Thermal Cycle and Capacitance Testing of Mezzo Industries Phase Changer Material Heat Capacitor

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Effective Thermal management is essential for the safety and performance of human spacecraft, especially during long-duration missions with fluctuating heat loads. Phase Change Material (PCM) heat exchangers offer a compact, efficient solution by storing and releasing thermal energy through latent heat during phase transitions. This allows PCM systems to buffer transient thermal loads without immediate heat rejection, reducing the need for oversized radiators – particularly critical during ascent and re-entry when radiators are stowed. By maintaining stable temperatures in crew cabins and equipment bays, PCM technology enhances crew comfort, protects sensitive systems, and supports long-term mission sustainability with minimal mass and volume impact. A phase change material heat capacitor prototype, designed and built under a NASA Small Business Innovation Research grant by Mezzo Technologies, utilizes a laser welding microtube manufacturing process that promises increased reliability and performance over current manufacturing methods like brazing. This heat exchanger was tested through coolant thermal cycling within the expected flow rates and temperature range of the Orion spacecraft, the crewed spacecraft taking NASA astronauts to the moon under the Artemis Program. The useful heat storage capacitance was measured and compared to Orion spacecraft requirements.

Acronyms and Nomenclature

ATCS	=	Active Thermal Control System
COTS	=	Commercial Off the Shelf
ESM	=	European Service Module
JSC	=	Johnson Space Center
PGW	=	Propylene-Glycol Water
P&ID	=	Process and Instrumentation Diagram
SBIR	=	Small Business Innovation Research Grant
TVAC	=	Thermal Vacuum

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I. Introduction

A Phase Change Material (PCM) heat capacitor is an effective solution for storing or absorbing thermal energy during critical temperature transitions or high-heat phases of spaceflight. [1] PCMs function by surrounding ATCS coolant passages with a phase change material that melts and freezes as the coolant heats up and cools down. This enables relatively large energy storage per unit mass by leveraging the latent heat associated with phase transitions, particularly through freezing and thawing within a narrow operational temperature range. A general diagram of PCM technology is shown below in Figure 1 with Propylene-Glycol Water (PGW) as the coolant, emulating the Orion spacecraft:

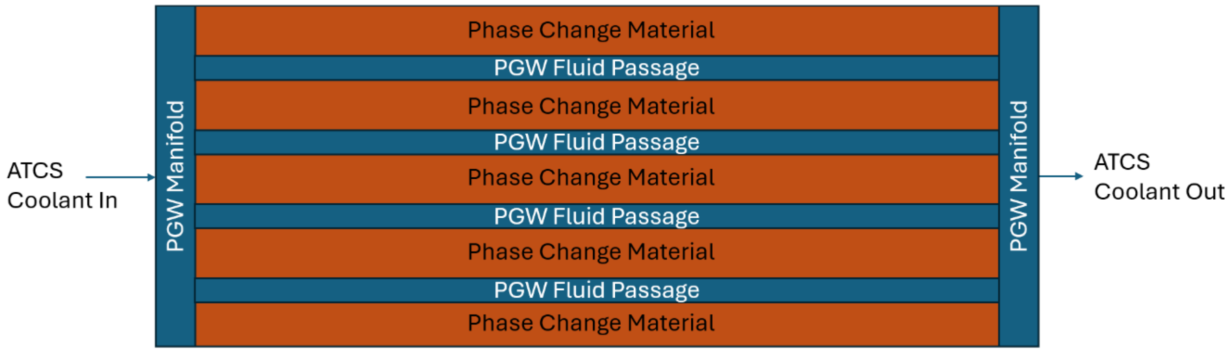

Figure 1. Simplified Diagram of PCM Technology

For the Orion spacecraft[1], heat capacitance plays a vital role in maintaining system temperatures within operational limits during the transitional period between the disconnection of ground support cooling systems at the launch pad and the activation of in-flight thermal management systems, namely, the ammonia boilers (after main engine cutoff) and the radiators, following the jettison of the European Service Module (ESM) fairings. In addition to this critical function, PCM-based heat capacitors help mitigate thermal transients caused by maneuvers, off-nominal attitudes, variable heat loads, or periods of solar eclipsing. Additionally, a secondary solid-solid phase change is exploited during pre-launch conditioning and cold soak phases to prepare for the thermal energy surge generated during launch, prior to the availability of active cooling systems.

