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Continued Water-Based Phase Change Material Heat Exchanger Development

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In a cyclical heat load environment such as low Lunar orbit, a spacecraft's radiators are not sized to meet the full heat rejection demands. Traditionally, a supplemental heat rejection device (SHReD) such as an evaporator or sublimator is used to act as a "topper" to meet the additional heat rejection demands. Utilizing a Phase Change Material (PCM) heat exchanger (HX) as a SHReD provides an attractive alternative to evaporators and sublimators as PCM HX's do not use a consumable, thereby leading to reduced launch mass and volume requirements. In continued pursuit of water PCM HX development two full-scale, Orion sized water-based PCM HX's were constructed by Mezzo Technologies. These HX's were designed by applying prior research on freeze front propagation to a full-scale design. Design options considered included bladder restraint and clamping mechanisms, bladder manufacturing, tube patterns, fill/drain methods, manifold dimensions, weight optimization, and midplate designs. Two units, Units A and B, were constructed and differed only in their midplate design. Both units failed multiple times during testing. This report highlights learning outcomes from these tests and are applied to a final sub-scale PCM HX which is slated to be tested on the ISS in early 2017.

Nomenclature

°C = degree celsius
DRM = design reference mission
LLO = low lunar orbit
HX = heat exchanger
SHReD = supplemental heat rejection device
PCM = phase change material

I. Introduction

Current Design Reference Missions (DRM) push the boundaries of current spacecraft technology, including the thermal control systems. Specifically, these DRM's require a spacecraft to operate under cyclical thermal environments such as Low Lunar orbit (LLO). As shown in Figure 1, the lunar surface temperature varies from approximately 400 Kelvin to less than 100 Kelvin. The hottest portion of the orbit corresponds to the subsolar point; i.e., the point directly aligned with the sun. Similarly, the coldest portion corresponds to the point directly on the opposite side of the moon. Because of the large variations in the temperature, the vehicle will experience large changes in radiative sink temperatures. Therefore, robust spacecraft thermal control systems must be developed to provide adequate heat rejection demands for both the hot portion and the cold portion of an orbit. Figure 2 plots an example of the variability of a vehicle's heat rejection capability using only radiators for a 100 km circular orbit with a beta angle of zero degrees, representing the worst-case hot LLO environment. The radiators are capable of rejecting the full vehicle heat load for the majority of the orbit period. However, when the vehicle is orbiting at or near the subsolar point (0 to 0.4 hours and 1.6 to 2 hours), the radiators do not meet the full heat rejection demands of the spacecraft. Thus, some type of Supplemental Heat Rejection Device (SHReD) is required to meet the

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vehicle's heat rejection requirement. SHReDs typically employed in thermal control systems are evaporators, submilators, or Phase Change Material (PCM) heat exchangers (HXs). Using a PCM HX as a SHReD can be advantageous for long mission durations because it does not require a consumable as is required in an evaporator or sublimator.

PCM HX's act as a thermal battery and store excess thermal energy during periods of high heat loads (hot thermal environments) by melting the PCM within the heat exchanger. The PCM is then refrozen during periods of low heat loads (cold thermal environments). Paraffin type phase change materials have been traditionally used on spacecraft but water is another alternative phase change material. Water is advantageous for use as a PCM due to water's large heat of fusion. When compared to n-pentadecane, the baseline wax for Orion, water is capable of storing about 1.6 more energy than of wax. The heat of fusion for n-pentadecane is 200 kJ/kg, whereas the heat of fusion for water is 333 kJ/kg. Thus, by increasing the amount of energy storage per unit mass, water has potential to significantly reduce a HX's mass and volume requirements.

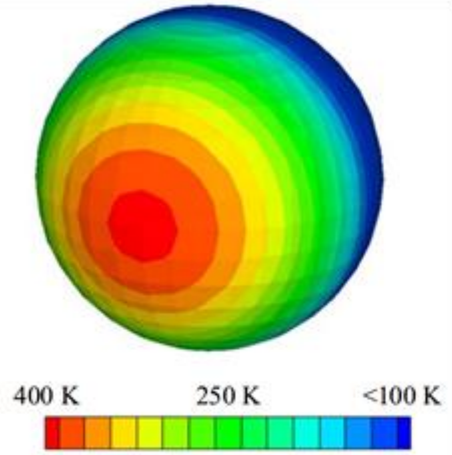


Figure 1. Lunar surface temperatures.

