangement. An optimistic look at the shell side mass and the tube packing density is reflected in the values presented in Table 3, which indicates that it may be competitive with the compact heat exchanger approach. However, actual thermal performance limitations, dynamic loading considerations and real manufacturing considerations are likely to increase the mass of the structure, which would result in a lower PCM mass percentage. The shell-in-tube design may also be limited to use with paraffin wax. Whereas the wax melt pressure can be mitigated by using carbon foam or a cross flow design, it is unlikely that these approaches would effectively control the freezing pressure caused by water ice. Additional features, with associated mass penalties, may be necessary if water is used as the PCM.

The last PCM heat sink arrangement that was considered in detail for this study was a packed bed of encapsulated PCM beads. Packed beds are frequently used in industrial and space applications to create large contact areas between the process fluid and a solid material such as a catalyst, an ion exchange resin or a molecular sieve. A PCM heat sink made using encapsulated beads would not require an interstitial material and would have the melting/freezing volume change taken up by the coolant system's accumulator. Some drawbacks to the packed bed approach include the need for a large coolant charge in the heat sink, relatively poor thermal conductivity into the beads of wax if they are made too large, and relatively high pressure drop in the coolant if they are made smaller. This type of heat sink is also limited to systems that have a pumped coolant loop. Very small beads of PCM could be loaded into another interstitial structure, like solid amines are loaded into aluminum foam for $CO_2$ removal. This would allow the beads to be used in surface mounted heat sinks while also solving the volume expansion issue. The drawback is that the mass % of PCM would be significantly lower than the other approaches discussed in this study.

**COMPARISON OF DESIGN APPROACHES**

Table 3 compares estimated mass characteristics for each of the three major design approaches considered at the baseline PCM capacity derived for this study. In each case, optimistic and pessimistic values are presented reflecting uncertainty at the present stage of development. Corresponding PCM mass fraction values for each heat sink design approach are applied in scaling for analyses at different heat sink capacities.

Table 3: Heat Sink Design Masses

| | | Compact Heat Exchanger | | Packed Bed | | Shell-in-Tube | |
|---|---|---|---|---|---|---|---|
| | | Maximum Mass | Minimum Mass | Likely Mass | Minimum Mass | Likely Mass | Minimum Mass |
| Wax | lb | 54 | 54 | 54 | 54 | 54 | 54 |
| Encapsulant | lb | N/A | N/A | 30 | 14 | N/A | N/A |
| Coolant Charge | lb | 0.1 | 0.1 | 66 | 48 | 60 | 56 |
| Structure | lb | 134 | 52 | 24 | 20 | 42 | 28 |
| Accumulator | lb | N/A | N/A | 2 | 2 | N/A | N/A |
| TOTAL | lb | 188 | 106 | 176 | 138 | 156 | 138 |
| Wax PCM Mass % | | 29% | 51% | 31% | 39% | 35% | 39% |

Both the packed bed configuration and the shell-in-tube configuration should be able to achieve a PCM mass percentage above 30%, but are unlikely to have a mass percentage over 40%, even with significant development efforts. The packed bed approach should be fully compatible with water as the PCM, with a wide range of shell walls available, including acrylic and other polymers. The shell-in-tube approach would likely need additional design features to manage the freeze pressure caused by ice.

**ESM TRADE**

An analysis of the Equivalent System Mass was done for the wax and water PCM configurations examined in the system and component portions of this study. The baseline system used 54 lb of pentadecane wax. The PCM mass percent was based on a total unit mass that was 3.25 times the wax mass, which results in 30.8% wax. The radiator mass factor was set at 1.0 lb/ft$^2$. The solar power mass factor was taken from NASA's 2004 Baseline Values and Assumptions Document (BVAD) as 44.1 lb/kW. The heat pump mass factor was taken from a sampling of small aircraft refrigeration systems. The curve fit to the data is 17 lb plus 14.4 lb per kW of cooling capacity. A similar look at the ASHRAE handbook values for heat pumps showed a significantly higher mass factor for ground based units.