Previous work has primarily explored water as a PCM due to its high latent heat capacity; however, its significant volumetric expansion upon freezing introduces substantial mechanical stress, making it not ideally suited for repeated cycling in spacecraft applications. Paraffin wax based PCMs, by contrast, have been extensively used in passive thermal management systems in both terrestrial and aerospace applications. These include building-integrated thermal storage, electronics cooling in aircraft, and space systems dating back to the Apollo program. Notable examples include the use of wax modules for heat management in the Lunar Rover Vehicle[2] as well as an ISS flight experiment in 2015[3].

The major risk with PCM technology is robust manufacturability. Large heat exchangers have traditionally required complex brazing where many units fail during qual testing, leading to increased cost and risk to the ATCS system. This paper covers the preliminary development and testing of a novel PCM prototype manufactured by Mezzo Technologies under a NASA SBIR grant with the goal of mitigating these issues with new manufacturing methods.

II. Design of Hardware

Mezzo utilizes a novel, laser-based welding technique to construct a microtube PCM heat exchanger. This heat exchanger was designed to be a near drop-in replacement for the legacy design used on the Orion spacecraft with the goal of increasing manufacturability & robustness while decreasing mass and volume. For this reason, the heat exchanger was designed to use the same internal ATCS coolant as Orion (40/60 PGW). Additionally, n-pentadecane is selected for its phase transition temperature, which closely aligns the desired operational temperatures of the Orion crew module. To emulate Orion, the Mezzo PCM needs to have at least 1074 Watts of heat capacitance with a similar or lighter dry weight of 65.8kg. A CAD model and real picture is shown below of the heat exchanger:

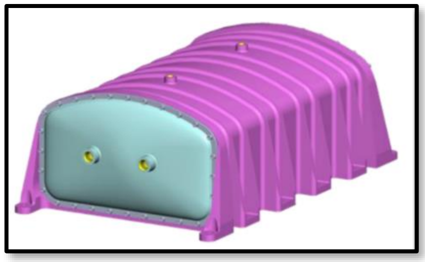

Figure 2. CAD Model of Mezzo Heat Exchanger

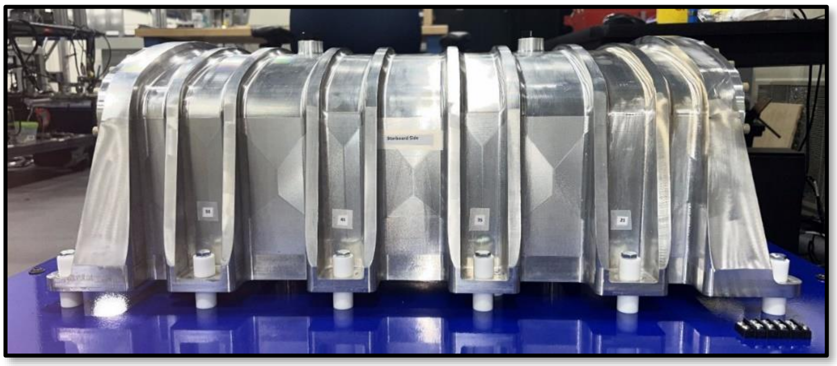

Figure 3. Mezzo Heat Exchanger, Starboard Side

The main advantage of the laser welding technology is robustness and the ability to manufacture microtubes (not shown above), which aid in maximizing surface area and heat transfer between the n-pentadecane and PGW. The Mezzo heat exchanger has over 2100 microtubes integrated into its core. Tube geometries, sizes, and connection methods are Mezzo intellectual property. Additionally, seventeen baffles assist in structural support for the microtubes and to mitigate sloshing of the n-pentadecane during flight. The novel microtube technology is meant to be scalable to various vehicle sizes and heat storage requirements. The overall dry mass of the Mezzo PCM (with n-pentadecane but no PGW) was weighed at approximately 54.9kg, over 9kg lower than the current Orion PCM, which carries a mass of 65.8kg. The united was filled with hot n-pentadecane at 60°C to allow for more headspace within the wax volume of the heat exchanger to allow for thermal expansion, leaving a headspace of 1.575L. This desired headspace was given by Mezzo.

