Multifunctional Space Evaporator-Absorber-Radiator (SEAR)

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A system for non-venting thermal control for spacesuits was built by integrating two previously developed technologies, namely NASA's Spacesuit Water Membrane Evaporator (SWME), and Creare's flexible version of the Lithium Chloride Absorber Radiator (LCAR). This SEAR system was tested in relevant thermal vacuum conditions. These tests show that a 1 m^2 radiator having about three times as much absorption media as in the test article would be required to support a 7 hour spacewalk. The serial flow arrangement of the LCAR of the flexible version proved to be inefficient for venting non-condensable gas (NCG). A different LCAR packaging arrangement was conceived wherein the Portable Life Support System (PLSS) housing would be made with a high-strength carbon fiber composite honeycomb, the cells of which would be filled with the chemical absorption media. This new packaging reduces the mass and volume impact of the SEAR on the Portable Life Support System (PLSS) compared to the flexible design. A 0.2 m^2 panel with flight-like honeycomb geometry is being constructed and will be tested in thermal and thermal vacuum conditions. Design analyses forecast improved system performance and improved NCG control. A flight-like regeneration system also is also being built and tested. Design analyses for the structurally integrated prototype as well as the earlier test data show that SEAR is not only practical for spacesuits but also has useful applications in spacecraft thermal control.

Nomenclature

AEMU	=	Advanced Extravehicular Mobility Unit
ECLSS	=	Environmental Control Life Support System
EMU	=	Extravehicular Mobility Unit
EVA	=	extravehicular activity
HoFi	=	Hollow Fiber(s)
ISS	=	International Space Station
JSC	=	Johnson Space Center
L/min	=	liters per minute
LCAR	=	Lithium Chloride Absorber Radiator
LCVG	=	Liquid Cooling and Ventilation Garment

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LEO = Low Earth Orbit
NEO = Near Earth Orbit
psia = pounds per square inch absolute
psid = pounds per square inch differential
PLSS = Primary Life Support Subsystem
SWME = Spacesuit Water Membrane Evaporator

I. Introduction

Since America's first space walks, EVA thermal control has challenged spacesuit system developers. The heavily insulated suits required to protect spacewalking astronauts from the extreme thermal environments of outer space and the surrounding vacuum severely limit opportunities to reject the waste heat generated by hard working astronauts and the equipment that keeps them productive and alive. Limited power availability to support heat transport in practical spacesuit systems and human thermoregulatory responses that demand lower skin temperatures as heat loads increase compound the challenge. Despite continuing research and development efforts, no satisfactory alternative to the thermal control approaches applied in the Apollo program spacesuits has been developed for autonomous EVA life support during the past half century. State-of-the-art space suits still rely on heat collection and transport using a liquid cooling garment and heat rejection by evaporating water into the surrounding space vacuum.

Currently, operational EVA thermal control systems reject metabolic and equipment waste heat as latent heat absorbed by water which is converted to steam and discharged to space from the life support system using a sublimator. This process requires heat transfer from cooling water circulating through the liquid cooling garment in the suit and from the suit's circulating ventilation gas requiring a complex and costly brazed multilayer assembly. It also depends on water and ice retention in a porous sublimator plate by surface tension, a process subject to degradation over time by the accumulation of contaminants carried to the unit by the evaporating water. This requires stringent feedwater quality controls which may be difficult to maintain in long space exploration missions and ultimately limits the sublimator's service life. Even more significantly, reliance on evaporating water for all heat rejection means that approximately 3.6 Kg (8 lbm) of water is lost to space for each EVA astronaut during a typical EVA. For long exploration missions with many EVA sorties the cumulative water loss has a dramatic effect on mission life support consumables that are required to support the mission as illustrated in Figure 1. In the figure, a dramatic increase in estimated ECLSS mass is shown 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.

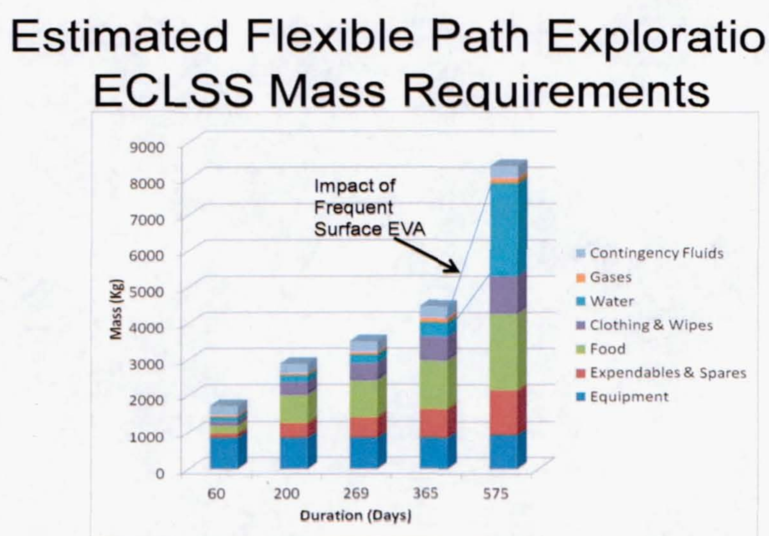

Figure 1. EVA water use for expendable cooling can lead to significant exploration mission mass penalties.

