Testing and Failure Mechanisms of Ice Phase Change Material Heat Exchangers

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Phase change materials (PCM) may be useful for thermal control systems that involve cyclical heat loads or cyclical thermal environments such as specific spacecraft orientations in Low Earth Orbit (LEO) and low beta angle Low Lunar Orbit (LLO). Thermal energy can be stored in the PCM during peak heat loads or in adverse thermal environments. The stored thermal energy can then be released later during minimum heat loads or in more favorable thermal environments. One advantage that PCM's have over evaporators in this scenario is that they do not use a consumable. The use of water as a PCM rather than the more traditional paraffin wax has the potential for significant mass reduction since the latent heat of formation of water is approximately 70% greater than that of wax. One of the potential drawbacks of using ice as a PCM is its potential to rupture its container as water expands upon freezing. In order to develop a space qualified ice PCM heat exchanger, failure mechanisms must first be understood. Therefore, a methodical experimental investigation has been undertaken to demonstrate and document specific failure mechanisms due to ice expansion in the PCM. A number of ice PCM heat exchangers were fabricated and tested. Additionally, methods for controlling void location in order to reduce the risk of damage due to ice expansion were investigated. This paper presents the results of testing that occurred from March through September of 2010 and builds on testing that occurred during the previous year.

I. Introduction

Future spacecraft thermal control systems may include a Phase Change Material (PCM) heat exchanger to ensure that the system maintains the required setpoint temperature throughout the mission profile. This setpoint temperature must be maintained despite radical changes in the vehicle's heat rejection requirement and ambient thermal environment throughout the mission.

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A rapidly changing thermal environment can occur throughout the solar system. One such example of a quickly varying thermal environment is that encountered by a spacecraft in Low Lunar Orbit (LLO). Figure 1 shows the spatial distribution of the Lunar surface temperature. Because the moon does not have an atmosphere, the Lunar surface temperature varies from approximately 400 Kelvin to less than 100 Kelvin. The hottest portion of the lunar surface corresponds to the point directly aligned with the sun. This large variation in Lunar surface temperature results in rapid changes in the incident infrared heat flux on a spacecraft's radiator panels throughout a low beta angle orbit. The resultant variation in sink temperature leads to cyclic fluctuations in the radiator capability as shown by the red curve in Figure 2.

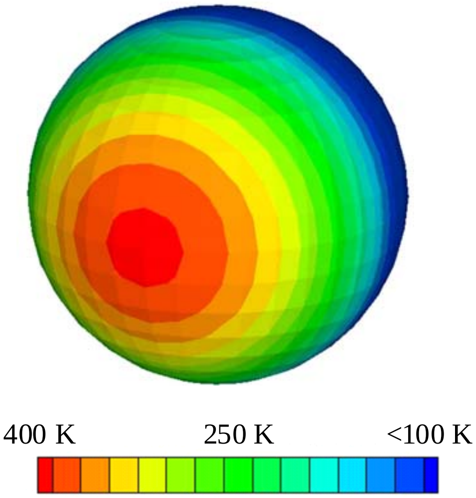


Figure 1. Lunar surface temperatures.

The radiator capability shown in this curve is representative of a 100 km circular orbit with a beta angle of zero degrees. In addition to the radiator capability, the vehicle heat rejection requirement is depicted by the blue curve. For this example, the vehicle heat rejection requirement is assumed to be a constant 4800 Watts. For the majority of the two-hour orbit, the radiator capability exceeds the heat rejection requirement. However, there are several times during the orbit, where the radiators are not capable of rejecting the full vehicle heat load. It is during these times, that a Supplemental Heat Rejection Device (SHReD) is required. The SHReD requirement is simply the difference between the heat rejection requirement and the radiator capability (shown as the green curve in Figure 2).

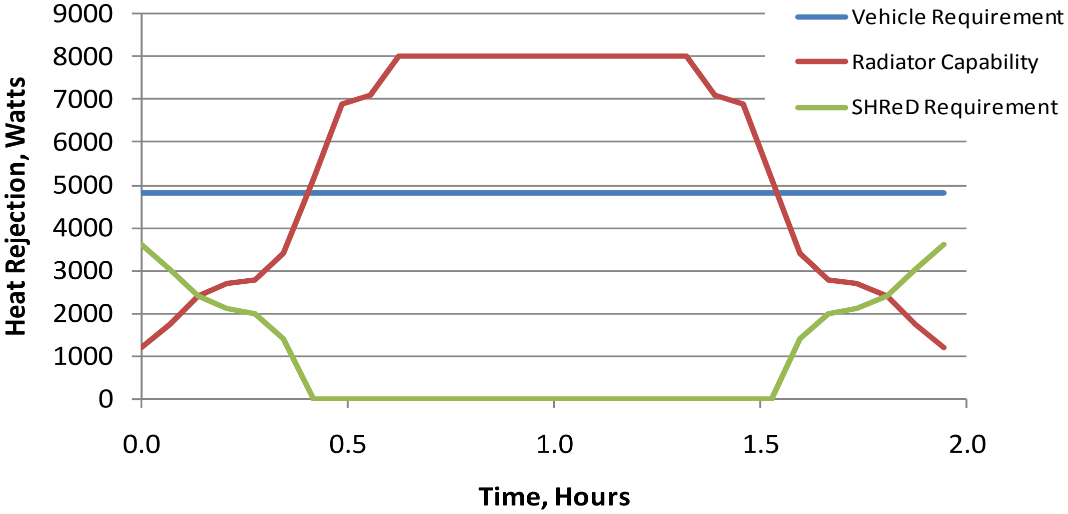


Figure 2. SHReD Requirements

Proper selection of the SHReD technology depends on the duration of the mission phase requiring a SHReD. For short missions, an evaporative heat sink may prove to be most mass effective. The rationale for this conclusion can be demonstrated by studying Equation (1).

$$Mass = \frac{E}{H_f} \tag{1}$$

In the preceding equation, E represents the energy requirement which is given by the integral of the green curve in Figure 2, and H_f is the change in enthalpy of the fluid medium in the SHReD. For an evaporator using water as the evaporant, the change in enthalpy is approximately 2500 kJ/kg. Using water as a solid-liquid phase change material results in a change of enthalpy of 333 kJ/kg. However, because an evaporator relies on a consumable fluid, it can become mass prohibitive for long duration missions. Therefore, a liquid-solid PCM heat exchanger is often chosen for long duration missions because it does not require a consumable.

The current state-of-the-art for PCM heat exchangers uses a paraffin wax as the phase change material. This project is investigating the use of water as a PCM due to water's significantly higher heat of fusion. Equation (1) can also be used to compare two separate phase change materials. A PCM with a high heat of fusion is desirable as it will reduce the mass of the vehicle's SHReD. The heat of fusion for n-pentadecane (a commonly chosen paraffin wax) is approximately 200 kJ/kg whereas the heat of fusion for water is 333 kJ/kg as mentioned above. The use of water as the phase change material has the potential to reduce the heat exchanger mass by approximately 70%.

The use of water is not without challenges, however. Unlike most materials, water expands as it freezes leading to concerns regarding structural integrity of the hardware. The objective of the current task is to assess the feasibility of replacing the commonly used paraffin-based material with water to realize the potential mass benefits associated with this change.