III. Testing Methods

To properly test the heat exchanger, a fluid loop / test stand is used to circulate PGW through the heat exchanger at Orion-like conditions (~0.3-2.84 L/min, inlet temperatures ~30°C). A fluid schematic of the test stand is shown:

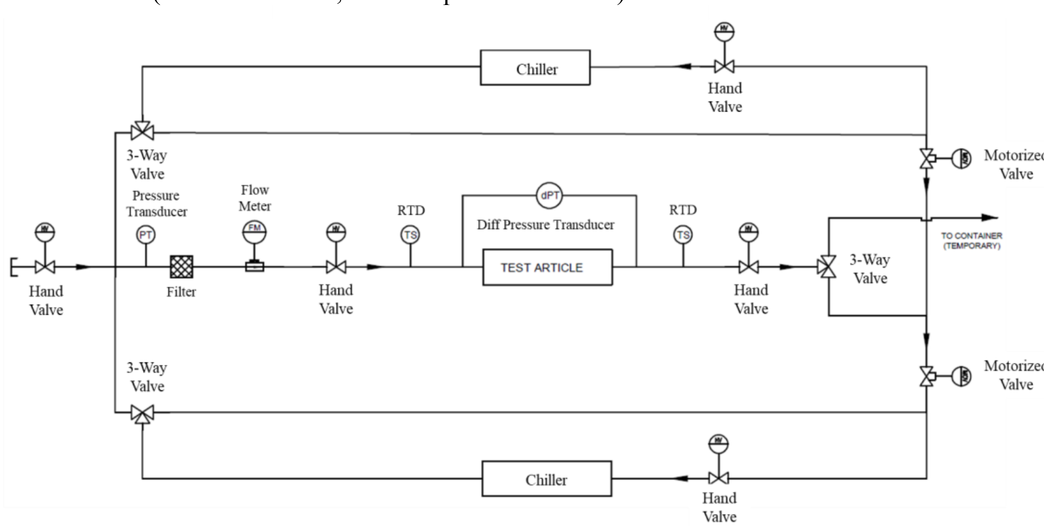

Figure 4. PGW Fluid Loop Used to Test PCM Heat Exchanger, P&ID

Prior to test, the n-pentadecane is degassed through thermal cycling under vacuum conditions in-situ. The setup for the n-pentadecane side of the heat exchanger is shown below:

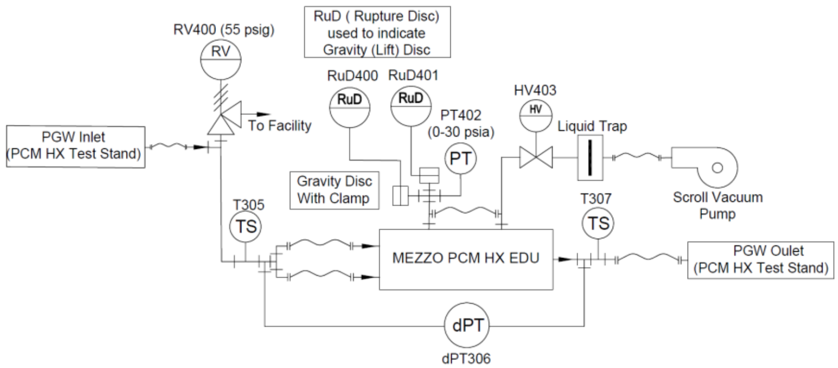

Figure 5. N-Pentadecane Side of PCM Heat Exchanger, P&ID

Prior to taking capacitance measurements, PGW was circulated through the heat exchanger at 2L/min to "cold soak" the heat exchanger and n-pentadecane to ensure it is fully frozen. The cold soak PGW temperatures ranged from 0°C to -10°C, which covered nominal and off nominal cold case temepratures from Orion. Additionally, the cold soak is held for a set period of time, either 3 or 6 hours. After cold soak, the inlet temperature from the chiller is immediately increased to an Orion-emulative hot inlet temperature (30°C) and the heat storage of the heat exchanger is calculated as the outlet temperature increases. On Orion, the acceptable outlet temperature limits of the heat exchanger are -2.7°C to 11.1°C, so the usable capacitance is only calculated between those outlet temepratures per the equation below:

$$E = \dot{m}_{PGW} c_p \int_{t(T=-2.7C)}^{t(T=11.1C)} (T_{in} - T_{out}) dt$$

Where E is capacitance / energy storage of the heat exchanger, t is time, T_{in} is PGW inlet temperature to the heat exchanger, T_{out} is heat exchanger PGW outlet temperature, c_p is the specific heat of PGW at the average of T_{in} & T_{out}, and $\dot{m}_{PGW}$ is the mass flowrate of PGW. In summary, the goal of this testing is to evaluate the heat storage capability of the heat exchanger with respect to differing cold soak times, cold soak lengths, test point flowrates, and to generally asses its performance in Orion emulative conditions. The heat exchanger integrated onto the test stand is shown:

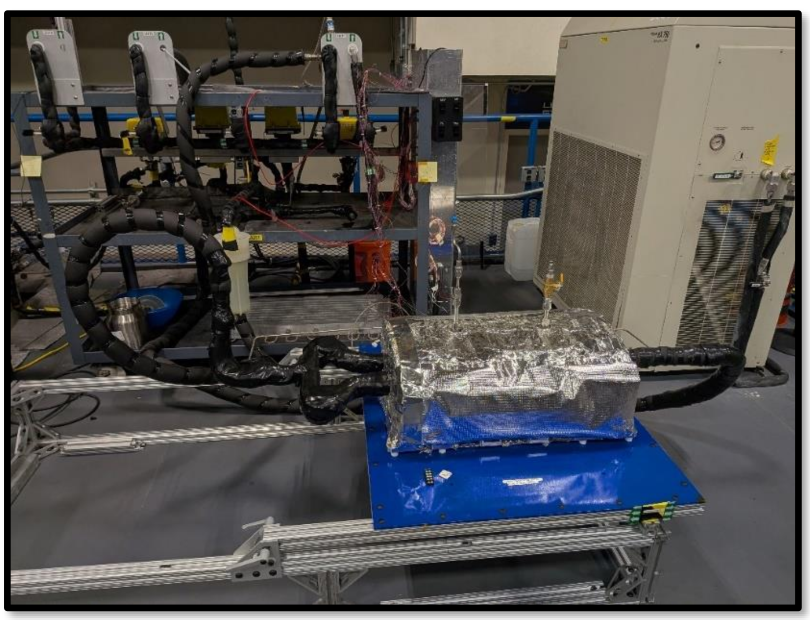

Figure 6. Heat Exchanger Integrated with Test Stand at Johnson Space Center

IV. Data & Results

The graphs below show an example of test point 4 at approximately 1.6L/min with a 3-hour cold soak. Figure 7 represents the inlet/outlet temperatures and mass flowrates over the cold soak and subsequent heat capacitance test point with a 30°C inlet temperature. The heat capacitance was integrated and calculated using a matlab script only from the -2.7°C to 11.1°C period shown (Orion requirements only allow credit to be taken in this temperature span), but there was more thermal capacitance observed outside of those bounds that could be applicable to other missions and spacecraft.