Spurred by recent technology advances at NASA and in NASA funded Small Business Innovative Research (SBIR) development programs, a new concept for integrated EVA thermal management has been developed which promises to change that situation. NASA's recent development of an effective spacesuit water membrane evaporator, and Creare's implementation of an absorption heat-pump radiator can be combined to achieve robust, non-venting, EVA heat rejection that eliminates EVA thermal control water loss over a wide range of operating conditions. The flexible panel design had been developed to be placed in a conformal way on the outside of the PLSS housing, which adds bulk and complicates suit operations. Furthermore the flexible design called for a network of axial and transverse channels to distribute the water vapor to the cylindrical stacks of desiccant storage media. This led to performance inefficiencies and problems with non-condensible gas (NCG) build-up in communicating channels that hindered absorption. Both storage bulkiness and NCG build-up problems could be elegantly solved by replacing the PLSS housing with a carbon fiber composite honeycomb, with the honeycomb cells packed with the stacks of desiccant sponges and grafoil interleaves. The entire stack would have a depth of ~12 mm, and include the storage stack honeycomb of ~8 mm in depth, an internal vapor header, and an external radiator face sheet. In this way, the housing multi-functionally provides the necessary housing protective structure, desiccant storage capacity and radiator surface to reject the heat. The 8mm depth of storage media suggests more efficient absorption resulting in a potential radiator temperature of 330K. A similar arrangement would be useful in providing a non-venting topping function for orbiting spacecraft during low lunar orbit where both heat rejection requirements and 290 K peak sink temperature are relatively high. Regeneration could be conducted during colder parts of the orbit where there is more available cooling for a condensing heat exchanger.

II. LCAR Concept

Figure 2. Lithium Chloride Absorber Radiator Test Article

LCAR contains a powerful LiCl desiccant that enables the SWME to generate cooling without venting water from the PLSS. The desiccant can effectively absorb water vapor produced by the SWME while operating at a temperature more than 30 °C higher than the SWME. High-temperatures result from heat released by the absorbed water vapor and enable heat rejection by radiation at a heat flux on the order of 50% greater than normal suit temperatures. Since the heat of absorption is no more than 20% greater than the heat removed from the SWME by the vapor there is a significant net gain in heat rejection capacity which enables the system to use a relatively small radiator. Under normal operating conditions, the LCAR cools the space suit without venting water. However, if the heat load is unusually high and/or the heat sink is unusually hot, then the LCAR may not be able to reject enough heat to absorb all the water vapor generated by the SWME. In this case, the system can be designed to vent the excess steam to space. An LCAR that operates this way will lose a small amount of water during periods when it is overloaded, but will be much smaller than an LCAR designed to absorb all water vapor under all conceivable heat loads and environmental conditions. The system can be implemented within expected PLSS volume constraints, adds very little (less than 1 W average for added sensors and control valve actuation) to the PLSS power requirement, and imposes modest on-back mass penalties (estimated to be approximately 4.5 – 7 Kg / 10 -15 lbm compared to current systems based on a consumable water heat sink).The basic process and the absorber/radiator panel technology have been demonstrated in the laboratory. [1,2] A 12 in. × 17 in. × 1.1 in. absorber/radiator module rejected heat at 33 W/ft² at a temperature of 50°C while absorbing water vapor from a 19°C evaporator. The absorber/radiator operates between 50 and 90% LiCl with an overall heat capacity of 123 W-hr/kg (including water). Previous studies describe the process in more detail.[1,2,3]

Because the desiccant absorbs water during the course of an EVA mission, the modules must be regenerated prior to the next mission by heating to moderate temperatures (120°C) and drying out the desiccant. This can be easily achieved in space by embedding electrical heaters in the LCAR or by passing heated air from a simple regeneration system through the absorber modules. The LCAR may be regenerated in place on the PLSS if a moderate amount of insulation is provided to protect thermally sensitive PLSS components, or it may be removed for separate regeneration. Water vapor may be condensed, separated, and collected in the regeneration system (as in any microgravity condensing heat exchanger) or may simply be released to the cabin ventilation return flow and condensed in vehicle condensing heat exchanger systems along with other vehicle latent loads. Regeneration details will require optimization based on mission and host vehicle specific factors as well as PLSS integration considerations as the design is developed and matured, but process feasibility has been established in cyclic operation of the current prototypes.