In previous testing[2], a series of water PCM test articles were procured and tested at JSC for the purpose of better understanding and documenting the technical issues associated with the expansion of water within a PCM heat sink. One of these test articles was the Replicative Ice PCM (RIP), owing its name to the fact that it replicates the 450 kJ latent energy storage capacity of the baseline wax PCM unit. Each of the two other test articles was a Small Heatsink of Replicative Ice Material for Phase change (SHRIMP). These smaller units had a 40 kJ latent energy storage capacity. Both SHRIMP's and the RIP included a 20% air gap for the purpose of accommodating the expansion of water upon freezing. A photograph of these test articles is shown in Figure 3.

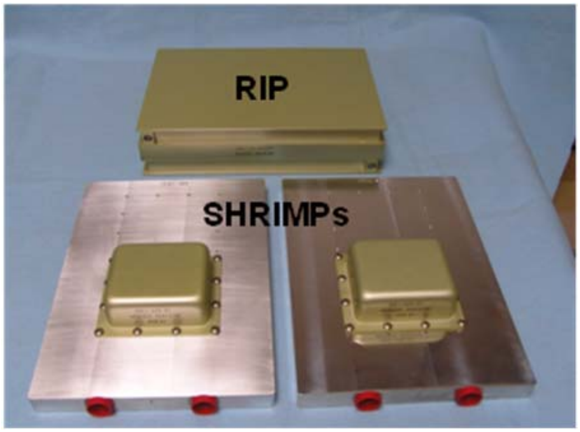


Figure 3. RIP and SHRIMP hardware.

The results of last year's testing led to a desire to test additional test articles to help validate theories explaining why those previous test articles experienced structural integrity issues. This paper documents the testing of those additional test articles that occurred from March through September of 2010.

II. Test Articles

The test articles used in this investigation encompassed various combinations of interstitial arrangements, cold plates, and size. As with last year's test articles, there were two types of interstitial arrangements. The Gen 1 arrangement, which was used in last year's RIP and SHRIMP-1 test articles, is shown in Figure 4-A. It consists of carbon fibers attached to aluminum fins, with the fibers from neighboring fins touching. Water is filled to 80% capacity, with the remaining 20% as an air-filled void space. In Figure 4-A, the water is shown at the bottom and the void space is shown near the top. If capillary effects dominate gravity effects, there is no preferred location of water and voids. In fact, the water and the void space may be randomly distributed. In this case a situation could occur where the freezing water is unable to "reach" the void space when necessary. The Gen 2 arrangement, used in last year's SHRIMP-2 test article, and shown in Figure 4-B, was designed to address this situation. In this design, the carbon fibers do not come into contact with other carbon fibers on neighboring fins. In this arrangement, carbon fibers wick up water so that the water is located top-to-bottom in the PCM module. This creates void space distributed between the aluminum fins instead of randomly located or at the top of the PCM module. In the discussion to follow, it will be stated which interstitial arrangement was used in each test article.

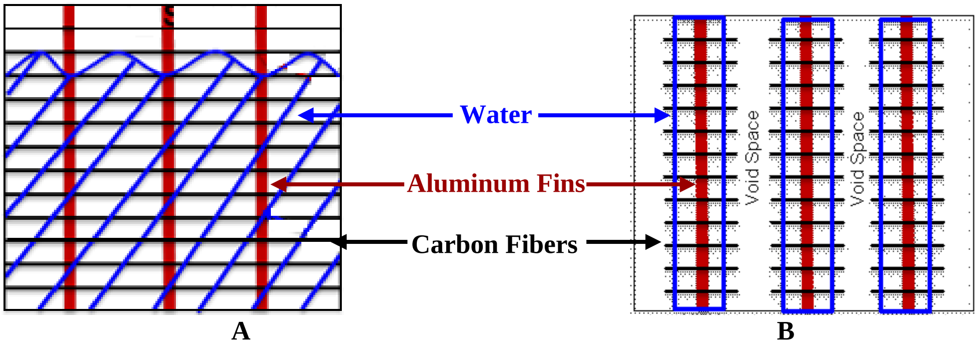


Figure 4: Interstitial Configurations. (A) Gen 1 (original SHRIMP 1 and RIP). (B) Gen 2 (original SHRIMP2).

The test articles were tested horizontally with either a favorable or adverse orientation with respect to gravity. The favorable gravity orientation is depicted in Figure 5, and represents either the top side of a two-sided test article or a one-sided test article positioned such that the PCM is located on top of the coldplate. With this orientation, freezing occurs from the bottom to the top. Assuming that gravity causes liquid water to be preferentially located at the bottom, the directional freezing from the bottom to the top pushes remaining liquid water into the available void space at the top.

The adverse gravity orientation is depicted in Figure 6, and represents either the bottom side of a two-sided test article or a one-sided test article positioned such that the PCM is located on the bottom of the coldplate. With this orientation, freezing occurs from the top to the bottom. Assuming that gravity causes liquid water to be preferentially located at the bottom, the directional freezing from the top to the bottom results in an ice layer that separates remaining liquid water from the void space at the top. As the remaining liquid water freezes and expands, it must either push the ice layer up into the void space, break through the ice layer into the void space, or push out on the PCM container and possibly cause damage.

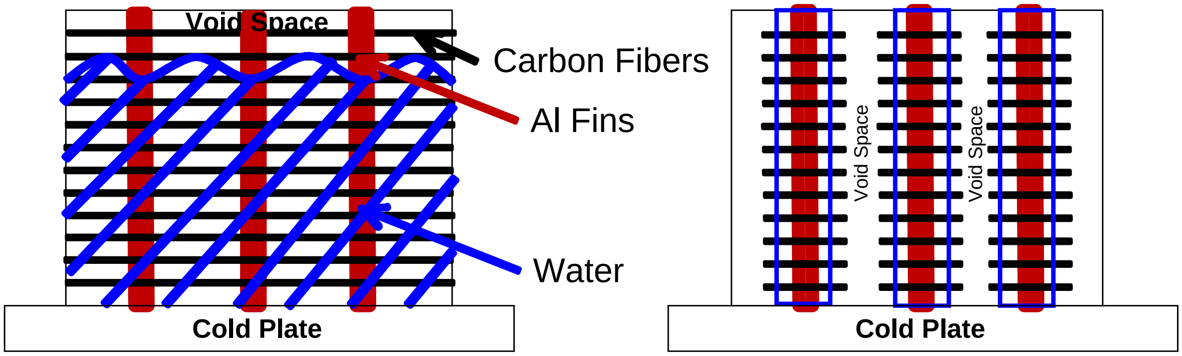


Figure 5: Favorable Gravity Testing Orientation

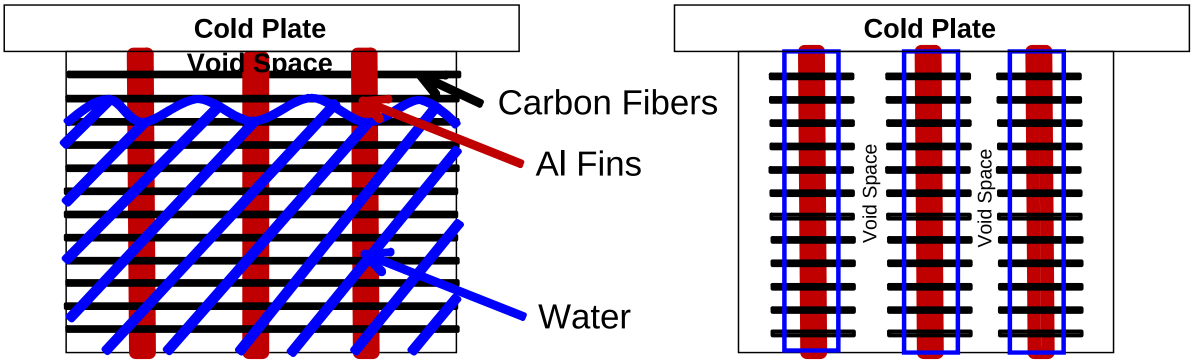


Figure 6: Adverse Gravity Testing Orientation

The following is a description of each heat sink tested during this year's investigation. The heat sinks are listed in the order they were received and tested. Each of the heat sinks used one of the following coldplates: a CP-30 coldplate, Figure 7, or a single-pass coldplate, Figure 8.

