High-Capacity Spacesuit Evaporator Absorber Radiator (SEAR)

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Future human space exploration missions will require advanced life support technology that can operate across a wide range of applications and environments. Thermal control systems for space suits and spacecraft will need to meet critical requirements for water conservation and multifunctional operation. This paper describes a Space Evaporator Absorber Radiator (SEAR) that has been designed to meet performance requirements for future life support systems. A SEAR system comprises a lithium chloride absorber radiator (LCAR) for heat rejection coupled with a space water membrane evaporator (SWME) for heat acquisition. SEAR systems provide heat pumping to minimize radiator size, thermal storage to accommodate variable environmental conditions, and water absorption to minimize use of expendables. We have built and tested a flight-like, high-capacity LCAR, demonstrated its performance in thermal vacuum tests, and explored the feasibility of an ISS demonstration test of a SEAR system. The new LCAR design provides the same cooling capability as prior LCAR prototypes while enabling over 30% more heat absorbing capacity. Studies show that it should be feasible to demonstrate SEAR operation in flight by coupling with an existing EMU on the space station.

Nomenclature (Lynne, please alphabetize)

SEAR = Spacesuit Evaporator Absorber Radiator
LCAR = Lithium Chloride Absorber/Radiator
SWME = Space Water Membrane Evaporator
EMU = Extravehicular Mobility Unit
ISS = International Space Station
EVA = Extravehicular Activity
PLSS = Portable Life Support System
TRBF = Tile Repair Backpack Frame

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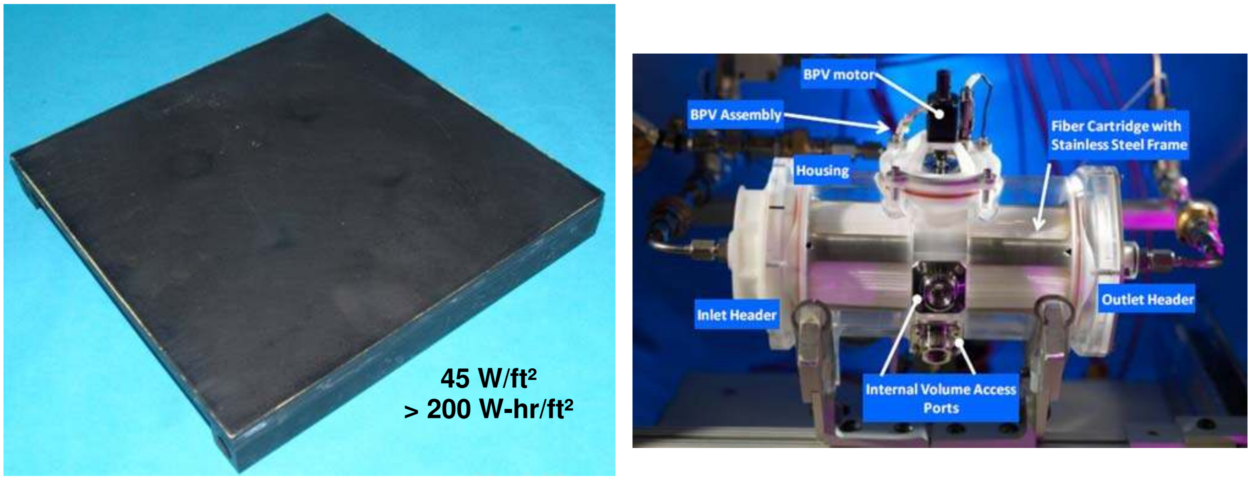
SCU = Service and Cooling Umbilical
SAFER = Simplified Aid for EVA Rescue
LCVG = Liquid Cooling and Ventilation Garment

I. Introduction

Future human space exploration missions will take astronauts far from earth into extreme thermal environments. Temperature control of spacecraft and space suits in these environments is a critical life support function. Existing thermal control technology relies on venting water to space to provide all or some of the required cooling. This approach is extremely costly, and possibly unsustainable, for future exploration missions. This paper describes recent advances in the development of a Space Evaporator Absorber Radiator (SEAR) system that will enable temperature control for space suits and spacecraft with much less water loss than conventional systems. The main components of a SEAR system are the LiCl Absorber Radiator (LCAR) and the Space Water Membrane Evaporator (SWME) (Figure 1). The SWME generates cooling by evaporating water through a bundle of porous hollow fibers. The LCAR contains lithium chloride/water solution that absorbs the water vapor and radiates heat to the environment at high temperature (typically 50°C). The LCAR is a multipurpose component, in which the LiCl is contained in a panel with an internal honeycomb structure. The honeycomb structure will enable the LCAR to replace structural components (Figure 2) and save considerable mass. This paper describes recent work to demonstrate the innovative honeycomb structure and develop a test package that meets requirements for demonstration on the International Space Station (ISS) (Figure 3).

We proved the feasibility of the SEAR approach through proof-of-concept demonstrations, model validation, and flight experiment design. The proof-of-concept honeycomb LCAR incorporates the basic internal construction needed for multipurpose heat rejection and structural strength. We measured the performance of the honeycomb LCAR in thermal vacuum tests and obtained data consistent with design predictions. We also formulated a conceptual design of an ISS flight experiment to demonstrate operation of the honeycomb LCAR using an extravehicular mobility unit (EMU) onboard the ISS. The flight experiment design includes a preliminary concept of operations and recommendations regarding suitable aqueous coolants for use in the SEAR.



(a) Lithium chloride absorber radiator (LCAR)   (b) Space water membrane evaporator (SWME)

Figure 1. Space Evaporator Absorber Radiator (SEAR) Components

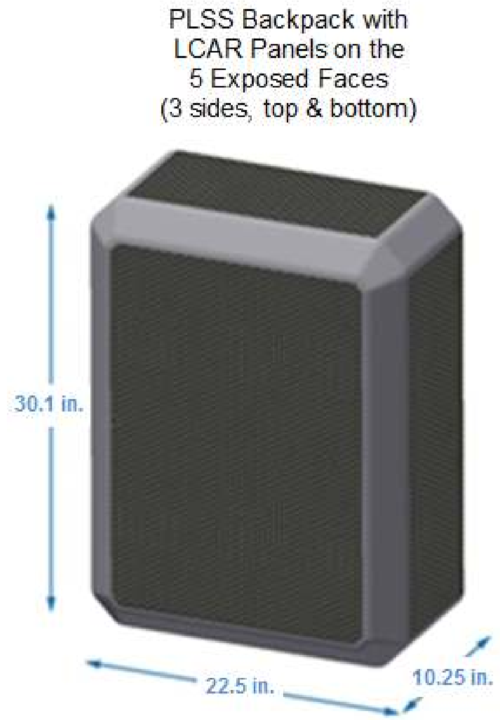


Figure 2. High-Strength Honeycomb Structure Will Enable the LCAR to Perform Multiple Functions.