Utilizing water has one particular disadvantage. Unlike most materials, water expands when frozen, thereby leading to concerns regarding structural integrity of the HX, especially when enclosed in a ridged structure. This report summarizes the design, manufacturing, and testing of two full-scale, Orion-like, water-based PCM HX's and subsequent sub-scale unit development.

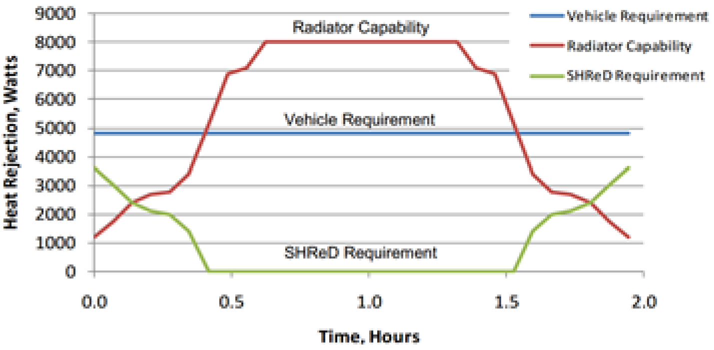


Figure 2. SHReD requirements.

II. Prior Copper Coupon Testing

Extensive research has been conducted on water based PCM HX's and freeze front propagation[1-10]. Specifically, the paper "Water Based PCM HX Development" focuses efforts on studying freeze front propagation and establishes three recommendations for HX design. These were:

- Uniform flow/freezing distribution should be utilized over outside-in and inside-out freezing
- Midplates could be utilized to alter location of freezing water
- Use of a bladder is feasible with a water-based PCM HX

These considerations were taken into account during the design and development of the two full-scale, Orion like heat exchangers, capable of storing 11.1 (3,700kJ) of water described in this paper.

III. Full Scale Design and Manufacturing

Two units were designed and constructed by Mezzo Technologies and were given the designations of Unit A and Unit B. Each unit is essentially identical and consists of three main components 1) a tube bank core 2) two manifolds and 3) either a metal shell or an acrylic "visualization" shell. Each core has 1,420 tubes (Figure 4) with an OD of 0.042", ID of 0.035", and wall thickness of 0.0035". These tubes are given a slight concentration in the middle of the HX which allows freezing to occur from inside-out. This concentration is about 10% greater in the middle than the perimeter tube spacing. This gradient would ensure fluid would freeze from the inside-out would not become hydraulically locked when frozen. Outer dimensions of the HX can be found in Figure 3.

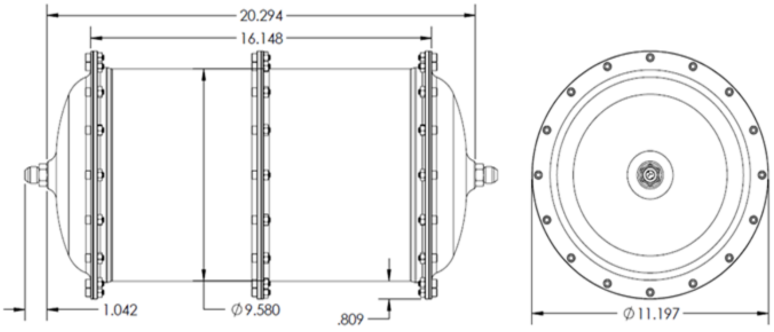


Figure 3. Outer dimension of each HX *(units in inches)*

The bladder is manufactured by Pelmore Laboratories and was injection molded using low-temperature Viton GLT. This bladder is filled 100% with degassed water and allows for water expansion/contraction during freezing and thawing. By filling 100% no air pockets are present, which elimates the uncertainty of void space location in microgravity orientations. This leads to similar freezing and thawing in gravity conditions as microgravity because the location of water is always know. Additionally, by filling 100% and using the bladder, water is allowed to expand at any location except the top or bottom tube sheet. A ¾” increase in radius was added for water expansion around the circumference of the HX. This allowed for 33% expansion of water. This is greater than the typical 20% expansion of water as has been utilized in the past. This was done to ensure that no deformation would occur to the outer shell and to ensure that the test article had sufficient space to expand. After testing and understanding freeze front propagation, this shell can be modified to reduce the excess void space. The clamping mechanism for the HX bladder consists of a two piece, overlapping ring that attaches to the tube sheet via screws. Once the bladder is installed, the bladder is filled with degassed water through an M2 fitting.