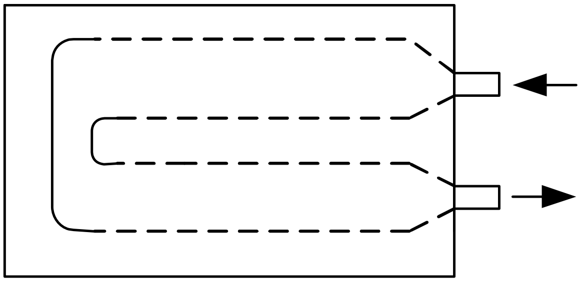


Figure 7: CP-30 Coldplate

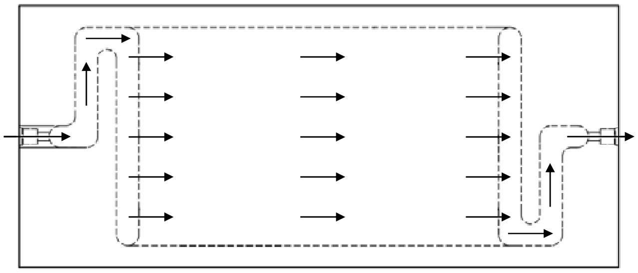


Figure 8: Single-pass Coldplate

A. Heat Sink 02 (HS02)

HS02,

Figure 9, is an arrangement of four SHRIMP's on a Lytron coldplate with the interstitial configuration shown in Figure 4-A (Gen1). The SHRIMP's are made from a machined aluminum base, with a drawn aluminum can and a laminate aluminum/carbon fiber core.

HS02 was developed to investigate directional freezing that was thought to occur in last year's SHRIMP-1 test article. In last year's SHRIMP-1, the SHRIMP unit was located in the middle of the CP-30 coldplate, where there is a no-flow region between the inlet and outlet legs of the flow passage. Since bulging occurred in the middle of the SHRIMP, it was thought that freezing had occurred from the outside to the inside, corresponding to freezing from the colder flow regions to the warmer no-flow region of the coldplate. The HS02 heat sink uses the same coldplate and the same type of SHRIMP unit, but now the SHRIMP units are located directly above the flow passages of the coldplate in an attempt to reduce the tendency for outside-to-inside directional freezing.

This discussion about directional freezing has an underlying assumption that contact resistance between the SHRIMP unit and the coldplate is uniform. However, this may not be the case since screws are used to attach the SHRIMP's to the coldplate, and the contact resistance is likely reduced in the areas near the screws.

For the purpose of testing, two of the SHRIMP's were removed from the coldplate. The two remaining SHRIMP's were located closest to the fluid connections of the coldplate. The SHRIMP units are in metal to metal contact with the coldplate; no thermal interface material was used. The SHRIMPs are attached directly to the coldplate with screws using the same torque values as the SHRIMP-1 test article.

Figure 9: Heat Sink 02 (HS02)

B. Heat Sink 04 (HS04)

HS04 (see Figure 10) is similar to the original RIP on a CP-30 coldplate, except that unlike the original RIP, HS04 has the Gen 2 interstitial arrangement of Figure 4-B. This unit was developed to compare to the original RIP and SHRIMP 2. HS04 can be compared to RIP in the same way that SHRIMP-2 was compared to SHRIMP-1, with the only difference in the comparison being the interstitial arrangement. Likewise, HS04 can be compared to SHRIMP-2 in the same way that RIP was compared to SHRIMP-1, with the only difference in that comparison being the size of the unit.

Due to the size and interstitial configuration of HS04 special handling instructions were followed. HS04 has 47 straight fins that span its width with carbon fibers (carbon velvet) on both sides as shown in Figure 11. Each fin has notches on both ends and in the center to connect the fin cavities with each other to allow the unit to be properly charged with water during assembly. To ensure a uniform distribution of water before testing, HS04 was first placed on edge as shown in Figure 12 to allow the PCM to pool along the edge of the heat sink. After hours of being on edge, HS04 was rolled back to the flat position allowing the PCM to redistribute uniformly between the fins. This process was done before HS04 was placed in the testing location and repeated once it was removed.

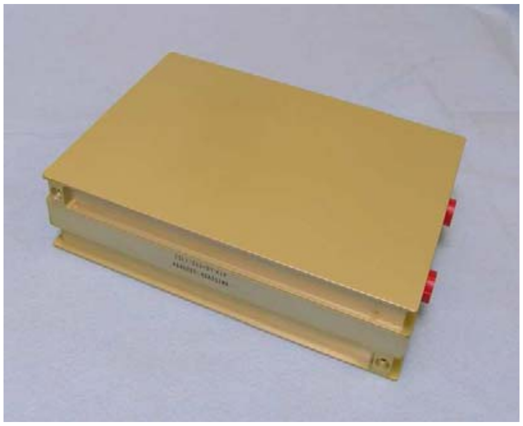


Figure 10: Heat Sink 04 (HS04)

Figure 11: HS04 Interior Configuration

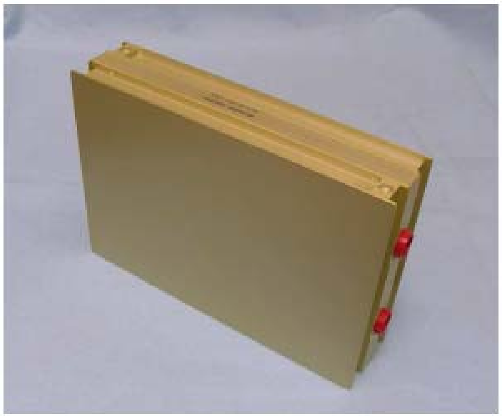


Figure 12: HS04 on Edge

C. Heat Sink 05 (HS05)

HS05 is similar to HS04 with the addition of a gel called polyacrylamide. The gel was added in an attempt to enhance the wicking ability of the fibers with the water. It is meant to be compared to RIP and HS04 since they are the same size. The water charge mass for HS05 was smaller than that of RIP and HS04 due to difficulties with the gelling process. The intended water charge level for HS05 was already 5.4% less than the RIP and HS04 charge levels due to the volume fraction displaced by the gel. However, the upper PCM chamber of HS05 ended up with a further reduction in water charge of approximately 14% due to the difficulties with the gelling process. The same special handling instructions described above for HS04 were used for HS05.

D. Heat Sink 03 (HS03)

HS03 is similar to HS02 in that it is comprised of an array of SHRIMP's on a coldplate. As with HS03, the SHRIMP's for HS02 have the Gen 1 interstitial arrangement shown in Figure 4-A.