Results of the ESM trade are shown in Figures 8 – 10. The first set of calculations compares the baseline pentadecane system with water heat sinks that use a heat pump to maintain the proper cabin inlet temperatures. The heat pump allowed water to be used as the PCM, which in turn allowed the PCM mass to decrease. The ESM calculations shown in Figure 8 were done assuming that the vehicle's solar panels and power system were large enough to accommodate the extra heat pump power demands. This provided an optimistic evaluation of the heat pump option. As Figure 8 shows, the savings from using a smaller PCM mass do not quite make up for the mass penalty of adding a heat pump. If a vehicle had to increase the size of its power system to use a heat pump, the water PCM option would be further burdened with 100 lb to 400 lb of extra power system mass. Figure 8 also shows that as long as the power system is large enough, the heat pump efficiency has very little effect on the overall system mass.

Figure 8 contains a curve that represents the change in system mass that can be realized if a heat pump can be made 12% lighter than the present small aircraft units. With the lighter heat pumps, and an adequately sized power system, the water PCM heat sink could be used without significant mass penalties or savings. Such a heat pump would have a cooling capacity of 4000 Watts and a mass of 65 lb.

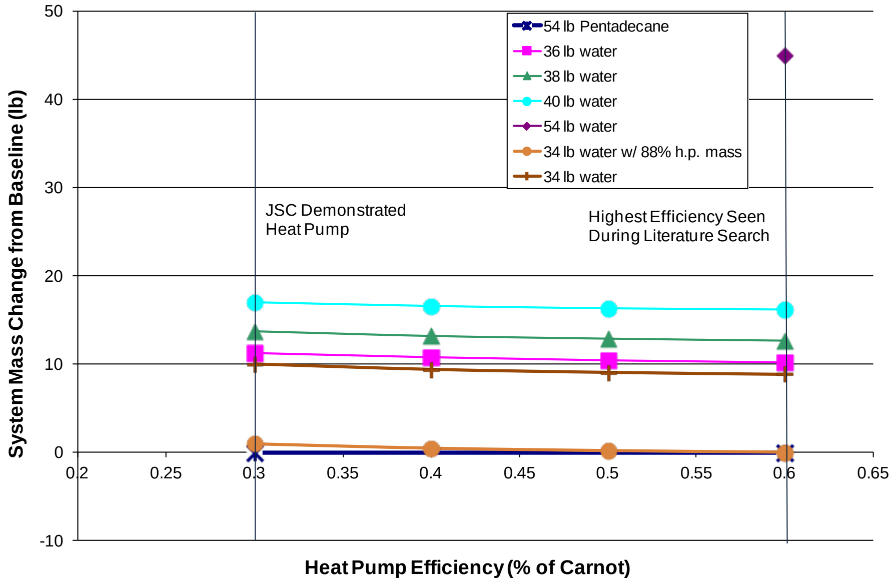


Figure 8: Heat Pumping Allows Use of Water PCM, but Requires Extra System Mass. Assumed 31% PCM mass and no additional solar panel mass

A second set of calculations was done to evaluate the merit of increasing the radiator size. These results are shown in Figure 9. Increasing the radiator size by only 2% allows a water PCM heat sink located at the outlet of the radiator to fully regenerate during the lunar orbit. Further increasing the size of the radiator allows smaller heat sinks to be used. However, the payback between a larger radiator and a smaller heat sink hits a maximum at about 5% extra area with 42 lb of water in the heat sink. When both the wax and the water heat sink are sized assuming a PCM mass fraction of 31%, the mass savings for using water rather than wax is 28 lb, or 7% of the original heat sink and radiator mass.