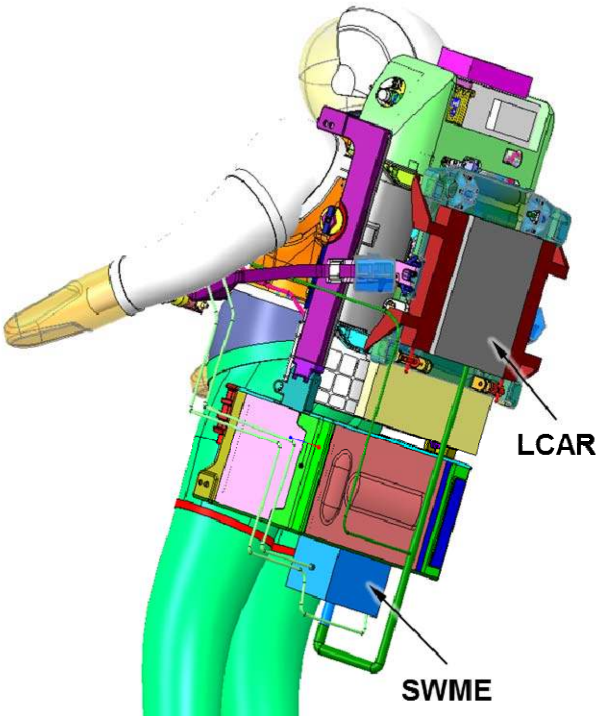


Figure 3. Concept for Demonstrating a SEAR System Using an EMU on the Space Station.

II. The Need for Advanced Thermal Management Technology

Exploration life support systems need advanced technology for thermal control. Water conservation is a critical challenge. Currently, operational extravehicular activity (EVA) thermal control systems reject metabolic and equipment waste heat as latent heat absorbed by water, which is converted to vapor and discharged to space from the life support system using a sublimator. Reliance on evaporating water for all heat rejection means that approximately 3.6 kg (8 lb_m) of water is lost to space for each astronaut during a typical EVA sortie. For long exploration missions with many EVA sorties, the cumulative water loss has a dramatic effect on life support consumables that are required for the mission (Figure 4). The estimated mass of the Environmental Control and Life Support System (ECLSS) nearly doubles when space missions of varying duration with little or no EVA are compared to a surface exploration mission requiring frequent EVA. The increase is primarily driven by expendable water requirements for EVA thermal control.

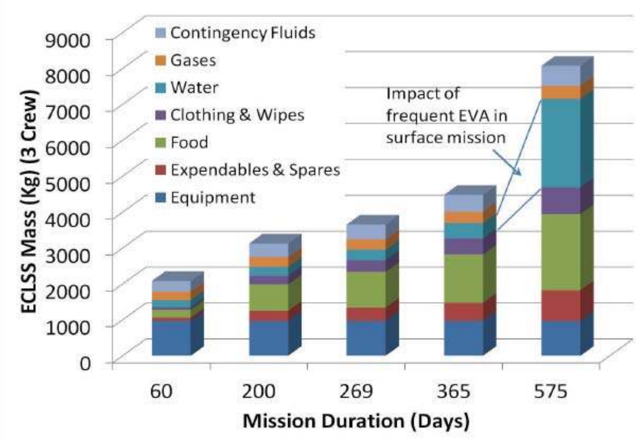


Figure 4. EVA Using Conventional Cooling Methods Can Consume > 2,000 kg of Water (Bue et al. 2013).

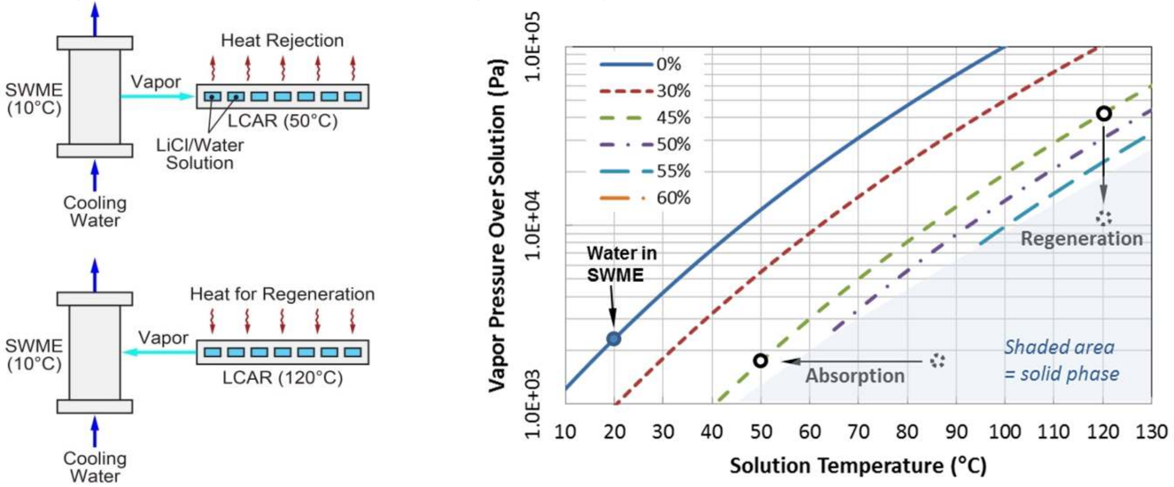
III. Space Evaporator Absorber Radiator (SEAR) Technology

SEAR exploits unique properties of LiCl /water solution to conserve water in thermal control systems. LiCl is a powerful desiccant with a very high affinity for water vapor, which enables both heat pumping and efficient thermal radiation. Absorption of water vapor in LiCl can reduce life support system mass significantly compared to venting to space. The water is recovered and the solution regenerated by heating the LiCl solution to moderate temperature (120°C).

A. Basic Principle of Operation

Figure 5 shows the basic process schematic for water vapor absorption in a SEAR system along with a plot showing the vapor pressure of LiCl/water solution. LiCl/water solution has a substantially lower water vapor pressure than pure water, which enables heat pumping because pure water will equilibrate with solution at a much higher temperature. The vapor pressure of evaporating water in the SWME is represented along the 0% solution curve in Figure 5*(*b). At a temperature of 20°C, for example, the vapor pressure in the SWME is greater than the vapor pressure of 45% LiCl solution at a temperature of 50°C. Therefore, vapor will flow from water at a temperature of 20°C to the LCAR if the LiCl solution concentration is greater than 45% and the temperature is 50°C. This is the basic process that occurs in the SEAR during absorption. As the process continues, the LiCl concentration decreases and the solution temperature must decrease as well. At the end of an absorption run, the solution temperature is as low as it can be while still rejecting the required amount of heat to the environment.

To recover the water that is absorbed in the LCAR, the solution must be heated to drive water back out. For spacesuit cooling applications, where the concentration swing is large, this is typically accomplished by heating the solution to moderately high temperatures (120°C) for several hours. This process is also shown schematically on the plot in Figure 5*(*b). Table 1 summarizes the regenerative cycle for the LCAR.