The difference between HS03 and HS02 is the coldplate. While HS02 used a CP-30 coldplate, HS03 used a single-pass coldplate as shown in Figure 13. The coldplate core is configured to provide uniform unidirectional flow beneath the footprint occupied by the SHRIMP's. The fluid inlet is located on one side of the coldplate and the fluid exit is located on the opposite side. HS03 was developed to continue the investigation into possible directional freezing by comparing it to SHRIMP-1 and HS02. Since the coldplate for HS03 does not have any no-flow regions in the SHRIMP footprint, it should provide more uniform heat flux than either SHRIMP-1 or HS02. Only a small amount of directional freezing from the colder inlet side to the warmer outlet side may occur (the coldplate surface temperature was subsequently measured to vary by approximately 1°C from the front of the SHRIMP to the back).

As with HS02, the discussion here about directional freezing has an underlying assumption that contact resistance between the SHRIMP unit and the coldplate is uniform. However, this may not be the case since screws are used to attached the SHRIMP's to the coldplate, and the contact resistance is likely reduced in the areas near the screws.

For the purpose of testing, two of the SHRIMP's were removed from the coldplate. The two remaining SHRIMP's were located closest to the fluid outlet of the coldplate. The SHRIMP units are in metal to metal contact with the coldplate; no thermal interface material was used. The SHRIMPs were initially removed from the coldplate and then re-attached with screws using the same torque values used for HS02. The same torque values were used to minimize or eliminate any differences in contact resistance between HS02 and HS03.

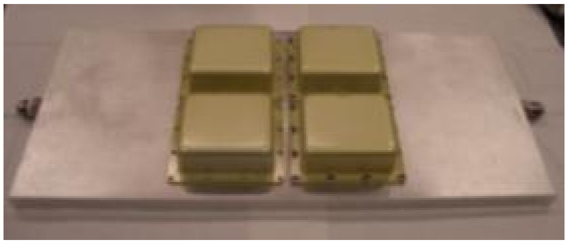


Figure 13: Heat Sink 03 (HS03)

E. Heat Sink 01 (HS01)

HS01, pictured in Figure 14, is a half RIP heat sink on a single-pass coldplate. Only a single RIP heat sink was chosen for this test article rather than the usual two RIP heat sink (top and bottom) to save on procurement costs. Rather than testing the top and bottom sides simultaneously, this heat sink can be tested in the favorable and adverse gravity test positions. HS01 has the Gen 1 interstitial arrangement shown in Figure 4-A. The use of the single-pass coldplate should provide more uniform heat flux as compared to the original RIP. HS01 can be compared to RIP in the same way that HS03 is compared to SHRIMP-1, with the only difference in the comparison being the coldplate. Likewise, HS01 can be compared to HS03 in the same way that RIP was compared to SHRIMP-1, with the only difference in the comparison being the size of the unit.

Figure 14: Heat Sink 01 (HS01)

A summary of all of these test articles will be presented later in Section V.B.

III. Test Set-Up

The ice PCM test cart was designed to accommodate up to four test articles (see Fig. 15). The test cart consists of two chiller carts arranged to provide both a hot loop and a cold loop, which were used to thaw and freeze the phase change material, respectively. A mixture of propylene glycol and water was used as the working fluid in each of the pumped fluid loops. Test article flow rates could be varied by computer control or by adjusting isolation valves located immediately upstream and downstream of the test articles as shown in Fig. 15. Most of the test points were executed using a test article flowrate of approximately 100 lb/hr.

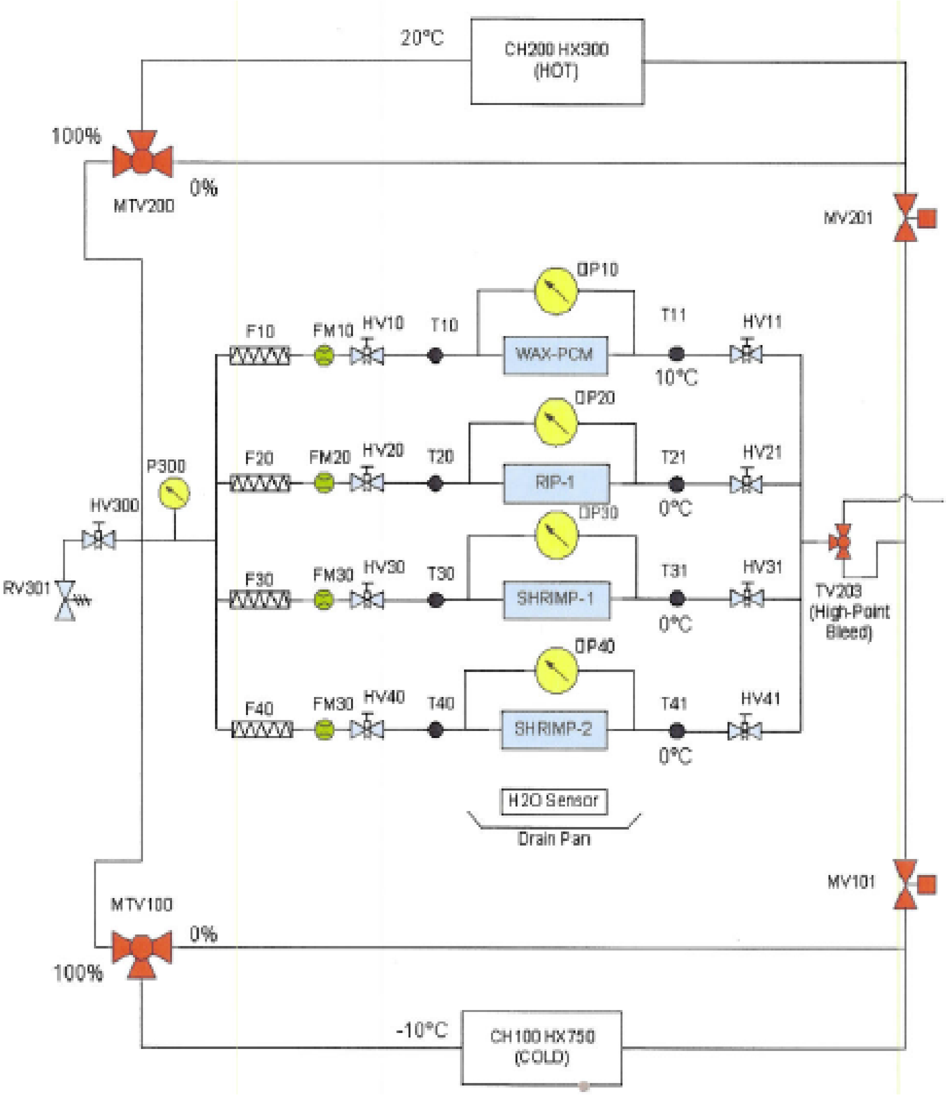


Figure 15. Test schematic.

Each test point began with an initial phase where the test article was cooled to 20˚C. After an isothermal temperature was achieved, the freeze cycle was started. Once an isothermal temperature was achieved throughout the test article (typically between -4˚C and -8˚C) hot flow was started and the test article was again warmed to 20˚C. Again, after an isothermal temperature was achieved at 20°C, the test cycle ended or was followed by another cold cycle.