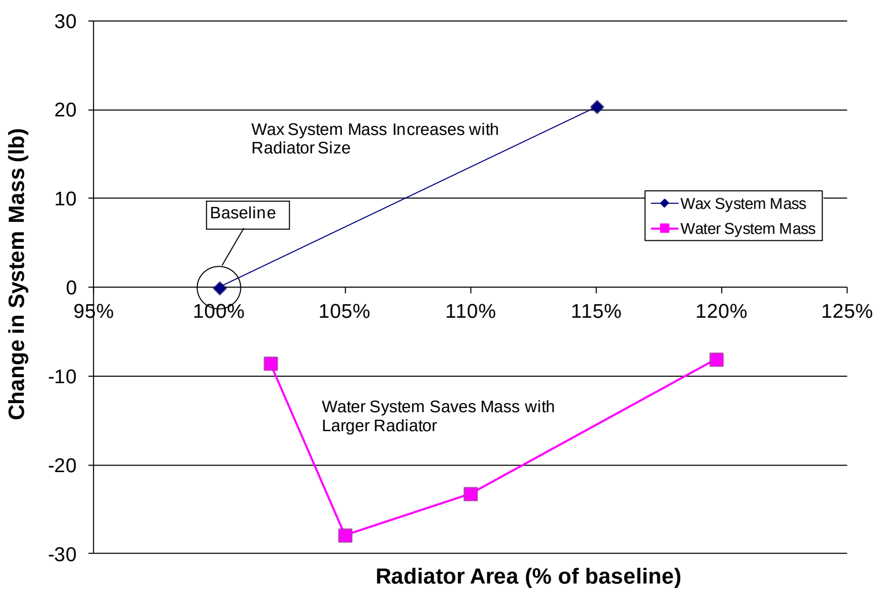


Figure 9: Adding Radiator Area Allows Use of Water PCM and Reduces Equivalent System Mass

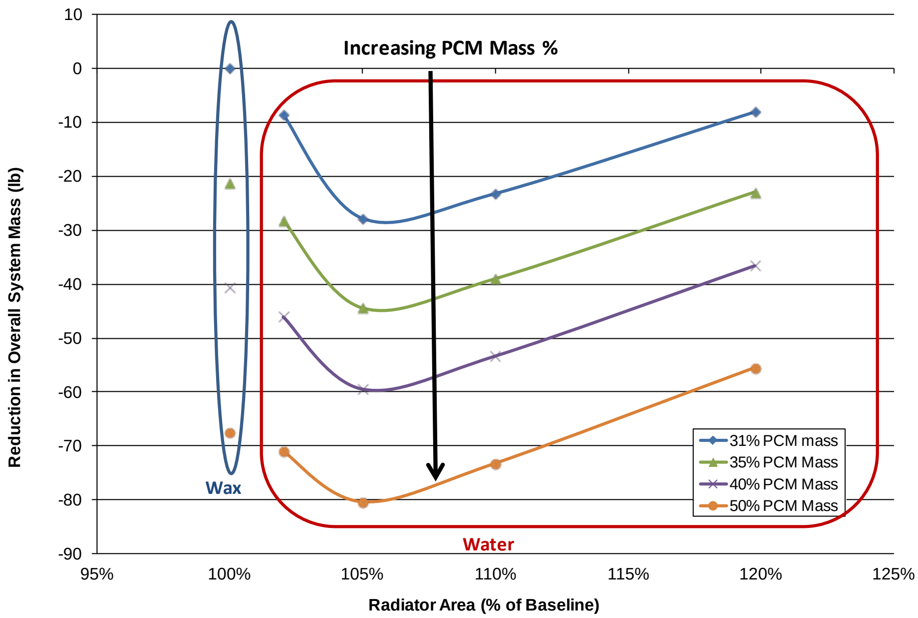


Figure 10: Increasing PCM mass % significantly reduces total system mass

Results from the component analysis showed that the PCM mass percent for a given technology and phase change material can range from 29% to 51%. The mass savings that can be realized by increasing the PCM mass percent in a heat sink are shown in Figure 10 for wax and for water. Each curve in the figure represents a PCM mass percentage, while points on a curve show the mass savings as a function of increasing radiator area. A significant mass savings can be realized for any selection of PCM if the mass percentage in the module is increased from 30% to 50%. An ATCS with a pentadecane heat sink can see a 68 lb decrease in mass if its PCM mass percentage increased across this range. The maximum system mass savings for this sample mission would be realized by using a PCM heat sink that is 50% water by mass. In such a case, the total heat sink and radiator system mass could be as low as 317 lb, reflecting a 20% savings of 80 lb.

<u>Sensitivity Analysis</u>

Although the trade study did not directly evaluate a system model with alternative cabin set point temperatures, certain conclusions were gathered from the results that used a 47 °F to 51 °F set point. The pentadecane wax heat sink provides an effective solution for leveling off the heat loads during a lunar orbit because it melts at 50 °F. This is important first of all because the melt point is below the maximum control point, which is necessary to provide effective temperature control. Second, the melting point is high enough that it creates the highest temperature potential possible between the cold coolant and the wax when regenerating the heat sink. If the cabin inlet temperature is lowered with the same external thermal environment, a wax PCM heat sink will end up paying similar system mass penalties to the water PCM heat sink. The maximum amount of wax that could be re-frozen in an orbit would decrease for a given radiator size, which would force the system to either increase the radiator area, use a topping evaporator, or add a heat pump to maintain the set point temperature. These penalties would make a water ice PCM heat sink more competitive due to its higher heat of fusion. A mission or vehicle that would allow a hotter control temperature would see decreases in the mass of a heat sink that used either water or wax. The exact break-even points between water and wax and trade results would have to be evaluated for any particular mission and vehicle