(a) Basic process schematic

(b) Vapor pressure of LiCl/water solution

Figure 5. Absorption and Regeneration Processes

Table 1. LCAR Regenerative Cycle

Mode	Use	LCAR State
Ready	In Storage	Sealed Internal pressure < 1 torr LiCl conc. constant, > 90%
Absorption	During EVA	Absorbing water vapor at 50°C Internal pressure 10–15 torr LiCl conc. decreases to 45%
Regeneration	Post EVA	Drying at 120°C Internal pressure decreases to 1 torr LiCl conc. increases to > 90%
Ready	In Storage	Sealed Internal pressure < 1 torr

		LiCl conc. constant, > 90%

B. SEAR for Space Suit Thermal Control

Figure 6 illustrates the SEAR concept for space suit thermal control. Metabolic heat generated by the astronaut inside the pressure garment is absorbed by water that circulates through a liquid-cooled garment (LCG). The warm liquid leaving the LCG flows through the SWME, which replaces the sublimator in conventional portable life support systems (PLSSs). The core of the SWME comprises a bundle of porous, hydrophobic hollow fibers with the circulating liquid inside the fibers and water vapor on the shell side. The small pores in the fibers prevent liquid from leaking out while presenting very low resistance to evaporation and vapor flow. The circulating water evaporates due to the low water vapor pressure on the shell side of the SWME, which causes the liquid to cool before it returns to the LCG.

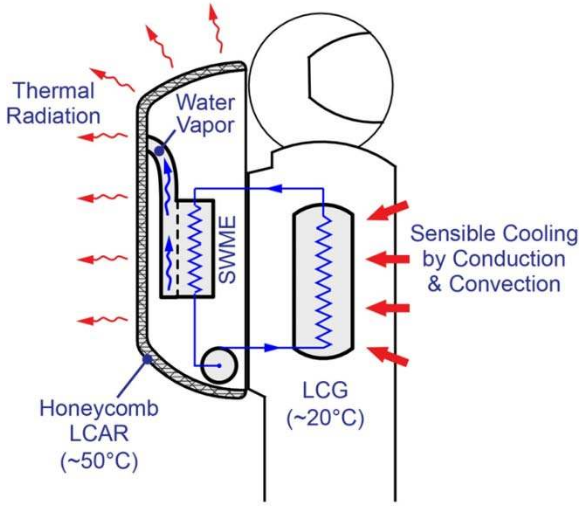


Figure 6. Non-Venting Space Suit Thermal Control Using SEAR.

The low water vapor pressure in the SWME enables water evaporation at temperatures (~20°C) suitable for metabolic cooling. This low vapor pressure is maintained by the LCAR, which is a compact heat/mass exchanger in which an array of absorber elements containing concentrated LiCl/water solution are maintained in close thermal contact with a radiating surface. Because the solution has an extremely high affinity for water vapor, it can maintain a vapor pressure lower than the SWME at temperatures that are 30°C or higher than the circulating water temperature (Figure 5). As a result, the heat generated when the water vapor condenses and is absorbed into the LiCl solution can radiate to space at a high heat flux due to the high radiator temperature (typically 50 to 100% greater than a simple non-absorber radiator, depending on environmental conditions).

During the course of an EVA sortie, the solution concentration in the LCAR gradually decreases as water is absorbed. The LCAR is sized so that the vapor pressure over the dilute solution at the end of the sortie is still low enough to maintain cooling. To prepare for the next EVA, the LCAR must be regenerated by heating to 120°C for several hours, which drives water out of the solution and returns the concentration back to the LCAR starting point.

Note that the presence of the LCAR does not prevent water venting during off-normal operation. In extremely hot environments or cases where the sortie lasts longer than planned, cooling can still be accomplished by venting water vapor from the SWME directly to the environment. Despite the need for occasional venting, use of the LCAR should drastically reduce water consumption compared to a venting-only system.

IV. High-Capacity LCAR Demonstration

We have demonstrated the feasibility of using a honeycomb LCAR in a SEAR system. Specifically, we produced a detailed design for the honeycomb LCAR, then fabricated and assembled a 1 ft² prototype LCAR panel. We found that the structure was robust enough for anticipated pressure loads. We measured performance of the LCAR in thermal vacuum tests and demonstrated regeneration. The radiation performance is consistent with past demonstrations, and the LiCl storage density (250 g per ft² of radiator surface) and energy storage capacity (194 W-hr/ft²) are 19% higher than achieved with the prior LCAR design. Improvements in internal design have enabled regeneration in only three hours, which is about half the time needed to regenerate prior LCAR prototypes.

C. Honeycomb LCAR Design

Figure 7 shows the overall design of the LCAR, which comprises two machined graphite plates that enclose an array of absorber sponges. The thicker plate includes the radiating (outboard) surface. The radiating plate is machined with features that make up the honeycomb structure as well as an array of thin pins that provide a low-resistance path for heat to flow from the absorber sponges to the radiating surface. The thinner (inboard) plate mates with features on the radiating plate to make a seal and provide structural bonds for rigidity and to hold internal pressure. The walls of the honeycomb cells are perforated to allow vapor to flow laterally through the LCAR. Simple headers are attached at either end to allow water vapor in and for removal of non-condensable gas. The size of the hex cells was chosen based on structural analysis of the assembly subject to a load of 20 lb_f applied to a three-inch circle in the middle of the panel. The calculated maximum stress in this case was 2.2 ksi, well within the capabilities of the graphite material (18 ksi).