IV. Test Parameters

A. HS02

- 25 test cycles were completed in the favorable gravity position followed by 25 test cycles in the adverse gravity position for a total of 50 cycles. All test cycles were run with as many back to back cycles in a day as possible.
- HS02 was inspected after the following test cycles: 1, 3, 5, 10 and 25 for the favorable gravity position and test cycles: 1, 3, 5, 10, 15, 20 and 25 for the adverse gravity position.
- Styrofoam insulation was used for test cycles 2-5 and Armaflex insulation was used to insulate HS02 during the first cycle and the remainder of the test cycles. It was originally planned to determine whether one type of insulation was better than the other, or if they were comparable to each other then the one that was just easier to remove and replace could be used. Eventually, it was determined that observation of the heat sink damage was more important than the latent energy calculation, so insulation was no longer used.

- HS02 torque values were recorded and later used to torque the screws on HS03

B. HS04

- 25 test cycles were completed. HS04 was flipped on what was labeled side 2 prior to every test cycle for test cycles 1-9. This side was later labeled as the bad side due to damage on the bottom on that side. To indicate when HS04 was flipped on the bad side the following acronym was used, FOBS (flipped on bad side). The other side was called the good side and FOGS (flipped on good side) was used to indicate when HS04 was flipped on that side. B2B (back to back) was used when back to back test cycles were done and FIO (flipped inlet and outlet) when the fluid inlet and fluid outlet were switched. FOBS was used for test cycles 1-9, FOGS for test cycles 10-14, B2B for test cycles 15-20 and FIO for test cycles 21-25.
- HS04 was inspected after the following test cycles: 1-14 (after every test cycle), 16, 18, 20, and 21-25 (after every test cycle).
- No insulation was used because the heat sink damage was more important than the latent energy calculation. Also, repeatedly insulating the heat sink after each test cycle would not have been cost effective due to increased handling time.

C. HS05

- 25 test cycles were completed in the same manner as for HS04. FOBS was used for test cycles 1-9, FOGS for test cycles 10-14, B2B for test cycles 15-20 and FIO for test cycles 21-25.
- HS05 was inspected after the following test cycles: 1-14 (after every test cycle), 16, 18, 20, and 21-25 (after every test cycle).
- No insulation was used because the heat sink damage was more important than the latent energy calculation. Also, repeatedly insulating the heat sink after each test cycle would not have been cost effective due to increased handling time.

D. HS03

- 43 test cycles were run in the favorable gravity position and 5 test cycles were run in the adverse gravity position for a total of 48 test cycles. (Only 5 adverse cycles were run because damage was already observed during these cycles, so additional cycles would have contributed little if any additional information about the failure mechanism.) The first 10 cycles were run one per day, while cycles 11-24 were run two per day, back to back. After the 24th test cycle for the favorable position, HS03 was put through continuous back to back test cycles for five days (a day represents an 8 hour work day) with as many back to back cycles in a day as possible. The 5 adverse cycles were run one per day.
- Inspections were done after each test cycle for the first 24 cycles and every other day for the remaining five test days (cycles 25-43) for the favorable gravity position. In the adverse gravity position, inspections were done after each test cycle.
- Armaflex insulation was used for all test cycles. Insulation was used on HS03 because it was compared to HS02 and insulation was used on HS02.
- HS03 screws were torqued to match HS02 torque values.

E. HS01

- 45 test cycles were run in the favorable gravity position and 4 test cycles were run in the adverse gravity position, for a total of 49 test cycles. (The original plan was for 44 favorable cycles and 5 adverse cycles, but the test article was inadvertently installed in the favorable orientation for one of the planned adverse cycles.) The first 10 cycles were run one per day, while cycles 11-24 were run two per day, back to back. After the 24th test cycle for the favorable position, HS01 was put through continuous back to back test cycles for five days (a day represents an 8 hour work day) with as many back to back cycles in a day as possible. The last 5 cycles were run one per day, and they were all in the adverse orientation except for the third one which was inadvertently run in the favorable orientation. This was the same general test plan as for HS03, with the difference in the total number of cycles due to different numbers of cycles completed during the back to back testing.
- Inspections were done after each test cycle for the first 24 cycles and once daily for the remaining five test days (cycles 25-44) for the favorable gravity position. In the adverse gravity position, inspections were done after each test cycle.
- Armaflex insulation was used for all test cycles.

V. Test Results

A. Test Article Damage

1. HS02

HS02 failed between test cycles 11 and 25 in the favorable gravity position as evidenced by the appearance of a bulge in the center of the SHRIMP on the fluid inlet side. It is not apparent which test cycle HS02 failed on because an inspection was not done after a given number of back to back test cycles. Since failure was not present at the inspection done after test cycle 10, it was decided to continue running through test cycle 25 without another inspection. In the adverse gravity test position, HS02 failed on the first cycle, with the existing bulge growing in size and a new bulge appearing on the other SHRIMP as well.

Failure in the adverse gravity position was expected. However, failure in the favorable orientation was unexpected since SHRIMP-1 showed no damage in the favorable orientation during last year's testing. One hypothesis for any damage that did occur with HS02 was that the SHRIMP's would fail near the outsides, not in the center, towards the no-flow areas of the coldplate. Instead, the SHRIMP on the fluid inlet side failed in the center (see Figure 16) and the SHRIMP on the fluid outlet side showed no sign of damage until it was tested in the adverse gravity position.

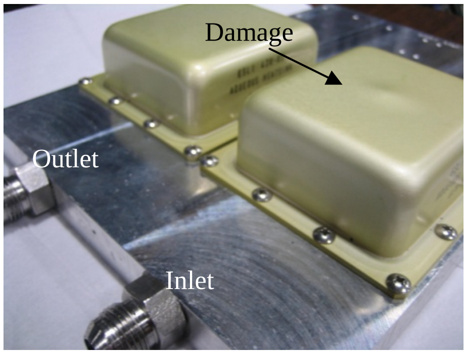


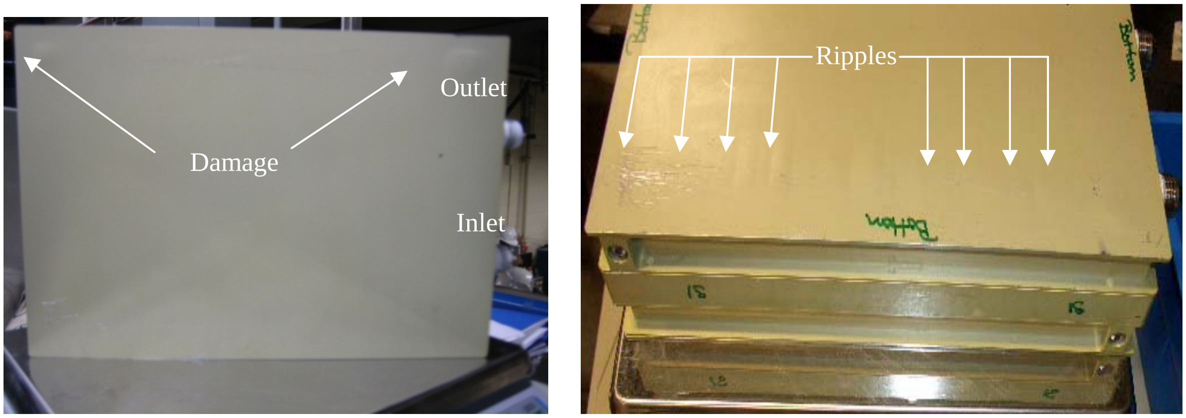
Figure 16: HS02 Damage

2. HS04

HS04 showed no damage on the top side after 25 cycles. This demonstrated that the Gen 2 interstitial configuration shown in Figure 4-B appears to reduce the susceptibility to ice expansion damage since RIP had failed with its Gen 1 configuration in the same favorable orientation during last year's testing.