III. Membrane Evaporator

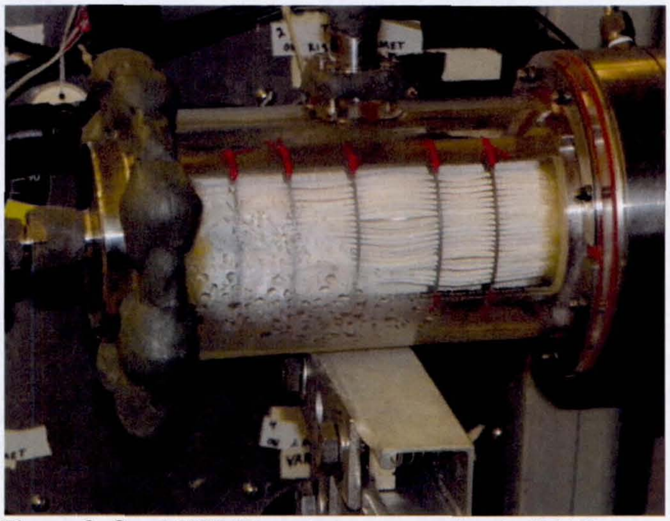

Figure 3. Gen1 SWME prototype operating in SEAR engineering evaluation

To extend life cycle requirements to 100 EVA's and provide heat rejection capability in Mars atmospheric pressures Spacesuit Water Membrane Evaporator (SWME) technologies have been developed with NASA in-house resources at JSC. A design built and tested in 1998 using a pair of concentric cylindrical membrane sheets supported by stainless steel screens, demonstrated feasibility. [4] Water flowed axially in the annular space between the membranes. The porous hydrophilic membranes allow water vapor to evaporate freely into the low pressure vent space on the screen sides of the cylinder thus cooling the water as it flows through the prototype. A full scale system consisting of three concentric pairs of cylinders was built in 2009. [5] Small scale tests of similar membranes made of self-supporting hollow fibers showed that this alternate geometry was promising. [6,7] A full scale prototype (Gen1) consisting of 14900 tubes in parallel, with an active region of about 16 cm in length was also built in 2009. [8] Testing of the sheet and hollow fiber prototypes proved that both types could meet the system requirements. [5,8] The Gen1 hollow fiber SWME is the membrane evaporator component of this SEAR engineering evaluation (see Fig. 3).

A second generation hollow fiber system (Gen2), built with light weight materials and a flight-like backpressure valve, has been tested. [9,10] Gen2 SWME has a mass of 1.87 kg (4.12 lbm) and a envelope volume of 5955 cm3 (363 in3) and in a vacuum environment rejects about 800W with 91 kg/hr (201 lbm/hr) water flow at water inlet operational pressures of 6.7 to 190kPa-d (9.8 to 27.7 psid), while also maintaining a water outlet temperature less than or equal to 10 °C (50 °F).. The backpressure valve controls heat rejection with 28 positions from fully open to fully closed. The system is freeze tolerant and self-degassing. In chamber pressures simulating Mars conditions, nominal heat rejection of 350 W was attained with no sweep gas. The performance characteristics of the Gen1 SWME (the evaporator for this SEAR evaluation) are very similar to the Gen2 SWME. A more compact Gen 3 SWME has also been developed. [11]

IV. LCAR Test Article

We have assembled two complete absorber/radiator panels, (see Fig. 2). Each panel comprises an array of nine absorber columns installed in a lightweight, flexible, plastic shell (see Fig. 4). The plastic shell is made from molded PPSU for ruggedness, flexibility, and compatibility with the absorber and the expected spacecraft environment. The side of the shell facing the environment is coated with high-emissivity coating. The absorber columns are assembled from stacks of sponge disks, spacer elements, and heat spreaders (see Fig. 5). The sponges contain the LiCl/water solution and provide a large surface area for mass transfer. The spacer elements support the sponge disks and maintain flow passages for water vapor. The heat spreaders maintain a uniform temperature throughout the stack by coupling the entire absorption surface of the sponge disks with the radiating surface of the module. The shell includes flow passages that allow water vapor to flow to or from manifolds to every absorber sponge disk. The shell is designed to withstand internal and external pressures expected for typical EVA missions without rupture or buckling.

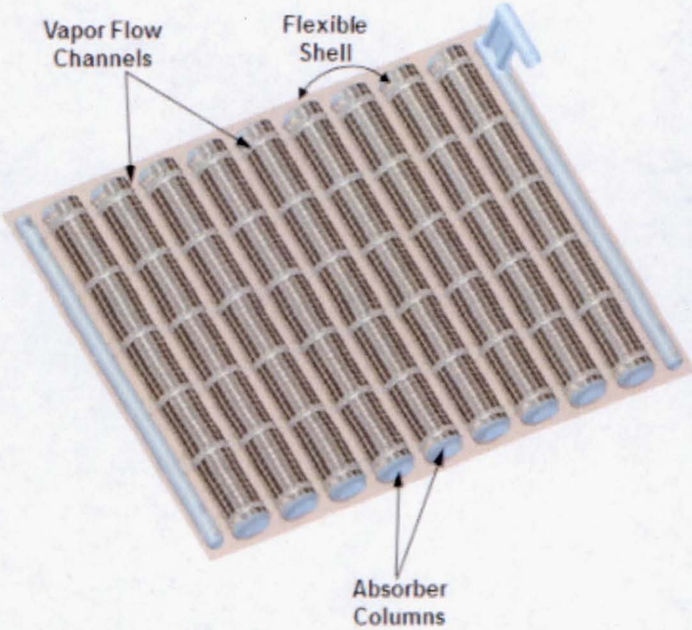

Figure 4. Overall Design Concept for the Absorber Radiator. Module Dimensions 12 in. × 17 in. × 1.1 in.