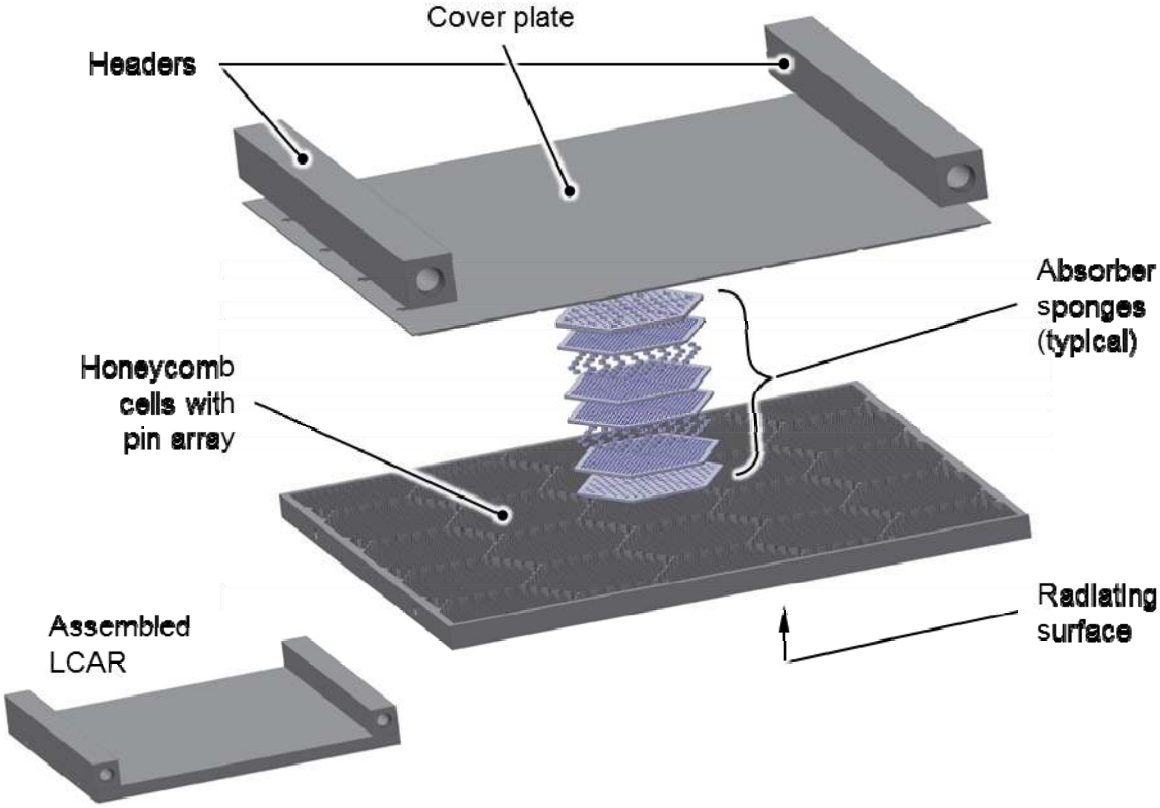


Figure 7. Design of a Honeycomb LCAR Module

Figure 8 shows a section view through the assembled LCAR that illustrates the internal structure. The assembly is designed to achieve efficient heat and mass transfer without large pressure losses due to vapor flow. Large surface areas are needed for contact between water vapor and the LiCl solution as well as between the absorber sponges and the heat-conducting pins. The absorber sponges are provided with an array of holes that enable vapor flow and contact with the graphite pins. The assembled sponge array leaves two layers open for lateral vapor flow. Additional holes in the sponge layer provide a large area for contact with water vapor to reduce mass transfer resistance. In addition to their roles as heat conductors, some of the pins are bonded to bosses on the inner surface of the cover plate to support the plates against internal pressure. Nominally 13 pins are bonded to the cover plate, which results in very low stress and deflection due to internal pressure. Our analysis shows that even with five of the 13 pins broken, the stresses will not reach the maximum allowable stress for the material.

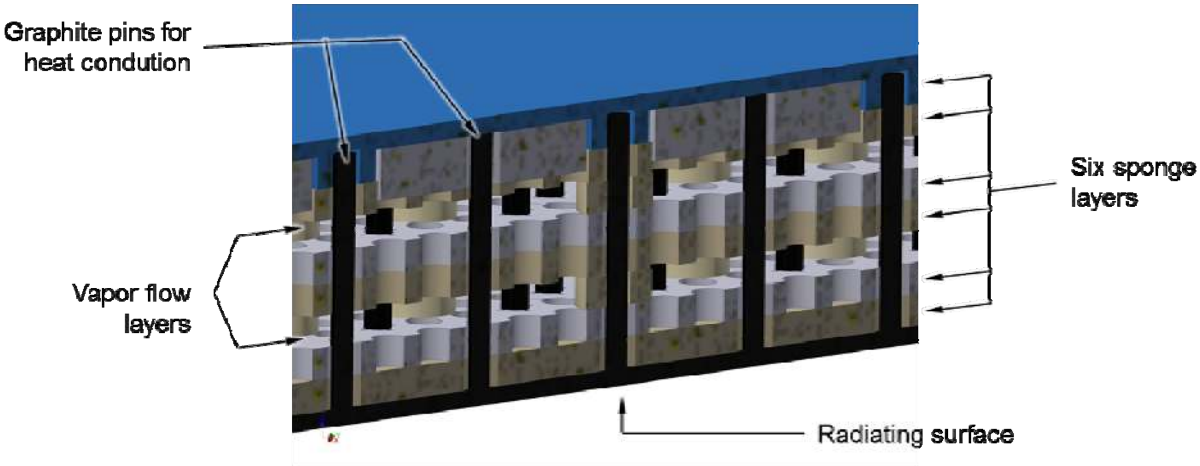
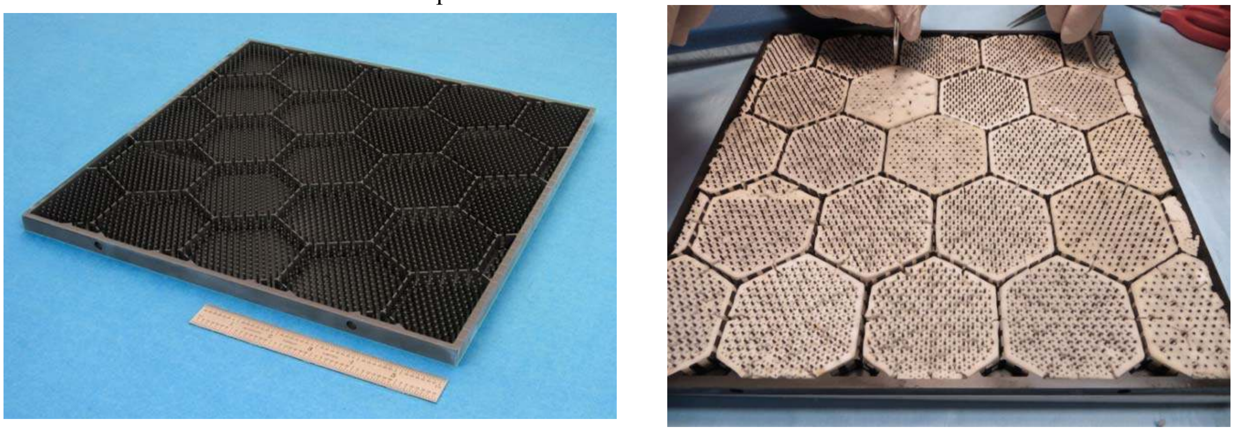


Figure 8. Internal Structure of Honeycomb LCAR Module

D. Honeycomb LCAR Fabrication and Assembly

We developed methods to machine the features needed for the honeycomb LCAR from graphite plates. Figure 9(a) shows the radiating plate, and Figure 9(b) shows the fully-loaded radiating panel just prior to attaching the cover plate. Sponges are loaded intot he radiating plate after charging with LiCl solution. During assembly we tracked the amount of LiCl added to the panel.