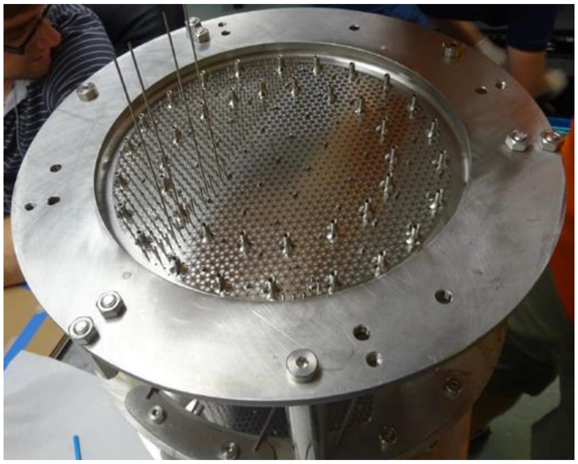


Figure 4. Tubes being inserted into HX core.
(Note: high pressure standoff bosses)

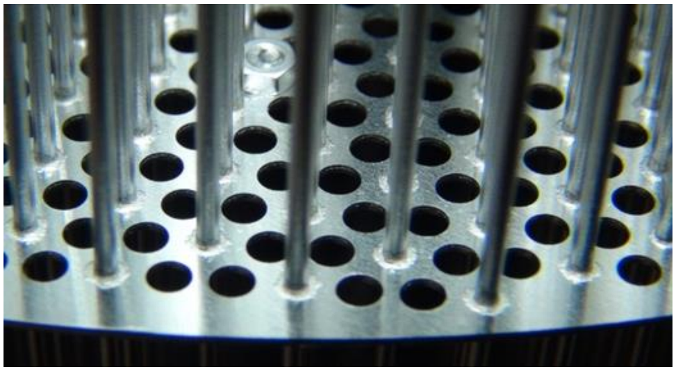


Figure 5. Unit B midplate geometry

Three midplates were added to the HX core to increase the structural integrity of the tube bank. These midplates were added equidistant from each other. The midplate designs are the only difference between the units. Unit A has a solid plate midplate whereas Unit B has a perforated midplate (Figure 5). The theory driving this design was that a perforated sheet could allow water to more easily pass through the heat exchanger than a solid plate, thereby reducing stress concentrations on each tube/midplate joint. This would be similar to allowing the wind to pass through a screen door on a windy day verses a solid door.

Table 1. Unit A Mass

Description	**Actual Weight (kg)**	**Flight-Like Weight (kg)**
Core Dry Mass (with fasteners)	5.717	5.717
Viton Bladder	0.86	0.86
Acrylic Shell	8.675	N/A
Metal Shell	2.59	2.59
Two Manifolds	2.22	2.22
Fasteners for Manifolds	0.453	N/A
PCM Mass	11.4	11.4
Perforated Sheet	0.61	0.61
Total Metal Mass	12.45	11.997
PCM Mass : Metal Mass	***01:01.1***	***01:01.0***

Masses of Unit A are recorded in Table 1. The 1:1 PCM mass to metal mass ratio meets current state-of-the-art water PCM HX technolgy such as in the RIP test articles. It is important to note that this unit is a development unit and are slightly heavier than their flight-like counterparts due to boss standoffs (for high pressure operations, Figure #), fasteners, and mating interfaces that allow for the HX to be disassembled and inspected for engineering evaluation. The flight version will be welded where fasteners are currently located which will reduce added weight due to these components. Additionally, the aspect ratio for a flight HX will be optimized to reduce the weight of the manifolds.

Once the final design review was complete, the units were manufactured and assembled at Mezzo Technologies facilities located in Baton Rouge, LA. During the braze process of Unit A, 71 tubes (5%) were blocked with all of the blocked tubes occurring around the high pressure standoff bosses. This was due to braze material wicking into the tubes around the bosses during the braze process. In order to prevent this issue in Unit B, tubes around the bosses were extended about ½” beyond the height of the boss. This caused the braze material to wick around the tube instead of into the tube.