On the bottom side, a bump was present after the first test cycle near the fluid outlet (see Figure 17). Damage had been anticipated to occur on the bottom side of HS04, but not necessarily so early into the test cycles due to the Gen 2 interstitial configuration. It was postulated that damage may have happened on the bottom fluid outlet side because HS04 was placed on the fluid outlet edge to allow the PCM to pool towards that edge before it was flipped back over to distribute the PCM evenly between the fins (refer to the aforementioned special handling instructions). Placing HS04 on the fluid outlet edge may have allowed the fluid outlet side to be concentrated with more of the PCM causing damage when frozen. To test this assumption, HS04 was placed on side 1, also known as the good side (FOGS), to see if damage would occur on the fluid inlet side. After the next five test cycles, there was no sign of damage on the fluid inlet side. Also, more damage was not present when HS04 was put through back to back test cycles although it was postulated that damage may occur since HS04 was not placed on its side after each test cycle to allow the PCM to redistribute evenly. It may have just been that two back to back cycles were not enough to significantly affect the distribution of the water.

Based on these observations, coupled with the location of bulges in RIP toward the fluid outlet side from last year's testing, a hypothesis was developing that the water PCM may be getting pushed generally from the inlet to the outlet side of the heat sink due to directional freezing from the coolant temperature gradient as it flows through the coldplate. To further investigate this hypothesis, 5 cycles were run with HS04 with the fluid inlet and outlet switched HS04 using flex hoses, as shown in Figure 18. More damage occurred in the form of ripples along the new outlet side (previously the inlet side) of the heat sink. This observation seems to support the hypothesis of water being pushed from inlet to outlet due to directional freezing.



(B)

Figure 17: HS04 Damage. (A) First adverse cycle. (B) After inlet and outlet switched.

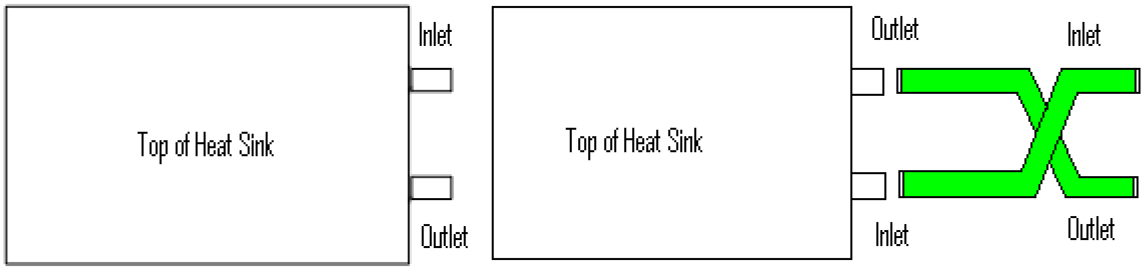


Figure 18: Flipped Inlet and Outlet Schematic for HS04

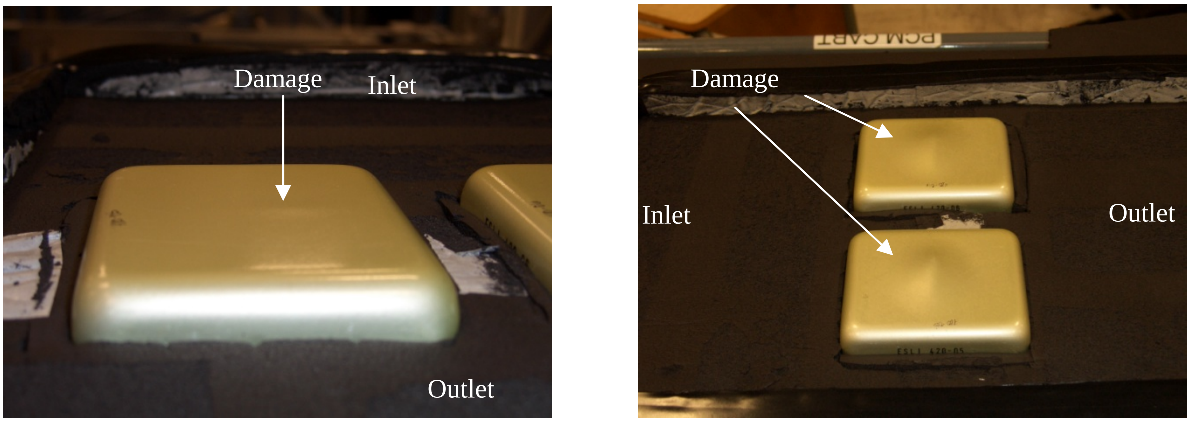
3. HS05

HS05 performed exceptionally well. No damage was observed on either the top side or the bottom side after 25 cycles. It appears that the Gen 2 interstitial arrangement (see Figure 4-B), coupled with the addition of the polyacrylamide results in decreased susceptibility to damage from ice expansion. A potential caveat to this observation may be the possibility that the aforementioned reduced charge of water could have provided more void space for ice expansion than the other test articles.

4. HS03

HS03 failed in the favorable gravity test position after cycle 22. It was anticipated that the SHRIMP's would show signs of damage on the back end, closest to the fluid outlet, since the PCM would start to freeze towards the fluid inlet and move back towards the fluid outlet side (assuming a uniform contact resistance between each SHRIMP and the coldplate). Contrary to this hypothesis, the SHRIMP on the fluid inlet side of HS03 failed towards the center in the favorable gravity position as shown in Figure 19. Once flipped to the adverse gravity position, both SHRIMP's failed after the first test cycle.

The shape of the damage present on HS03 in the adverse gravity position differed from the damage seen on the other heat sinks. Damage to the other heat sinks formed in a circular shape. Once turned to the adverse gravity position bumps usually got wider and some increased in height, but they remained in a generally circular shape. However, the bumps present on HS03 formed into an elliptical shape when flipped to the adverse gravity position. They got wider in the direction perpendicular to the coldplate flow path, as shown below in the right side of Figure 19.