(a) Honeycomb structure and radiating surface

(b) Honeycomb cells loaded with LiCl sponges

Figure 9. Machined Graphite Honeycomb Panel

E. Structural Testing.

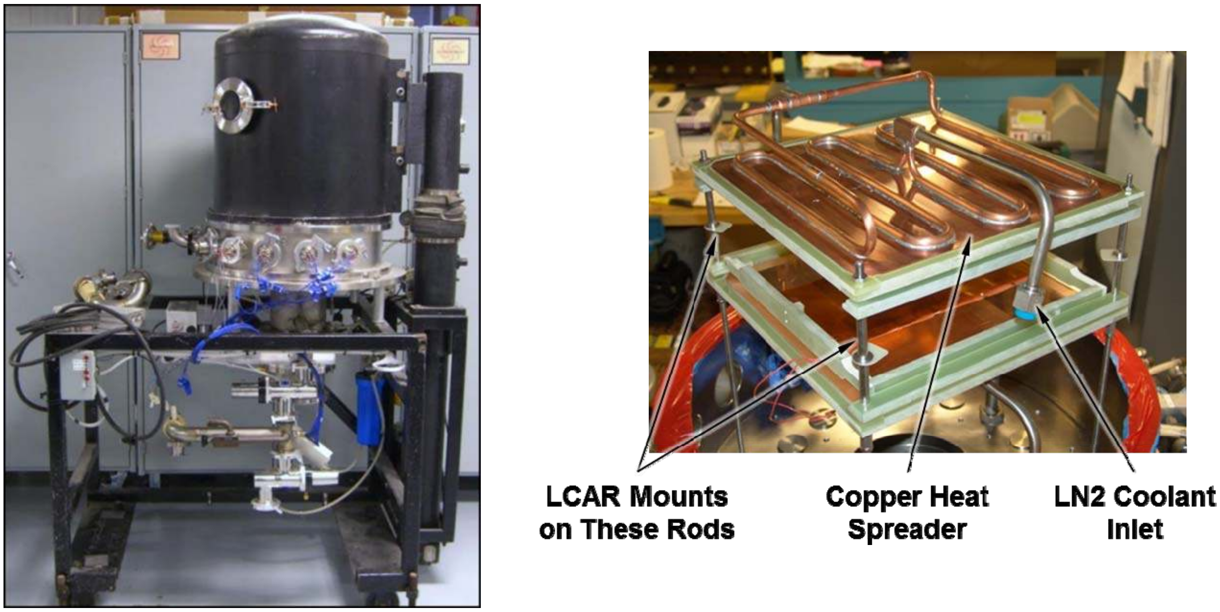
We measured the ability of the honeycomb cells to support internal pressure. We used prototypical methods and materials to attach a single hex cover plate to a prototypical, single hex cell sample We coupled the assembly to a tube that enabled us to pressurize the interior, and then tested the sample to failure at 26 psi. This is greater than predicted by our model and much greater than the internal pressures we expect to see during preliminary testing.

F. Thermal Vacuum Testing.

We installed the honeycomb LCAR in our thermal vacuum test rig (Figure 10) and measured its ability to absorb water under conditions that simulate operation in space. The facility comprises a vacuum bell jar with an internal test assembly that supports the LCAR panels between a pair of cryogenically cooled shrouds. The photographs in Figure 10 show the vacuum bell jar and the internal frame assembly that supports the LCARs and shrouds. The right-hand photo shows the back sides of one of the cryogenically-cooled shroud panels. The chamber can accommodate two 12 in. square LCAR panels in a back-to-back, stacked configuration, each facing a 14 in. square cooling shroud, although in the most recent tests we measured the performance of only a single panel. At a separation distance of 0.5 in., this geometry provides a view factor of 0.98 from the radiating side of each LCAR panel to the corresponding shroud, ensuring that we are able to accurately control and measure the heat transfer from the radiator panels.

The vacuum chamber could maintain vacuum levels in the range from 10^{-5} to 10^{-6} torr. At this level of vacuum, the thermal conductivity of the remaining gas in the system will be less than 2×10^{-5} W/m-K, effectively preventing heat conduction from the LCAR panels to the shroud. For example, for an LCAR temperature of 323 K and a shroud temperature of 180 K, the calculated radiation heat transfer will be roughly 46 W compared to a calculated conduction heat transfer of less than 2 mW.

The schematic in Figure 11 shows the overall test setup. Water vapor is generated in an external loop by a custom capillary evaporator built by Creare. Heat to generate the water vapor is provided by a circulating water loop that is maintained at a constant temperature of roughly 20°C using a laboratory chiller. Platinum Resistance Thermometers (PRTs) at the inlet and outlet of the evaporator along with a calibrated rotameter provide calorimetric data to measure the amount of heat transfer from the circulating loop that produces water vapor. Water vapor flows into the vacuum bell jar and then into the pair of LCAR panels. The far ends of the panels are plumbed together, so that noncondensible gas from the panels flows through a capillary tube, then through a desiccant bed, and finally to a vacuum pump that exhausts to ambient.