IV. Initial Testing

Both units arrived at JSC in Fall 2014, and were immediately assembled and tested. Testing was completed on the Replicative Ice PCM (RIP) test stand. This stand was modified from previous PCM testing to accommodate transient temperature profile testing. It allows for data acquisition, flow and temperature control, and various temperature and pressure readings of the test article. 50/50 PGW was used as a coolant in this system. Two chillers are used to circulate PGW through a liquid/liquid heat exchanger and fluid temperatures were controlled to inlet temperatures of -12°C during freezing and 30°C for thawing. These temperatures represent the expected minimum and maximum operating temperatures of Orion's thermal control fluid. RTD's are included in the fluid loop to measure inlet and outlet PCM temperatures. During initial testing the structural integrity of the HX was given primary concern, so instantaneous inlet temperature changes between -12°C and 30°C were used to allow for quicker freezing and thawing. Additionally, an acrylic shell replaced a metal shell so the heat exchanger could be photographed during freezing and thawing.

A. Prototypic Freeze Cycle

Both units performed optimally during freezing, however, freezing occurred differently than hypothesized. It was expected that during freezing that as the freeze front propagated from inlet to outlet, more water would be "pushed" to area near the outlet. Therefore, the greatest bladder deformation would occur at this location (estimated to be a ¾" inch increase in radius). However, testing results showed uniform bladder expansion during freezing with a maximum radius increase of ½" for all three orientations; favorable, unfavorable, and neutral. Image comparison photographs for each orientation can be seen in Figures 6,7, and 8. One possible explanation between expected versus actual results is that no large ice spikes formed because the water is allowed to expand evenly over a large area due to the bladders flexibility. Additionally, in testing it appeared that most of the water expansion occurred in initial cooling of the water, prior to when solidification occurred.

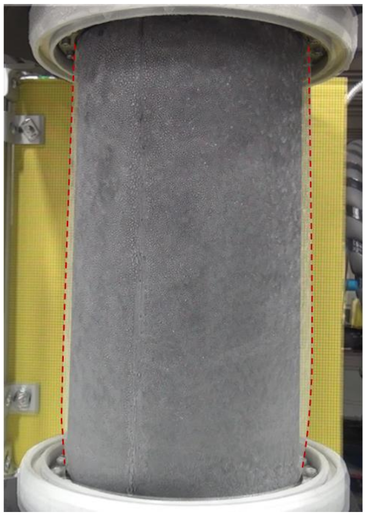


Figure 6. Image Comparison, Favorable (Dotted Line Indicates Fully Frozen)

Figure 7. Image Comparison, Unfavorable (Dotted Line Indicates Fully Frozen)

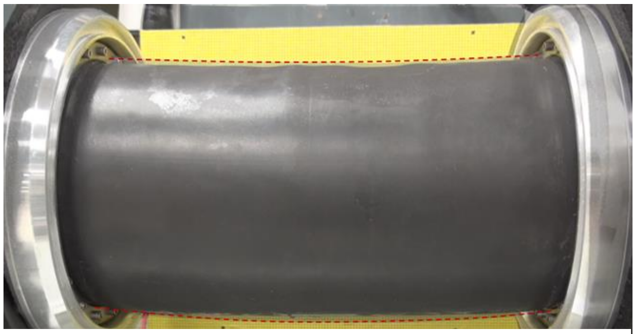
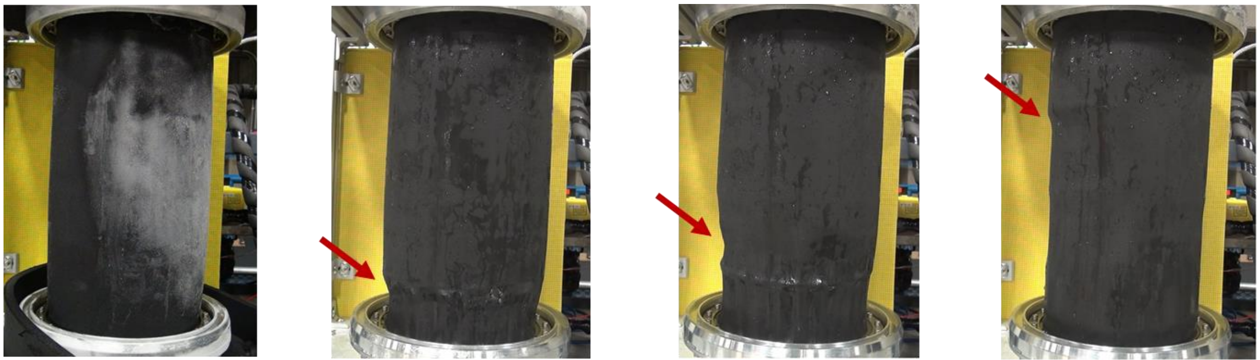