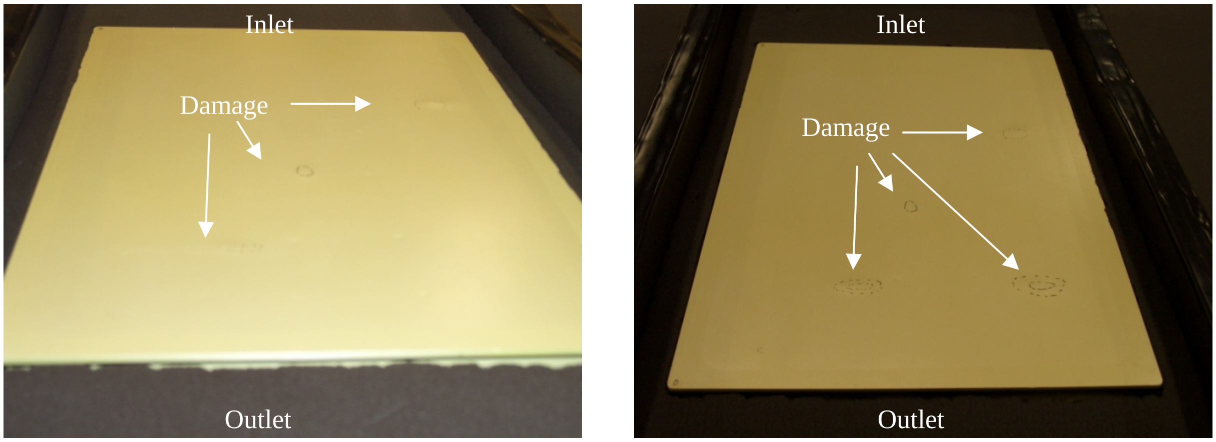


Favorable **Adverse**

Figure 19: HS03 Damage

5. HS01

HS01, the half RIP heat sink, failed after test cycle two in the favorable gravity test position as shown below in Figure 20. It had been anticipated that any bumps would have occurred toward the outlet side of the heat sink due to directional freezing resulting from the coolant temperature gradient from the inlet to the outlet of the coldplate. However, the location of the bumps observed on HS01 seemed to be randomly distributed. When tested in the adverse orientation, two of the bumps that were formed in the favorable test position slightly expanded in width and an additional bump was formed.



Favorable **Adverse**

Figure 20: HS01 Damage

B. Heat Sink Comparisons

To aid in understanding the relationships among the various test articles, a summary of all the test articles is provided in Table 1. There are several levels of grouping in this table. The top row contains test articles with the larger size heat sinks (RIP's) and the bottom row contains test articles with the smaller size heat sinks (SHRIMP's). The type of interstitial arrangement is indicated across the top of the table as either "Gen 1" (see Figure 4-A), "Gen 2" (see Figure 4-B), or "Gen 2 (with gel)". Each grouping of interstitial arrangements is further subdivided by the type of coldplate. "CP-30" refers to the CP-30 coldplate with the PCM heatsinks centered on the coldplate. "CP-30 array" refers again to a CP-30 coldplate, but with an array of SHRIMP's that are positioned directly above the flowpaths in the coldplate. (Note that this designation is not applicable to the larger size heatsinks, and is therefore grayed out in the corresponding sections of the table.) "Single-Pass" refers to the single-pass coldplate. Finally, each test article is represented in the appropriate location of the table by a sketch showing the appearance of the test article as well as a sketch depicting the interstitial material arrangement.

Additionally, a summary of the damage observed for each test article is provided in Table 2. This table is arranged in the same manner as Table 1, but with the rows further subdivided into favorable and adverse orientations with respect to gravity. A red-yellow-green scheme is used to help visually depict how well the various test articles performed relative to each other in terms of susceptibility to damage from ice expansion. Red is used where damage was observed within the first 5 cycles, yellow is used where damage was observed after the first 5 cycles, and green is used where damage was not observed during any of the testing completed so far.

General pre-test predictions were that performance was expected to improve as you move to the right in these tables. At the top level, Gen 2 test articles were expected to perform better than Gen 1 test articles, and test articles with gel were expected to perform better than those without gel. Furthermore, moving to the right within a given generation of interstitial materials was expected to result in increasing uniformity of heat fluxes and improved performance. Whether these predictions were realized during the testing will be discussed next.

The rest of this section discusses observations from the testing across various logical groupings of the test articles.

Table 1: Summary of Test Articles

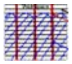
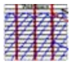
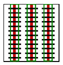
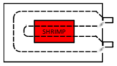
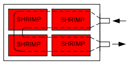
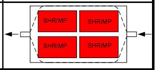
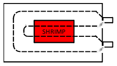
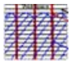
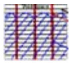
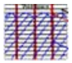
	Gen 1			Gen 2			Gen 2 (with gel)		
	CP-30	CP-30 array	Single-Pass	CP-30	CP-30 array	Single-Pass	CP-30	CP-30 array	Single-Pass
Large	**RIP**	**N/A**	**HS01**	**HS04**	**N/A**		**HS05**	**N/A**	
									
									
Small	**SHRIMP-1**	**HS02**	**HS03**	**SHRIMP-2**					
									
									

Table 2: Summary of Test Article Damage

Number of cycles until damage										
		Gen 1			Gen 2			Gen 2 (with gel)		
		CP-30	CP-30 array	Single-Pass	CP-30	CP-30 array	Single-Pass	CP-30	CP-30 array	Single-Pass
Large	Orientation	**RIP**	**N/A**	**HS01**	**HS04**	**N/A**		**HS05**	**N/A**	
	Favorable (top)	≤2		2	No damage after 25 cycles			No damage after 25 cycles		
	Adverse (bottom)	≤2		1	1			No damage after 25 cycles		
Small	Orientation	**SHRIMP-1**	**HS02**	**HS03**	**SHRIMP-2**					
	Favorable (top)	No damage after 25 cycles	11-25	22	No damage after 25 cycles					
	Adverse (bottom)	1	1	1	≤20					

1. *SHRIMP 1, HS02 and HS03*

SHRIMP 1 and HS02 use a CP-30 coldplate, while HS03 is mounted on a single-pass coldplate. Each heat sink has the same Gen 1 interstitial arrangement (see Figure 4-A).

All three of these test articles showed damage after the first cycle in an adverse orientation, which shows the deficiency of the Gen 1 interstitial arrangement. It is unclear why SHRIMP-1 did not show any damage during testing in the favorable orientation while HS02 and HS03 did. If anything, the opposite trend may have been expected due to the potentially more uniform heat flux associated with the location of the HS02 and HS03 SHRIMPs on their respective coldplates.

2. RIP and HS01

RIP and HS01 both have the larger PCM heat sink and the Gen 1 interstitial arrangement. The only difference between these two test articles is the coldplate. Both test articles showed damage on both the top and the bottom (both favorable and adverse orientations) within the first 2 cycles, which shows the deficiency of the Gen 1 interstitial arrangement. It is unclear why the locations of the bulges seen on HS01 appeared to be randomly located.

3. SHRIMP-1 and SHRIMP-2

Even though both of these test articles were tested last year, a comparison between them is included here for completeness.

SHRIMP-1 and SHRIMP-2 are both the smaller size heat sinks mounted in the middle of a CP-30 coldplate. The only difference between these two test articles is the interstitial arrangement. Both of these test articles showed no damage after 25 cycles in the favorable orientation. This is likely due to the favorability of the orientation since it results in freezing from the bottom to the top, with any void space always available for the remaining liquid water on top to expand into as it freezes.

The Gen 2 interstitial arrangement did show some improvement over the Gen 1 interstitial arrangement for the adverse orientation tests. This seems to support the hypothesis that the Gen 2 interstitial arrangement may do a better job at maintaining a more even distribution of void space and reduced susceptibility to ice expansion damage.

4. RIP, HS04, and HS05

All three of these test articles have the larger size heat sinks mounted on a CP-30 coldplate. The only differences are the interstitial arrangement and whether gel has been added to the water. On the top side, the Gen 2 interstitial arrangement showed significant improvement over the Gen 1 arrangement, with HS04 and HS05 showing no damage after 25 cycles while RIP showed damage within the first two cycles. On the bottom side, it appears that the gel was necessary to help the Gen 2 interstitial arrangement show improved performance, with HS05 still showing no damage on the bottom after 25 cycles while RIP and HS04 showed damage within the first two cycles. As pointed out earlier, a potential caveat to this observation may be the possibility that the reduced charge of water in HS05 could have provided more void space for ice expansion than the other test articles.