(a) Thermal vacuum chamber (b) Cooled shrouds and LCAR mounting arrangement

Figure 10. Thermal Vacuum Facility for Measuring LCAR Performance

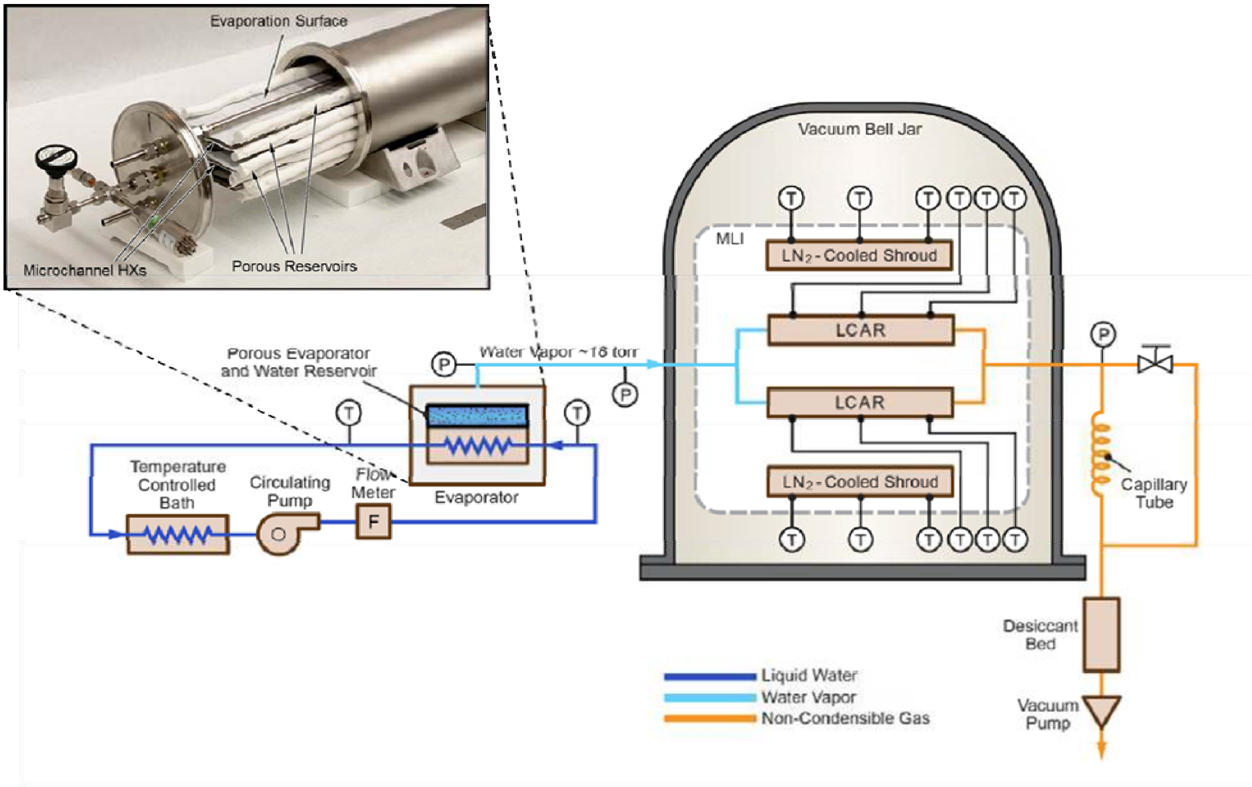
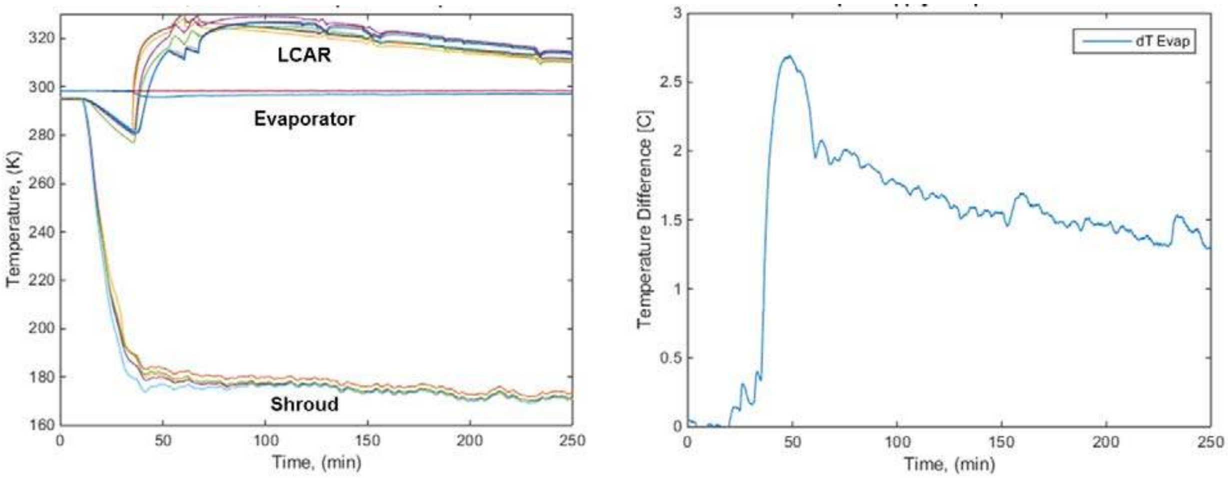


Figure 11. Schematic of Thermal Vacuum Test Facility

Figure 12 shows plots of data from the absorption test. Figure 12(a) shows a plot of the LCAR surface temperatures, shroud temperatures, and the inlet and outlet temperature of the circulating water stream used to heat the evaporator. LCAR surface temperatures were measured by nine thermocouples attached to the radiating surface in a 3×3 square array. We computed the amount of cooling provided by the LCAR by calorimetry on the evaporator stream.

The data show very uniform temperatures across the LCAR panel, consistent with our prior experience testing similar graphite LCAR panels. The LCAR panel began the absorption run at an average temperature of about 325 K (52°C) and ran for over three hours. The average temp fell to about 316 K (43°C) at the end of the run. The shroud temperature was very steady, beginning at about 180 K and gradually falling to 170 K during the course of the test. (This change in shroud temperature would amount to only a 2% difference in heat transfer for the same LCAR temperature.) The evaporator inlet temperature was held at 25°C throughout this test. The temperature difference in the evaporator circulating loop began the test close to 2°C and gradually fell to about 1.5°C. The evaporator flow rate during this test was 380 g/min, implying a heat transfer rate of 53 W early in the test dropping to 40 W at the end of the test. The evaporation rate fell as the LiCl concentration decreased. These heat rejection rates are very similar to those measured in 2013 (35 to 45 W/ft^2) and reported in an earlier paper.

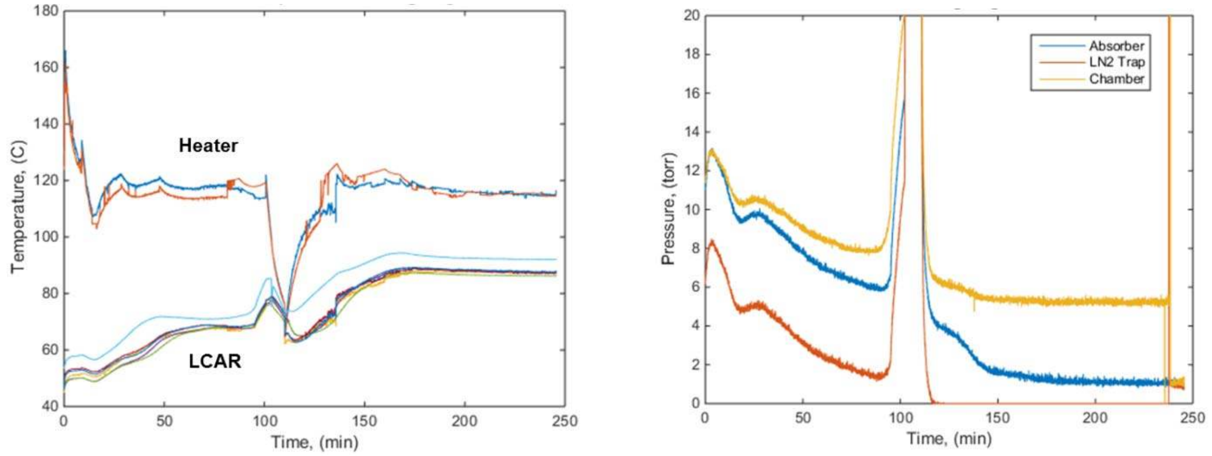


(a) LCAR, shroud, and evaporator temperatures (b) Temperature difference in evaporator

Figure 12. Key Data from Thermal Vacuum Absorption Testing of the Honeycomb LCAR. Heat transfer varied from 40 to 50 W/ft^2, consistent with tests of earlier LCARs.