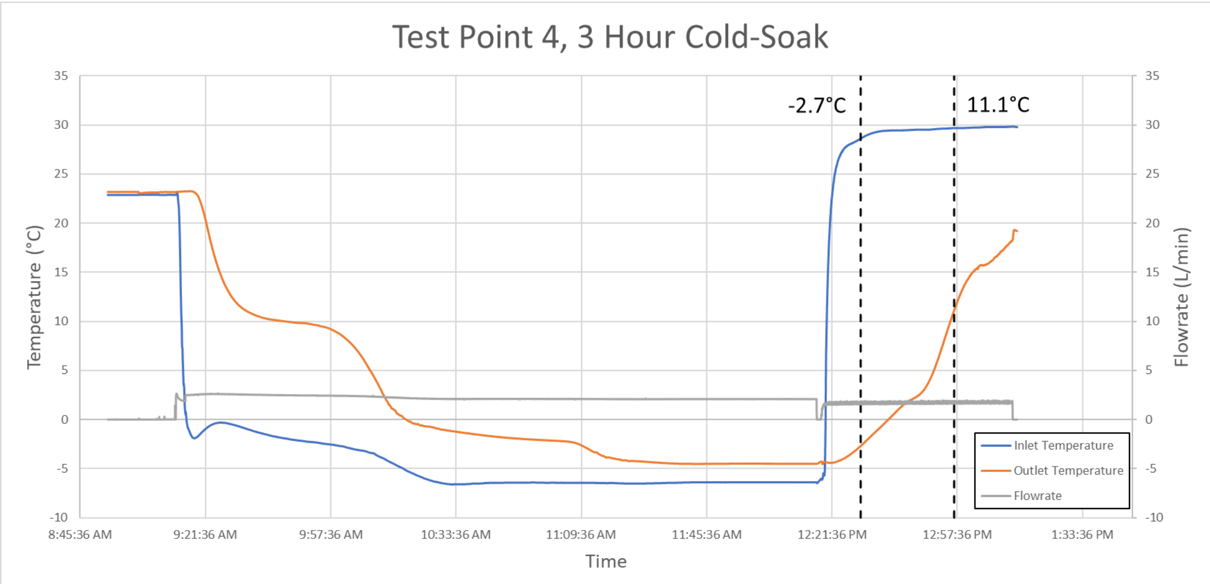

Figure 7. Inlet/Outlet Temperature & Mass Flowrate v. Time

Table 1 below shows a summary of multiple test points with varying heat soaks, flowrates, and PGW inlet temperatures for cold soak. All testing held the inlet PGW temperature (during test phase) at 30°C. The overall heat capacitance is shown along with its margin against the 1074 Watt requirement. Figures 8 and 9 show the heat exchanger's heat storage capacity in comparison to cold soak PGW temperature and test point flowrate, respectively.

	Cold Soak Phase			Test Phase			
As Run Test #	Cold Soak Flow Rate (L/min)	Cold Soak PGW Temperature (°C)	Cooling Time (hr)	PGW Inlet Flow Rate (L/min)	PGW Inlet Temperature (°C)	Measured Capacitance (Watts)	Margin Against Requirement (Watts)
1	1.97	-10.10	3	2.84	36.00	1327.960141	254.3962485
2	2.04	-6.40	6	1.06	29.40	1375.146542	301.5826495
3	2.04	-6.40	6	2.16	29.60	1400.937866	327.3739742
4	2.08	-6.50	3	1.59	29.50	1302.168816	228.6049238
5	2.12	-6.50	3	0.34	28.80	1300.996483	227.4325909
6	2.12	-6.50	3	0.72	29.20	1255.275498	181.7116061
7	1.89	-0.80	3	1.82	29.30	988.2766706	-85.28722157
8	2.54	-0.61	6	1.40	29.60	951.9343494	-121.6295428
9	1.82	-6.50	6	1.93	29.80	1339.976553	266.4126612
10	1.85	-6.50	3	2.20	29.90	1309.202814	235.6389215