## CONCLUSION AND RECOMMENDATIONS

This trade study evaluated the major system impacts of using water ice as a replacement for pentadecane wax in a heat sink designed for a manned lunar vehicle. The study used a model of a lunar vehicle's active thermal control system to evaluate the impacts of using different phase change materials, various sizes of heat sinks, different heat pump configurations and larger radiator sizes. The study also evaluated the most promising PCM heat sink technologies with respect to mass, structural loads, materials compatibility, and technology readiness level. Results showed that water ice was a credible replacement for pentadecane wax when either a light weight heat pump was added to the system or the radiator area was increased by as little as 2%. Other conclusion are:

- A 42 lb water PCM heat sink with 5% additional radiator area provided 28 lb of system mass savings
- A 34 lb water PCM heat sink combined with a state of the art heat pump would be about 9 lb heavier than the baseline pentadecane PCM heat sink.
- Decreasing the heat pump mass by 12% would allow the water heat sink system to break even with the baseline option
- The largest mass savings was found by increasing the PCM percentage in the heat sink. Increasing the PCM mass from 30% to 50% of the total heat sink can save up to 68 lb.
- Compact heat exchanger type heat sinks have the potential to achieve the lowest mass among the options that were evaluated (51% PCM)
- Packed bed and shell-in-tube type heat sinks offer alternative paths for developing heat sinks with low to medium PCM mass percentages. (31% to 39%)
- Lower ATCS control temperatures, such as those required for systems with a condensing heat exchanger, will favor the use of a water PCM heat sink

The numerical results of this trade study are dependent upon the thermal environment of the spacecraft, the availability of ample power, the ability to increase radiator panel area, and the structural loads found on the sample mission vehicle. Changes in these parameters will skew the results in different directions. For example, lower structural loads will increase the PCM mass percentage of the heat sink for any of the compact heat exchanger approaches. A colder thermal environment may allow a water ice heat sink to be used without using a heat pump or increasing the radiator area. The optimal design solution for a particular mission will be dependent on all of these factors, but this trade study shows that there are viable ways of implementing a heat sink that use heat pumps, slightly larger radiators, and water ice. Future manned space vehicles should consider all of these options while the overall ATCS is still evolving so that the maximum mass savings can be achieved. In addition, development of PCM heat sink technology should focus on the following issues:

- Both water and wax as phase change materials
- Design approaches that eliminate the high pressures caused by melting and freezing
- The likely structural loads experienced during launch

## ACKNOWLEDGEMENTS

The authors would like to acknowledge NASA Johnson Space center for funding the study and Tim Knowles at ESLI for sharing his knowledge regarding the Carbon Core and Fiber Core materials.

## REFERENCES

1. Sharma, A., Tyagi, V., Chen, C.R., Buddhi, D., “Review on Thermal Energy Storage with Phase Change Materials and Applications”, Renewable & Sustainable Energy Reviews, 13 (2009) 318-345.

2. Kandasamy, R., Wang, X., Mujumdar, A., “Transient Cooling of Electronics Using Phase Change Material (PCM)-Based Heat Sinks”, Applied Thermal Engineering, 28 (2008) 1047-1057.

3. Creel, R., “Apollo Rover Lessons Learned: Applying Thermal Control Experiences On Apollo Lunar Rover Project To Rovers For Future Space Exploration”, Presentation located at http://history.nasa.gov/alsj/creel_lrv_experiences_alsj.pdf (2007)

4. Energy Science Laboratories, Inc. Phase Change MaterialProduct Datasheet located at http://www.esli.com/downloads/pcm_heatsink_description_sheet.pdf

5. Medrano, M, et al., “Experimental Evaluation of Commercial Heat Exchangers for use as PCM thermal Storage Systems,” Applied Energy (2009), doi:10,1016

6. Alvarado, J., Marsh, C., Sohn, C., Phetteplace, G., Newell, T., “Thermal Performance of Microencapsulated Phase Change Material Slurry in Turbulent Flow Under Constant Heat Flux”, International Journal of Heat and Mass Transfer, 50 (2007) 1938-1952.