G. Regeneration Testing.

We found that the honeycomb LCAR could regenerate in a significantly shorter time than prior designs, which we believe is due to the larger vapor/solution contact area. To regenerate, the LCAR vapor fittings were left open and the assembly was placed on a heater in a low pressure vessel that was evacuated by a rough vacuum pump. An LN$_2$-cooled water trap was placed between the low pressure vessel and the vacuum pump to capture the water released from the LCAR. Figure 13 plots temperatures and pressures during this regeneration run. The heater temperature was held steady at about 120°C throughout the test, and the LCAR temperatures increased gradually to ~85°C over the course of three hours. Pressures fell gradually as water evaporated from the LiCl solution and its concentration increased.



(a) LCAR and heater temperatures[7] (b) Pressure during regeneration

Figure 13. Honeycomb LCAR Regeneration

The three-hour regeneration time is much shorter than prior LCAR units. Our experience with the GEN2 LCARS is that 6–8 hours were required for a typical regeneration run. We believe the faster regeneration is because the total vapor/solution contact area in the honeycomb LCAR is roughly three times great than in the GEN2 LCAR.

280 g of water was collected during this regeneration run. This implies a LiCl loading of about 250 g, based on a typical concentration swing from 90% to 45%. Furthermore, this much LiCl implies a total energy storage

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[7] The sudden change in temperatures and pressure at ~100 min was due to a brief interruption in testing needed to remove water from the ice trap.

capacity of about 194 W-hr/ft² (or 2,100 W-hr/m²), which is a 19% improvement relative to the GEN2 LCAR. Further improvements (up to 215 W-hr/ft²) should be possible with improved fabrication and assembly methods in the future.

Concept for ISS Flight Demonstration

During start-up from low temperature and near the end of the absorption process, liquid water or liquid LiCl solution can be present in the vapor channels of the LCAR. The vapor channels are relatively large and the distribution of vapor and liquid in the channel will depend strongly on the magnitude of the gravity force. The actual performance of the absorber during these operational modes can only be demonstrated in a microgravity environment, such as the ISS. Furthermore, the dynamic behavior of the system will depend on the thermal environment and heat rejection properties of the radiator. For this reason, overall system performance needs to be demonstrated in an operational thermal environment.

In addition to demonstrating the physical operation of the LiCl absorber system in zero gravity and operational thermal conditions, the ISS demonstration will also demonstrate that the LCAR technology can be designed and qualified for use in manned spacecraft. To show the feasibility of a flight demonstration, we have:

- Developed a plan for testing a prototype SEAR system using an EMU onboard the space station.
- Assessed critical flight requirements for the LCAR.
- Developed a preliminary concept of operations for the flight test.
- Assessed the suitability of existing aqueous coolants for use in the SEAR system.

H. Plan for Flight Test of Prototype SEAR.

Figure 14 shows how a SEAR flight test system can couple to an EMU life support system using an existing coupling for the Service and Cooling Umbilical (SCU). This coupling enables the circulating water that flows through the sublimator to flow through the SWME as well. If the sublimator vent is closed during this test, then the SWME alone would provide cooling for the circulating water. The vapor side of the SWME is coupled to a tee that leads to both the LCAR and a high-capacity vent valve. Since the single, 1 ft² LCAR that can be accommodated in this test is not large enough to radiate all metabolic heat, the SWME must vent vapor continuously during the test.

Figure 15 shows the concept for mounting the LCAR on the EMU. The concept is to use the Tile Repair Backpack Frame (TRBF), which is an existing, qualified piece of EVA gear. The TRBF provides a flat surface in a prototypical location for mounting an LCAR on the EMU. The TRBF attaches to the SAFER with four bayonet couplings, which provide sturdy attachment points for a frame that supports the LCAR. Figure 16 shows the TRBF with the LCAR mounted on the EMU and the SWME mounted on the bottom of the SAFER. The SWME requires two water umbilicals (inlet and outlet) that run to the SCU connector on the displays and control module. A vapor umbilical is also required to connect the SWME to the LCAR, along with a fourth umbilical leading from the SWME to the vapor vent. This last umbilical requires a control valve within reach of the crew member to enable manual adjustment of the vent rate.

Paragraph on impact loads…

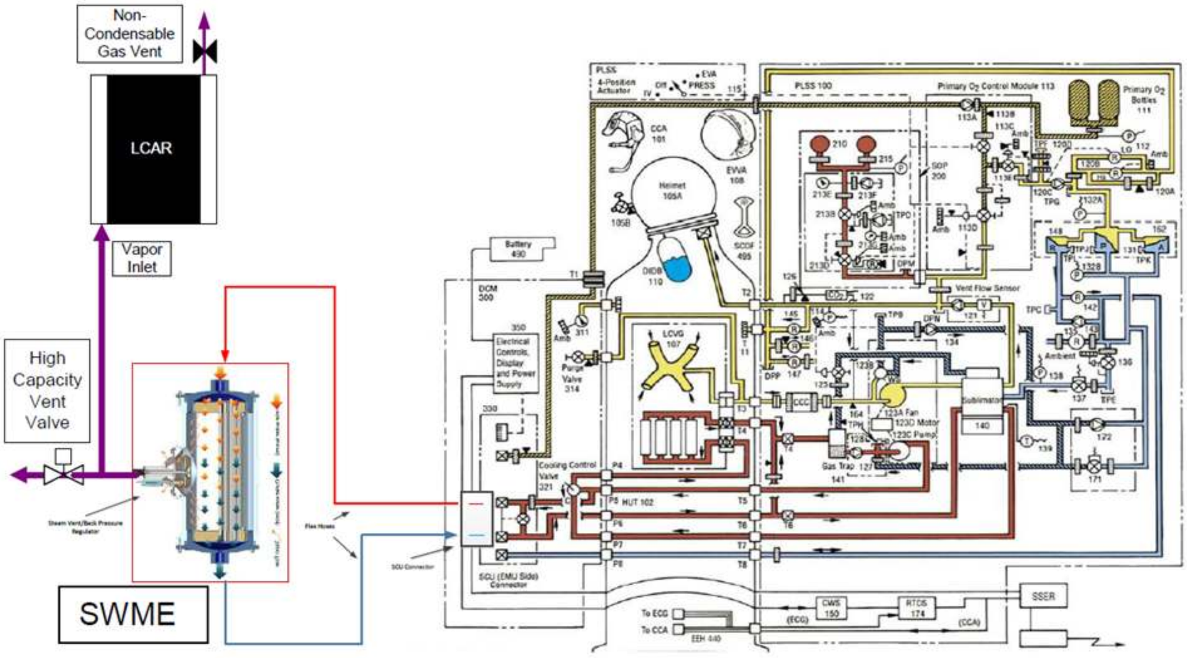

Figure 14. SEAR Test System Connects to EMU Portable Life Support System via Existing Connector for the SCU.