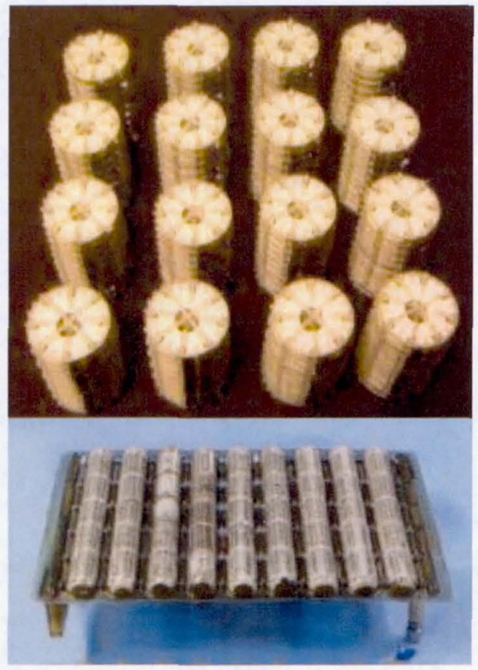

Figure 5. Absorber Elements and Assembled Module

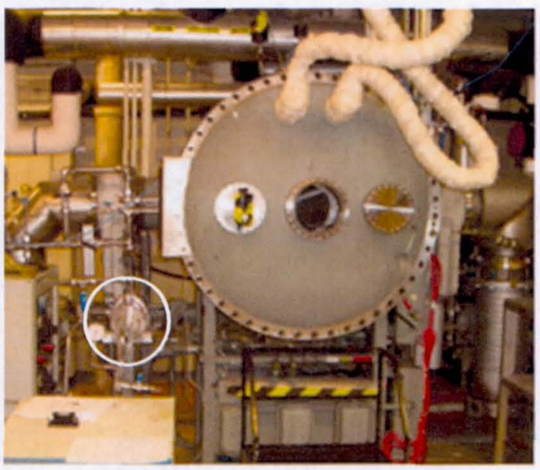

Figure 6. Chamber N With SWME (circled)

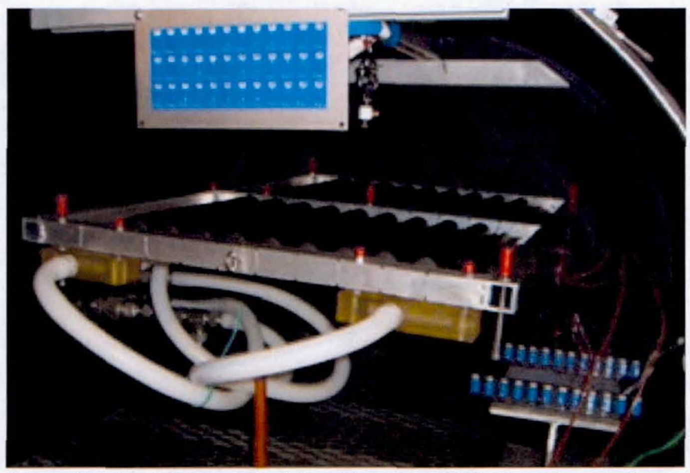

Figure 7. LCAR Installed in Chamber N Before Insulation

V. Experimental Assessment

A. Test Setup

A series of four tests were conducted to assess SEAR performance across the range of metabolic load conditions and EVA thermal environments (see Fig. 6 and Fig. 7). These tests were performed in Chamber N, a 5-foot thermal vacuum chamber in Building 33 at NASA Johnson Space Center (see Fig. 8). Figure 8 is a schematic of the test loop illustrating the SEAR water vapor transport loop, the SWME water loop, the thermal conditioning water loop, and key instrumentation. The SWME water inlet temperatures were controlled by a chiller cart via a liquid-to-liquid heat exchanger. The chiller cart also had an 800-W heater. Makeup water was continuously supplied from the reservoir feedwater tank as the SWME lost water due to evaporation.

Pressure in the reservoir was at ambient. The SWME water flow rate was adjusted by regulating the pump motor speed controller. SWME heat-rejection rates were controlled by the back-pressure valve called the Exit Valve, that when adjusted changes the SWME vapor side pressure—this is also called backpressure.

The Lithium Chloride Absorber Radiator (LCAR) test component is comprised of two of the 12 in. × 17 in. × 1.1 in. panels connected in parallel suspended in a test rack and thermally isolated from the rack. One end of LCAR is