Figure 8. Image Comparison Freezing, Neutral (Dotted Line Indicates Fully Frozen)

B. Prototypic Thaw Cycle

Thawing of the PCM did not occur as was predicted. It was hypothesized that during thawing, the bladder would simply return to its original position. However, during thawing a vacuum was formed from water contraction due to thawing and the bladder was pressed against the tube core. This caused the tubes nearest to the outer perimeter of the HX to bend and, in some cases, crack or break. Figure 9 shows a time lapse of the thawing process of the PCM HX. Figure 10 shows typical bending damage to the HX tube core. It is hypothesized that this phenomenon occurs because as melting occurs, a small "cone" of melting occurs as the HX is given a slight preference to freeze from the inside-out. As this thawing occurs, the ice decreases in volume and pressure is reduced in the bladder, therby "sucking" the bladder in and deforming tubes.



Fully Frozen *10 min* *20 min* *25 min*

Figure 9. Timelapse of prototypic thawing, favorable orientation.

C. Perforated Sheet Testing

To alleviate the forces exerted on the tube bank during thawing a perforated metal sheet was manufactured, spot welded, and tested. Figure 11 shows the sheet in place on the HX. Initial testing with the perforated sheet was done with a visualization shell to visually ensure and photograph the structural integrity of the perforated sheet during freeze/thaw cycles. Once these tests were complete the metal shell will installed and back-to-back unmanned testing took place.

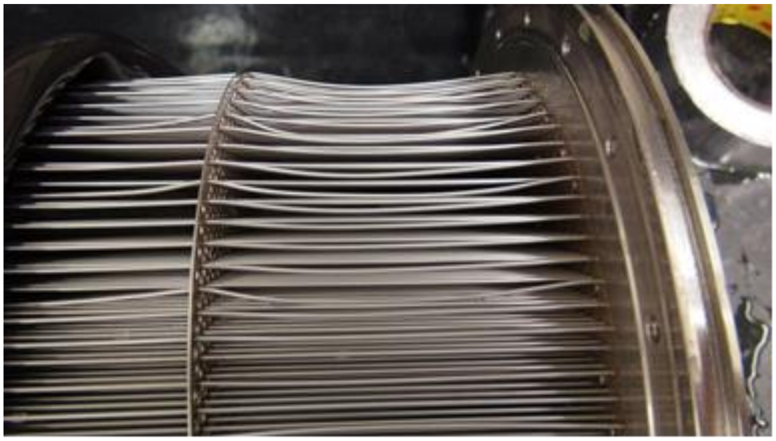


Figure 10. Tube deformation due to thawing.

D. Unit A Testing Summary

Table 2 summarizes the tests conducted on Unit A. Initial testing took place on September 25 and two cycles were completed before failure of the HX was observed. This failure took place on an outer tube and was caused by the forces exerted during thawing. After this failure, the perforated sheet was installed and perforated sheet testing took place. 4 cycles were completed before the unit failed on an internal tube next to the tube sheet. The tube was repaired and testing resumed. 15 cycles were completed and the unit failed again on an internal tube at the intersection of a tube and midplate.

It is hypothesized that since the HX's is given a slight preference to freeze inside-out, that during thawing, a small "cone" of melting occurs within the HX. As this cone reaches a midplate and passes it, large forces are exerted from hydraulically locked water as the midplate does not allow water to pass through it. These forces cause the tubes at the midplate/tube interface to break. Because of the two internal tube failures experienced on Unit A, testing did not continue on this unit after the second internal failure.

Table 2. Unit A testing summary

Orientation	Initial of Cycles	Perforated Sheet Cycles
Favorable	2	26
Unfavorable	0	21
Neutral	0	0
Total	**2**	**47**

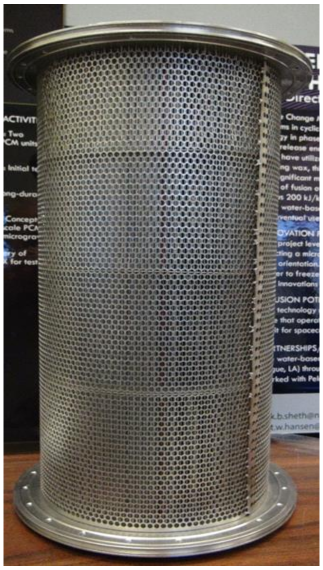


Figure 11. Perforated sheet installed.