Table 1. Heat Capacitance Summary Table

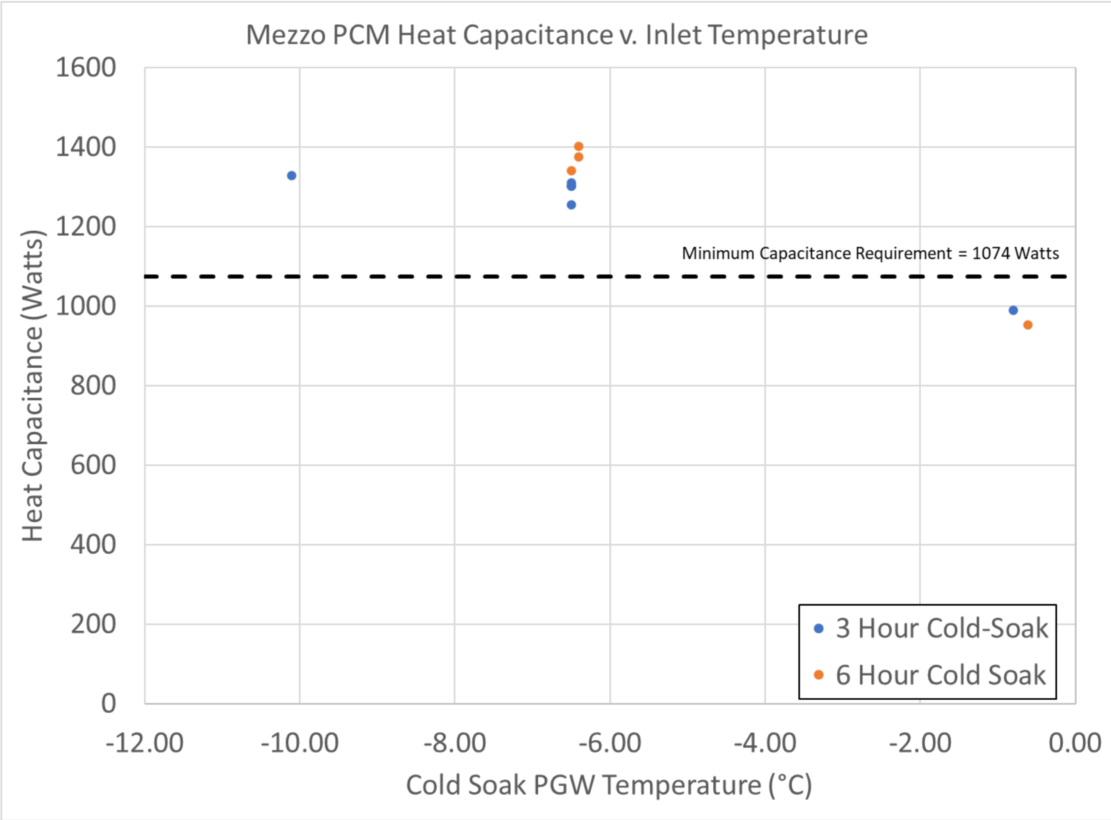

Figure 8. Heat Capacitance v. Cold Soak PGW Temperature

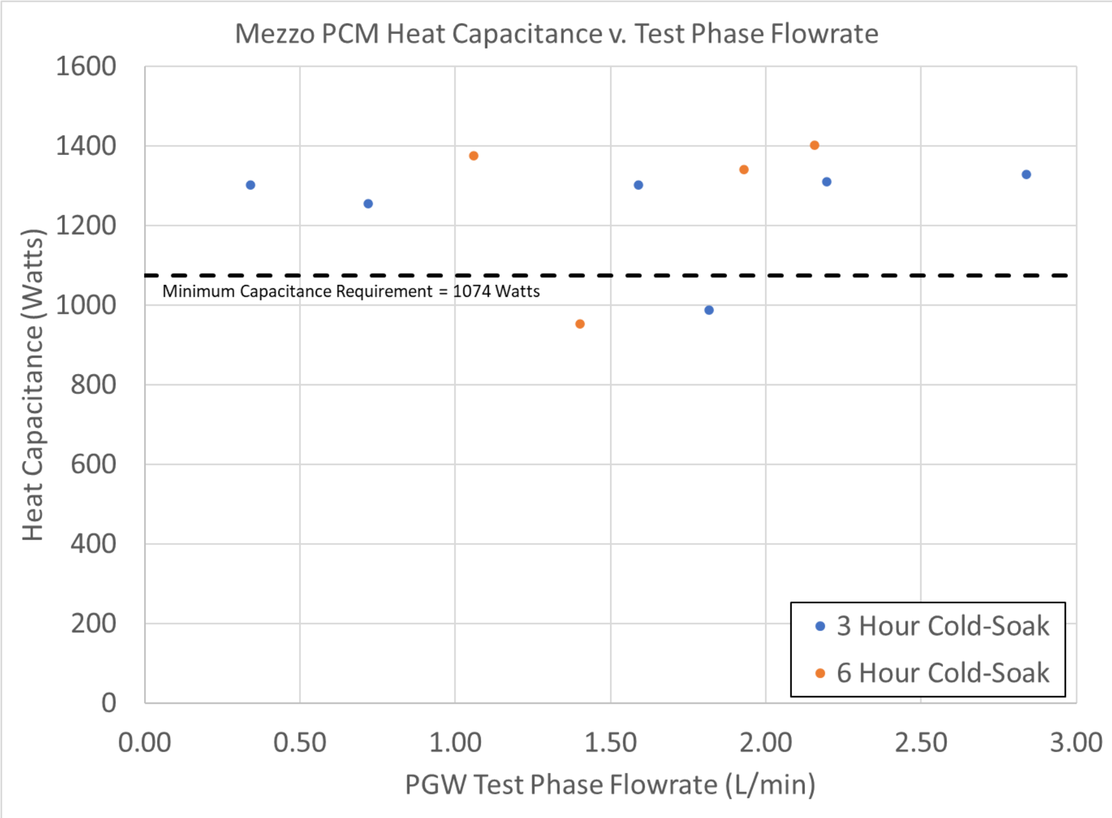

Figure 9. Heat Capacitance v. Test Phase PGW Flowrate

In summary, longer and colder cold-soaks led to higher heat capacitance. It can be inferred that the phase change material (n-pentadecane) is not fully frozen at test points where the cold soak PGW temperature was higher than -1°C, which leads to test points 7 and 8 not meeting the minimum capacitance requirement. All test points with a cold soak temperature less than -6.4°C met the minimum capacitance requirement. Additionally, test points with a 6 hour cold soak outperformed heat storage compared to similar 3 hour cold soaks. Test Phase PGW flowrates did not appear to have a considerable affect on heat storage capacity.

V. Forward Work

More testing is planned to guarantee the heat exchanger's ability to integrate into an actual human-rated ATCS system. This includes, but isn't limited to:

- Further flow through lab testing to bound performance amongst a wider range of test conditions (wider flowrate ranges, cold soak ranges, hot case temperatures, etc.)
- Testing in TVAC to guarantee robustness in a similar environment. The current PCM on Orion is stowed in the ESM, which is exposed to space vacuum.
- Further testing at multiple orientations to guarantee robustness to microgravity.
- Verification that the degas cycles prevent pressure spikes in the n-pentadecane during phase change.
- Shock and vibration testing to guarantee ability to survive launch loads.
- Testing with different internal ATCS coolants to verify functionality across a multitude of spacecraft outside Orion.
- Scaling the design up or down to meet varying vehicle heat storage requirements.

VI. Conclusion

Mezzo technologies manufactured a PCM heat exchanger under a NASA SBIR grant with novel manufacturing techniques in an effort to decrease lead time, increase reliability, and decrease mass of the technology for human ATCS applications. The PCM weighed 9kg less than the PCM on Orion and demonstrated comparable heat storage capability when showed simulated fluid conditions. More testing is required in the future to advanced the technical readiness level of the technology and make it suitable for integration on human spacecraft.

Acknowledgments

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