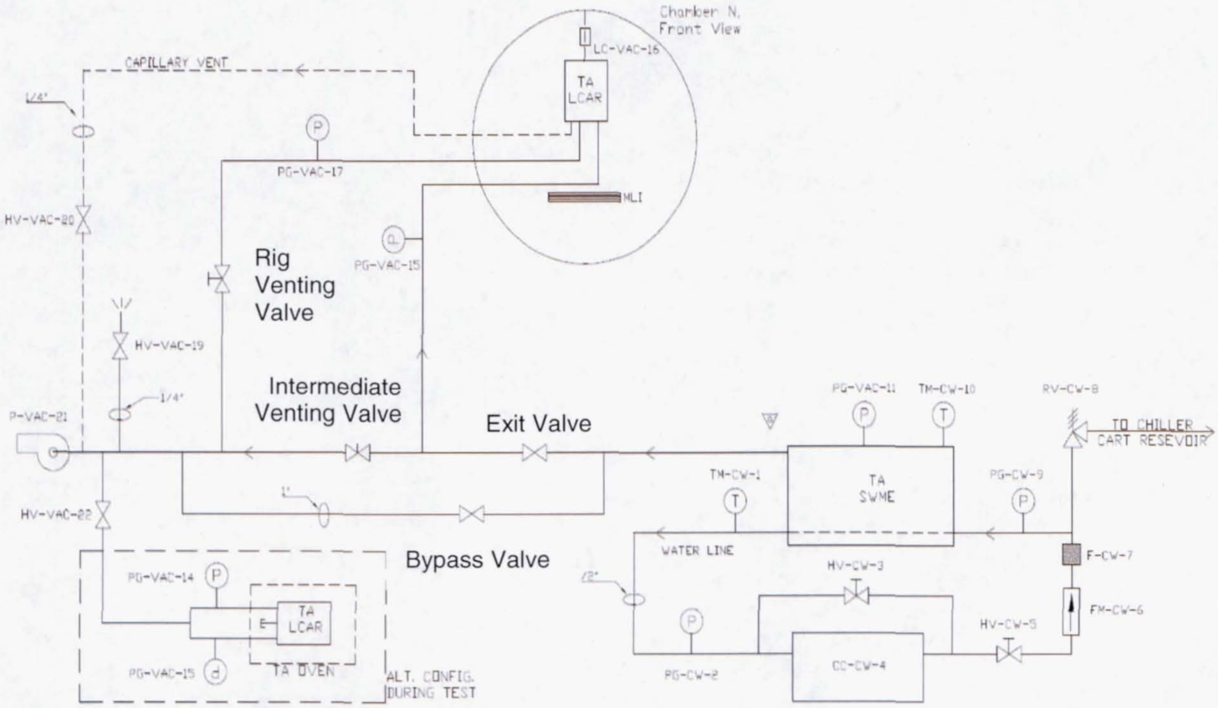

Figure 8. Schematic Thermal Vacuum Test Setup for SEAR.

connected to the evaporator vapor source. The other end is connected to a Rig Venting Valve (RVV), to eliminate air in the system following regeneration which occurs at ambient pressure. The LCAR has a capillary vent that runs in parallel from the distal end of the LCAR directly to the vacuum line on the downstream side of the RVV. This vent is necessary because it will be virtually impossible to keep all non-condensable gases out of the cooling system. Even a small amount of air dissolved in the LCG circulating water, for example, can come out of solution in the SWME and accumulate in the LCAR. The purpose of the capillary vent is to prevent non-condensable gases from blocking the flow of water vapor to sections of the absorber. The amount of water lost through the capillary vent is negligible compared to the amount of water absorbed in the LCAR. The LCAR was exposed to the thermal shroud and surrounded with multilayer insulation (aluminized Mylar) such that the view factor of the radiating surface to the Chamber N thermal shroud was essentially 1.0, whereas the non-radiating backside could only see itself. The LCAR was suspended from a load cell above the insulation by four wires. The load cell monitored water absorption rates of the LCAR continuously. LCAR temperatures on the radiation surface and back-side surface were monitored with 24 surface mounted thermocouples. The shroud temperature above the radiating surface was monitored with 3 surface mounted thermocouples.

Water vapor flow to the Lithium Chloride Absorber Radiator (LCAR) was controlled through an Intermediate Venting Valve (IVV). The IVV can split flow between the LCAR and an external facility vacuum source. In three of the tests, the IVV was set to shunt all of the water vapor to the LCAR to test radiator performance with complete absorption. Heat rejection rates beyond the capacity of the LCAR absorption capability was tested in two ways. The first was through the IVV, adjusted for partial venting to the facility vacuum and partial absorption by the LCAR. The second required full water vapor flow through the IVV to the LCAR and venting of excess water vapor to the facility vacuum through throttling the RVV.

All vent lines, coolant lines and valves were insulated inside Chamber N. In addition, the vent lines and vent valves were heated to 30 °C with heater tape to prevent water vapor condensation in transit between SWME and LCAR. After each test, the LCAR was removed from the thermal vacuum chamber for regeneration. After weighing the LCAR, it was connected it to a vacuum pump, and then warmed it to 120°C it using an external radiative heater. The LCAR was held at 120°C for several hours while pumping water vapor from the internal volume. The amount of water removed was measured by weighing the LCAR after regeneration was complete.

C. Testpoint Matrix

Table 1 presents a thermal vacuum test conducted in JSC Chamber N in Building 33, consisting of 4 full absorbtion runs. This test series was designed to test the performance limits of the SEAR system for rejecting heat over the range of saturation states of the LCAR and for different modes of operation. Run 1 explores the practical limit for non-vented heat rejection performance. A 20 °C SWME outlet temperature corresponding to the same LCG inlet temperature would reject about 375 W from the crew. This test point is run until the LiCl mass fraction declines to 40%, as deemed by real time mass measurements of the LCAR and heat rejection degradation of the SWME with constant outlet temperature and valve positions.

Run 2 and Run 3 are similar to Run 1 but with a 1-sun space environment of -25 °C. At lower heat rate rejected from the radiator, a longer time was need to get to the saturation limit of the LCAR.

Run 4 explored the partial venting operation mode, to investigate the fraction of water that can be absorbed when metabolic requirements call for more heat rejection than can be achieved through pure absorption/radiation. Two types of external ventilation are tested, one through the IVV that splits the SWME outflow between the facility vacuum and venting the LCAR, and the other through the RVV that directs all flow through the LCAR venting the non-absorbed fraction at the distal end. Additionally various states of exit valve closure were tested to show control at low heat rejection requirements.