E. Unit B Testing Summary

Table 3. Unit B testing summary.

Orientation	Initial of Cycles	Perforated Sheet Cycles
Favorable	14	73
Unfavorable	17	31
Neutral	23	11
Total	**54**	**115**

Table 3 summarizes the tests conducted on Unit B. A total of 54 cycles were completed with this unit before failure of the HX was observed. This failure took place on an outer tube and was caused by the forces exerted during thawing. After this failure, the tube was epoxied, a perforated sheet was installed, and testing continued. 25 additional cycles were completed before failure occurred. This failure occurred in an outer tube during thawing as the bladder deformed and pressed against the perforated sheet. This force slightly deformed the metal sheet which caused the sheet to press against the a tube and caused it to break. This tube was epoxied closed and testing continued. An additional 90 successful cycles were completed in favorable and unfavorable orientation. At this point, the unit was changed from favorable orientation to neutral orientation. Upon analyzing the temperature verses time data during the neutral cycles it was suspected that a tube had developed a small crack. Upon discovery of this, the unit was removed from the test stand and a 1% PGW concentration was found in the water indicating that a small leak was present. Additionally, the unit was leak checked by pressurizing from the tube side. This revealed a “hairline fracture” on an inner tube at the middle midplate/tube location. This suggests that the failure was caused by freeze front propagation, as was similar to occur on Unit A. The individual tube could not be identified because of the perforated sheet installed around the unit, so it was removed and re-pressurized. Unfortunately during pressure testing, the manifold detached which caused the top tube sheet to bend. Attempts were taken to identify the exact tube where the failure occurred, but was unsuccessful. Further testing cannot take place with this unit, however, destructive evaluation of the unit is currently taking place.

It is hypothesized that failure occurred through one or a combination of three potential causes. First, it is possible that the tube was damaged from initial testing. This is evidenced by initial testing data by a slightly irregular thaw profile. However, this pattern was normally seen for all cycles leading up until the unit failed. Additionally, the unit was leak checked prior to testing, which did not reveal any leaks. It is possible that damage occurred when the HX core was installed into the shell and was “undisturbed” until the damaged tube was “aggravated” when it was repositioned from favorable orientation to neutral orientation. The second cause of failure could have possibly been from freeze front propagation. Similar to what was hypothesized for Unit A, as the cone of melting ice reaches a midplate and passes it, forces could be exerted from hydraulically locked water at the midplate/tube junction which could lead to a tube cracking. Coupled with the second cause is the third cause. It is possible that the brazing and annealing process could have weakened the tube/midplate joint. Because of this, during freeze and thawing, pressure from freeze front propagation could have caused this weakened tube to develop a hairline fracture.

V. Future Water-Based PCM Development

In order to develop a unit that can be tested in a microgravity environment, a subscale unit was designed and is currently being constructed. This unit is planned for flight aboard the International Space Station’s Phase Change Material Fluid Loop, a double mid-deck sized locker available for freezing/thawing water and wax PCM’s. The subscale design is based on the two full-scale designs and takes into account the lessons learned from the full scale units. These include the following items:

1. The use of perforated sheets to protect the outer tubes during thawing.
2. The use of a protective boss for tube sheet/tube joint.
3. The use of a tube sheet that is able to accommodate pressure requirements to reduce assembly complexity.

Additionally, since brazing and associated annealing has been a cause for concern in the full-scale unit, the sub-scale units will be epoxied rather than brazed. Doing this removes uncertainty associated with the possibility of the braze process weakening each tube. Additionally, the sub-scale unit will use non-annealed tubes. Doing this allows for the use of tubes that have not been weakened by the annealing process. Since future units are expected to be manufactured by using a low temperature braze, where annealing does not occur, tubes retain their full strength. Hence, sub-scale units are to be tested by with non-annealed tubes.

Testing with the sub-scale unit will take place during summer 2015 at JSC. Additionally, a system level analysis of utilizing water-based PCM’s should be completed to determine the viability of using it on Orion. If testing is successful and the system level analysis proves water PCM’s viability on Orion, an identical sub-scale unit will be constructed for flight aboard the ISS for testing in a relevant environment. Expected launch date for this test article is Fall 2016. If testing proves successful in microgravity, manufacturing a full-scale PCM will be investigated for possible use aboard Orion.

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