It is a little surprising that the bottom side of HS04 showed damage already after the first cycle. It was anticipated that the Gen 2 interstitial arrangement would have provided some degree of improvement over the Gen 1 arrangement in the RIP, but this was not the case in the adverse orientation.

5. RIP and SHRIMP-1

Even though both of these test articles were tested last year, a comparison between them is included here for completeness.

RIP and SHRIMP-1 both have the Gen 1 interstitial arrangement and are mounted on CP-30 coldplates. The only difference between these two test articles is the size of the PCM heat sinks. Both of these test articles showed damage on the bottom side (adverse orientation) within the first two cycles. On the top side (favorable orientation), however, RIP showed damage within the first two cycles, but SHRIMP-1 did not show any damage after 25 cycles. Again, the only difference between these two is the size of the heatsinks, with the smaller SHRIMP-1 performing better than the larger RIP. The difference in performance between these two test articles contributes to the hypothesis that directional freezing may push water around inside of the heatsink, and this effect may be more pronounced in the larger heatsinks since there is more room to push the water around.

6. HS01 and HS03

HS01 and HS03 both have the Gen 1 interstitial arrangement and both are mounted on a single-pass coldplate. The only difference between these two test articles is the size of the PCM heat sinks. Both of these test articles showed damage in the adverse orientation on the first cycle. In the favorable orientation, however, HS01 showed damage on the second cycle, but HS03 did not show any damage until cycle 22. Again, the only difference between these two is the size of the heatsinks (similar to the previous paragraph), with the smaller HS03 PCM heat sinks performing better than the larger HS01. The difference in performance between these two test articles contributes to the hypothesis that directional freezing may push water around inside of the heatsink, and this effect may be more pronounced in the larger heatsinks since there is more room to push the water around.

7. HS04 and SHRIMP-2

HS04 and SHRIMP-2 both have the Gen 2 interstitial arrangement and both are mounted on a CP-30 coldplate. The only difference between these two test articles is the size of the PCM heat sinks. Both of these test articles showed no damage on the top (favorable orientation) after 25 cycles. On the bottom (adverse orientation), however, HS04 showed damage on the first cycle, but SHRIMP-2 did not show any damage until a number of cycles (less than 20) later. Again, the only difference between these two is the size of the heatsinks (similar to the previous two paragraphs), with the smaller SHRIMP-2 performing better than the larger HS04. The difference in performance between these two test articles contributes to the hypothesis that directional freezing may push water around inside of the heatsink, and this effect may be more pronounced in the larger heatsinks since there is more room to push the water around.

VI. Conclusions

To better understand the rationale behind why the original SHRIMP 1, SHRIMP 2, and RIP heat sinks encountered damage in the manner they did due to water expansion, and to understand the failure mechanisms of ice PCM heat exchangers in general, additional heat sinks were developed. HS02 was developed to compare it to SHRIMP 1. HS04 gave insight on how the SHRIMP 2 interstitial arrangement would work in a bigger heat sink, while HS05 did the same, but with the addition of a gel. HS03 was compared to SHRIMP 1 and HS02 regarding location of the SHRIMPs relative to the location and direction of flow in the cold plate. The larger HS01 was compared to the similar but smaller HS03. All heat sinks were tested in the same manner as the comparative heat sinks to make the best possible comparisons.

Upon completion of testing this year's heat sinks, several hypotheses were not confirmed. The assumptions that HS02 would show damage toward the outer edges in the no flow regions and HS03 would show damage towards the back end of the SHRIMP's did not hold. Instead HS02 and HS03 showed damage in the center like SHRIMP1. It was also believed that HS01 would not show damage in the favorable gravity test position since it was on a single pass coldplate and was getting uniform heat flux throughout. It failed after test cycle 2.

Some predictions were shown to be correct. It was assumed that the interstitial arrangement in SHRIMP 2 would also work in a bigger heat sink in a favorable orientation. This assumption was shown to be correct since HS04 did not fail in the favorable gravity test position. Failure in the adverse test position was expected. The assumption stated above also ties in with the comparison of RIP and HS04. RIP's interstitial arrangement allowed for expansion only at the top surface of the interstitial material, whereas HS04's interstitial arrangement was arranged to create void spaces between the aluminum fins. Changing the interstitial arrangement in HS04 appears to have aided in it being successful in the favorable gravity test position. The addition of polyacrylamide gel in HS05 may have added enough wicking ability that it did not fail in the favorable or adverse gravity test positions, although a reduced charge of water may have also played a role.

Generally, the Gen 2 interstitial arrangement provided reduced susceptibility to ice expansion damage as compared to Gen 1, and the addition of polyacrylamide gel provided further improvement. A few exceptions to this trend provide the following questions that remain unanswered at this time:

- Why did HS02 and HS03 fail in the favorable orientation, but SHRIMP-1 did not?
- Why does a smaller heatsink have better resistance to ice expansion damage than a corresponding larger heatsink (SHRIMP-1 vs. RIP, HS03 vs. HS01, SHRIMP-2 vs. HS04)?

Testing observations seem to support the hypothesis that directional freezing from coldplate inlet to coldplate outlet tends to push PCM water toward the coldplate outlet, resulting in damage in that location, at least for the larger test articles.

Except for HS05, the bottom of the test articles (adverse orientation) always performed worse than the top side (favorable orientation), indicating that for these test articles, gravity plays a role in the distribution of the PCM water; the distribution is not completely dominated by surface tension effects.

Outside-in freezing for the smaller SHRIMP test articles may be due more to reduced contact resistance at the fasteners around the periphery of the test article rather than to flow and no-flow areas of the coldplate. A means of providing a more uniform contact resistance between the PCM heatsink and the coldplate should be investigated.

The following summarizes these observations in four different categories:

A. Gen2 vs. Gen1 Interstitial Arrangement

The Gen2 interstitial arrangement does appear to provide better void control than the Gen1 interstitial arrangement. All Gen2 test articles showed no damage in the favorable gravity orientation after 25 cycles. However, damage was still observed for the adverse orientation for HS04 and SHRIMP-2.

B. Gel

The addition of polyacrylamide gel to the water may have helped improve wicking and void control. However, the lack of damage observed on HS05 may also be due to a reduced charge of water that could have provided more void space for ice expansion than the other test articles.

C. Directional Freezing Pushing Water

The results are not consistent with regard to the possibility of directional freezing pushing water around the inside of the test articles. Observations of damage location from HS04 and RIP seem to indicate the water gets pushed around due to directional freezing from inlet to outlet. However, damage on HS01 seemed to be randomly located. Additionally, it is unclear why HS02 and HS03 showed damage, but SHRIMP-1 did not. Furthermore, damage on all SHRIMP's occurred in the middle rather than toward one side or the other, indicating that something other than freezing direction may be determining the location of the damage. Non-uniform contact resistance between the SHRIMP and the coldplate is one possibility to be considered for further investigation.

D. Size

Smaller test articles performed as well as or better than their larger counterparts with respect to the number of cycles endured before damage occurred. This may be due to larger test articles having more room for water to get pushed around.

VII. Acknowledgements

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