Table 1 SEAR Testpoint Matrix

Run 1	Full Absorption Test, Deep Space					
Duration (min)	T_{Shroud} (°C)	Target T_{rad} (°C)	$T_{inlet,SWME}$ (°C)	Exit Valve SWME Venting	IVV Venting	RVV Venting
340	-100	65	20	full open	None	None

Run 2	Full Absorption Test, 1 Sun					
Duration (min)	T_{Shroud} (°C)	Target T_{rad} (°C)	$T_{inlet,SWME}$ (°C)	Exit Valve SWME Venting	IVV Venting	RVV Venting
400	-25	65	20	full open	None	None

Run 3	Repeat Full Absorption Test, 1 Sun					
Duration (min)	T_{Shroud} (°C)	Target T_{rad} (°C)	$T_{inlet,SWME}$ (°C)	Exit Valve SWME Venting	IVV Venting	RVV Venting
400	-25	65	20	full open	None	None

Run 4	Full Absorption Test, Valve Position Variations, 1 Sun					
Duration (min)	T_{Shroud} (°C)	Target T_{rad} (°C)	$T_{inlet,SWME}$ (°C)	Exit Valve SWME Venting	IVV Venting	RVV Venting
400	-100	variable	20	variable	variable	variable

D. Data Reduction Methods

The following data used to compute LCAR performance:

- Flow rate of circulating water through the SWME.
- SWME inlet and exit temperatures.
- Temperatures measured by thermocouples attached to the LCAR radiating surface.
- The three temperatures measured on the shroud.
- The mass of the LCAR before and after each absorption test.
- The mass measurements from the load cell that supported the LCAR inside Chamber N.

The mass of water carried out by the non-condensable gas through the capillary tube was found to be negligible. SWME pressures where used to estimate thermistor offsets and/or detect the presence of non-condensable gases.

Based on the test data, the heat transfer rates and water absorption rates that can be used to assess the LCAR performance were calculated. The rate of water evaporation from SWME was computed as follows:

$$\dot{m}_{SWME} = \frac{\dot{m}_{circ}\, c_p\, (T_{in} - T_{out})}{h_{fg}} \tag{1}$$

where:

$\dot{m}_{SWME}$ is the calculated rate of water evaporation from the SWME (g/s)

$\dot{m}_{circ}$ is the flow rate of circulating water entering the SWME (g/s)
c_p is the specific heat of water (4.187 J/g-K),
T_{in} is the temperature of the circulating water that enters the SWME (°C)
T_{out} is the temperature of the circulating water leaving the SWME (°C)
h_{fg} is the heat of evaporation for water (J/g)

The amount of water evaporated from the SWME is computed by integrating $\dot{m}_{SWME}$ over the duration of the absorption test, or an interval of interest.

Absorption of water vapor in the LiCl desiccant generated heat in the LCAR that was dissipated by radiation to the cooled shroud in Chamber N. The amount of water absorbed was estimated from the rate of radiation heat transfer which, in turn, can be estimated from the LCAR and shroud temperatures. The average heat sink temperature from the measured shroud temperatures was calculated as follows:

$$(\bar{T}_{sink})^4 = f_1 T_1^4 + f_2 T_2^4 + f_3 T_3^4 \tag{2}$$

where:

$\bar{T}_{sink}$ is the radiation-averaged temperature of the shroud (K)
T_1, T_2, and T_3, are the measured shroud temperatures (K)
f_1, f_2, and f_3 are quasi "view factors" based on shroud thermocouple position equal to 0.18, 0.44 and 0.38

The average radiating temperature of the LCAR panels is computed assuming that each thermocouple measures the temperature of the same radiator area that has the same view factor to the sink as all other thermocouples:

$$(\bar{T}_i)^4 = \frac{1}{N} \sum_{j=1}^{N} T_j^4 \tag{3}$$

where:

$\bar{T}_i$ is the average radiating temperature of panel i (K)
T_j are the temperatures measured from the panel surface thermocouples (K)
N is the number of thermocouples on panel i

The rate of water accumulation in the LCAR were estimated from the rate of radiation heat transfer calculated from the average panel and heat sink temperatures:

$$\dot{m}_{rad} = \frac{A_{panel}\, \sigma\, \varepsilon \sum_{j=1}^{2} \left(\bar{T}_j^4 - \bar{T}_{sink}{}^4\right)}{h_{fg} + h_{dil}} \tag{4}$$

where:

$\dot{m}_{rad}$ is the rate of water absorption calculated from radiation heat transfer (g/s)
A_{panel} is the radiating surface area per LCAR panel (m^2)
σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m²-K⁴)
ε is the emissivity of the LCAR radiating surface
$\bar{T}_j$ is the average radiating temperature for LCAR panel j (K)
h_{dil} is the average heat of dilution for water in LiCl solution (roughly 350 J/g)

In this report, we have used a constant value of h_{dil} = 350 J/g. In reality, h_{dil} varies with LiCl concentrations, and future efforts should include this effect. The amount of water absorbed in the LCAR can be computed by integrating $\dot{m}_{rad}$ over the duration of the absorption test or an interval of interest.

The water accumulation based on LCAR weight is simply the change in LCAR mass during an absorption test:

$$\Delta m_{LCAR} = (m_{LCAR})_{final} - (m_{LCAR})_{initial} \tag{5}$$

where:

$(m_{LCAR})_{final}$ is the weight of the LCAR and panel assembly after an absorption run (kg)
$(m_{LCAR})_{initial}$ is the weight of the LCAR and panel assembly before the absorption run (kg)

The water accumulation based on the load cell measurement is the difference in load cell readings at the end and the beginning of the absorption test:

$$\Delta m_{load.cell} = m_{load.cell}(t_{end}) - m_{load.cell}(t_{start}) \tag{6}$$

where:

$m_{load.cell}(t_{end})$ is the load cell reading when the absorption run ends (g)
$m_{load.cell}(t_{start})$ is the load cell reading at the start of the absorption run (g)

This water accumulation could be monitored continuously but was sensitive to shroud temperature, and water vapor flow.