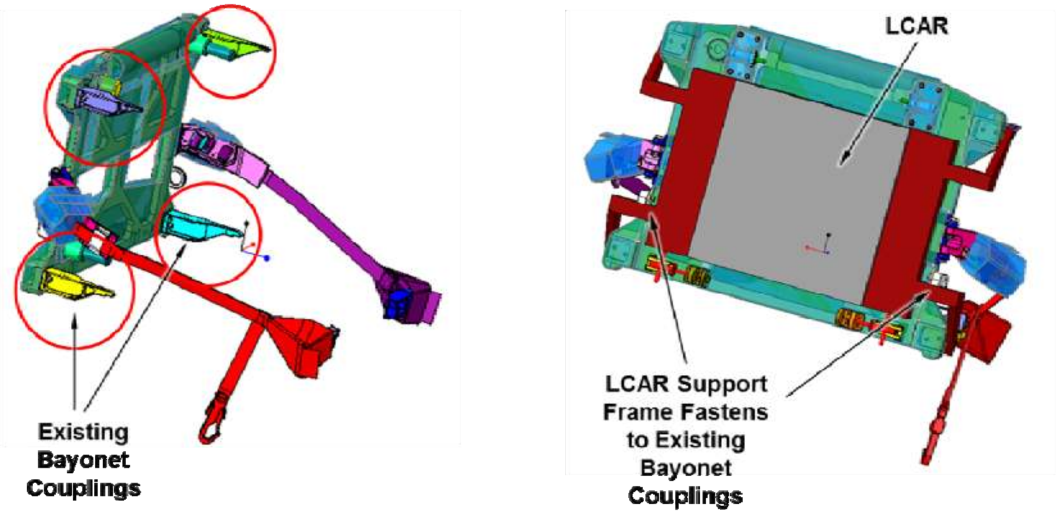

Figure 15. LCAR Module Mounted on the TRBF

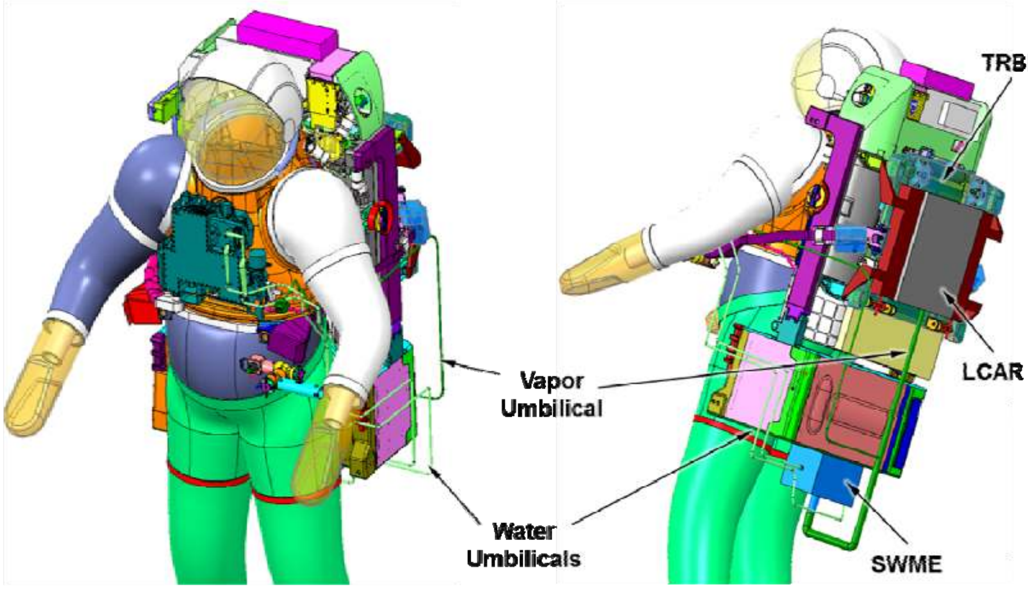

Figure 16. SEAR Flight Test System Mounted on EMU

I. Suitability of Existing Aqueous Coolants for SEAR.

The SEAR system places new requirements on the aqueous coolant/refrigerant that circulates through the SWME and liquid cooling and ventilation garment (LCVG). The coolant must be suitable both for evaporation in the SWME and absorption in the LCAR. UTAS's investigation[8] found that additives that are used currently in the space suit aqueous coolant can evaporate in the SWME and then react chemically with the LiCl solution in the LCAR. Two compounds are of particular concern: Ortho-phthalaldehyde (a biocide) and benzoic acid (a corrosion inhibitor). Prior tests conducted by UTAS have shown that these compounds will evaporate through the SWME membranes, and a thermodynamic analysis shows that they will probably undergo irreversible chemical reactions with LiCl in the LCAR. This process would definitely lead to the need to replenish the additives in the coolant periodically, and also raises concerns about possible effects on LCAR performance. Based on this assessment, UTAS has concluded that the existing coolant formulation is not suitable for use in a SEAR system and recommends that additional R&D efforts be initiated to reformulate the coolant. We propose to work with UTAS to identify suitable formulations as part of the proposed Phase II project.

V. Conclusion

Recent work has shown the feasibility of: (a) using a SEAR system for non-venting thermal management of future exploration space suits, and (b) using a space station EMU as a test bed for a SEAR flight demonstration.

Expected performance of the honeycomb LCAR? Thermal vacuum and regeneration testing showed that the honeycomb LCAR design provides an energy storage capacity of 194 W-hr/ft^2 (2,100 W-hr/m^2), which is a 19% improvement compared to prior LCAR designs. This energy density is not the maximum that can be achieved, because during assembly of the proof-of-concept panels, there was some loss of LiCl solution. Refined assembly techniques that build on lessons learned during this work should be able to more closely approach the maximum loading based on design calculations, which is 215 W-hr/ft^2 (2,314 W-hr/m^2). The radiating capacity of the honeycomb LCAR was measured at roughly 40 W/ft^2 (428 W/m^2). The Phase I LCAR was not coated with high-emissivity paint, so its emissivity was estimated to be about 0.8. If the unit were coated with Aeroglaze ($\varepsilon = 0.9$), then the performance would have been 45 W/ft^2 (482 W/m^2).

SEAR integration with a space station EMU. We have proposed a concept in which the LCAR is mounted on a frame that attaches to the bayonet couplings on TRBF. The SWME mounts underneath the SAFER. The proposed test assembly should fit inside the ISS airlock and through the hatch, but may restrict use of the mini workstation. We have also identified key structural requirements based on impact load requirements for

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[8] Conducted under Contract NNX14CJ12P, "Space Evaporator Absorber Radiator (SEAR) for Thermal Storage on Manned Spacecraft."

operation outside the space station, and identified concerns with existing aqueous coolants and recommends additional R&D to identify aqueous coolant formulations that are compatible with SEAR components.

Design and expected performance of an ISS flight experiment. The proposed test package comprises a 1 ft² LCAR mounted on the back of a PLSS and a SWME mounted underneath the SAFER. Water flows to and from the SWME through an umbilical that connects to the SCU port on the display and controls module. Because the 1 ft² LCAR is not large enough to radiate all metabolic heat to space, the SWME must vent continuously during the SEAR test. UTAS also proposed a preliminary concept of operations and a small number of modifications to EVA procedures (eight additional steps) to accommodate the SEAR test.

Acknowledgments

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