VI. Test Results

The SEAR prototype hardware was tested in Chamber N at the NASA Johnson Space Center between May 7 and May 15, 2012. Actual test points and the test sequence were changed from the original plan in response to challenges encountered in controlling chamber test conditions and the results obtained in initial test runs, but major objectives of the test plan were achieved and expected thermal control performance capabilities were successfully demonstrated.[3]

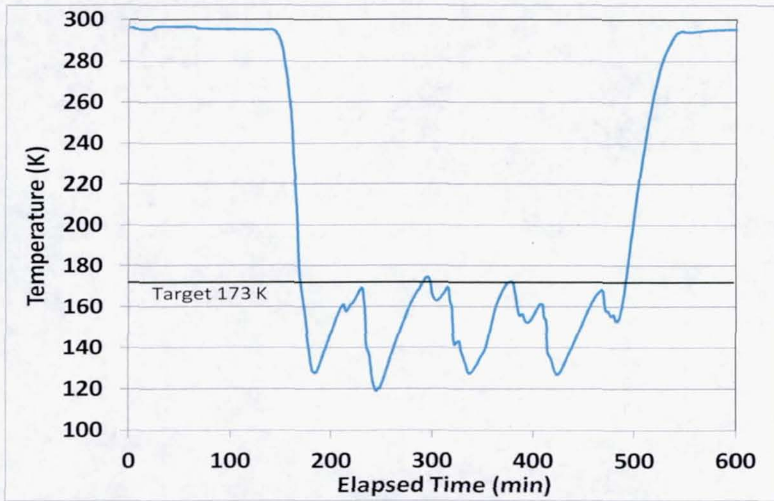

Figure 9. Run 1, Average Shroud Temperature

Figure 9 shows that for Absorption Run 1 the average temperatures of the shroud determined from Equation (2) were colder than the target of 173 K. Temperatures oscillated mostly below the target having an average of 152 K.

Key temperatures from Run 1 are presented in Figure 10. The actual absorption run begins at an elapsed time of 129 minutes, which corresponds to when the SWME exit valve opens and water vapor enters the LCAR, leading to the rapid drop in SWME exit temperature and rise in LCAR temperatures at t = 129 min. The two warmer temperatures ("Avg T.Rad A" and "Avg T.Rad B") are the radiation-averaged temperatures for LCAR panels A and B, calculated using the data from intact thermocouples and Equation (3). The two panels decrease in

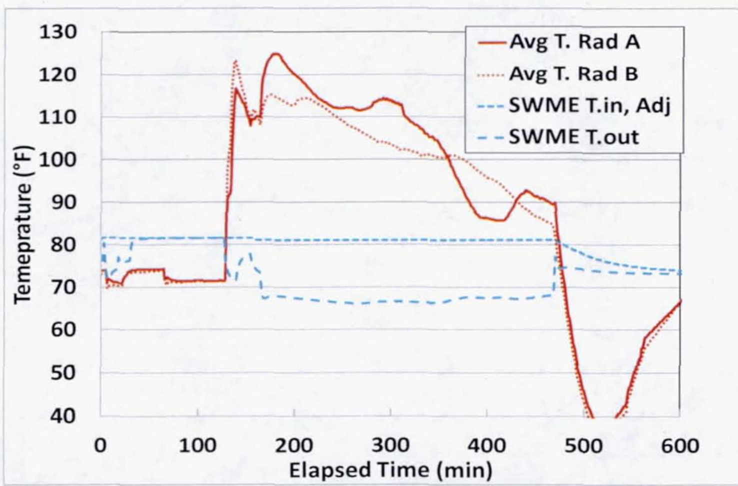

Figure 10. Run 1, LCAR Panel and SWME Temperatures

temperature, as expected, with increasing saturation of the LiCl. Panel temperature varied within this trend presumably reflecting transient obstructions by NCG and/or condensation in vapor channels decreasing water vapor flow to certain regions of the panels. SWME T.in and SWME T.out are the data from the SWME inlet and exit thermistors, respectively. The "Adj" of the SWME T.in reflects the correction of the is the inlet temperature for the offset observed between the inlet and exit temperatures during the SWME idle period leading up to absorption test 1, prior to any degassing and testing of the SEAR.

Figure 11 plots the SWME power, LCAR radiator power, and water accumulation as a function of time for absorption run 1. The three independent measures of water accumulation are displayed, namely the SWME Evaporation derived from Equation (1), Load Cell derived from Equation (6) and Water from Rad derived from Equation (5). These three measure track well with each other until the Exit Valve is closed. The SWME power and LCAR power vary together between 120 and 200 W. The LCAR power is consistently larger than the SWME power (Figure 12), beginning about 40% larger and decreasing steadily throughout the test to about 10% at the end. The radiation power is larger than the SWME power due to the additional heat of dilution that is liberated when water vapor from the SWME is absorbed by the LiCl solution in the LCAR. The decreasing ratio is roughly consistent with the fact that the heat of dilution decreases as the solution becomes more dilute during the test.[12]

Figure 13 shows the Average Shroud Temperature for Run 2 oscilating at about 241 K, for the most part slightly below the target environment temperature of 248 K. Figure 14 shows the SWME inlet

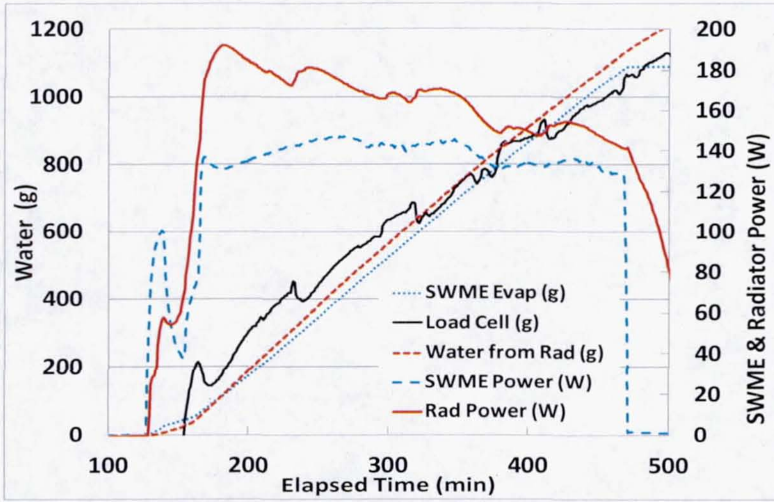

Figure 11. Run 1, SWME Power and Water Accumulation

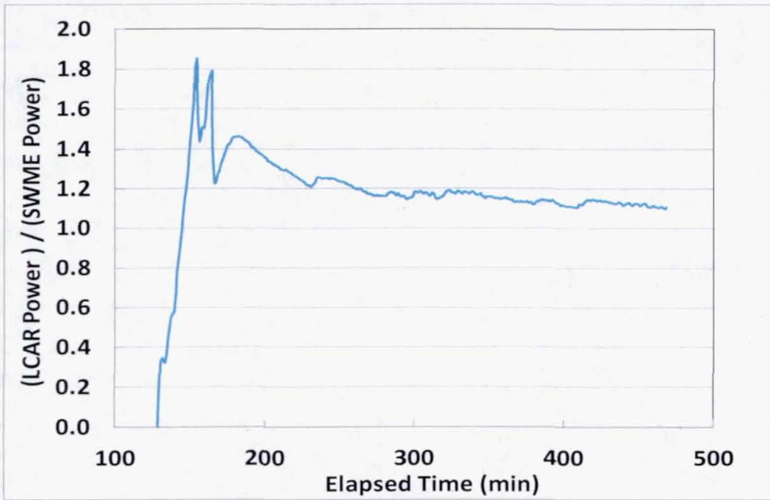

Figure 12. Run 1, LCAR to SWME Power Ratio

Figure 13. Run 2, Average Shroud Temperature

and exit temperatures and the average radiating temperatures of the two LCAR panels during absorption run 2. During this test, the capillary vent seems to have become plugged at ~ 220 min. LCAR surface temperatures dropped rapidly as the buildup of non-condensable gas inside the panel prevented water vapor from reaching the LiCl absorber elements. Plugging of the capillary may have been due to condensation and subsequent plugging by a liquid drop. To continue testing, the LCAR was vented through the Rig Venting Valve, with the Exit Valve closed which purged the LCAR of NCG and enabled continued testing. Several additional purges were needed to continue testing. Figure 15 plots the power computed from the SWME temperature difference and the radiation temperature difference, which are generally in good agreement throughout the test. The figure also shows water accumulation in the LCAR calculated from SWME power and radiation power alongside the load cell data. The valve manipulations at the beginning of the absorption run and blocking of water vapor inflow from capillary plugging may have deflected the vapor housing and perturbed the load cell measurement.

Run 3 is essentially a repeat of Run 2 with a target environment temperature of 248 K. Figure 16 show the actual average during the actual absorption run between 134 minutes and 536 minutes was 239 K.

Figure 17 shows the SWME and LCAR panel temperatures during absorption run 3. Prior to 134 minutes, a number of valve adjustments had to be made to emulate capillary valve which was unfunctional due to a post test mishap. Once corrected, this test showed relatively steady behavior for both LCAR panels, similar to absorption run 1. At ~350 min, panel A began to cool rapidly, but recovered by ~400 min. Figure 18 plots the instantaneous thermal

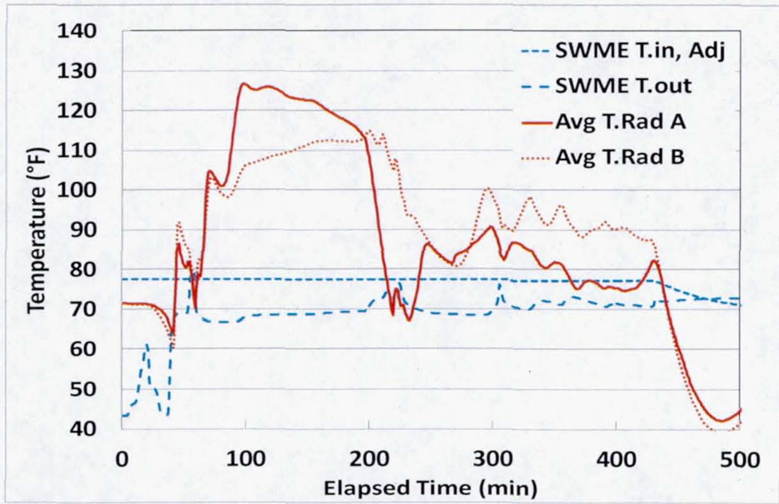

Figure 14. Run 2, LCAR Panel and SWME Temperatures

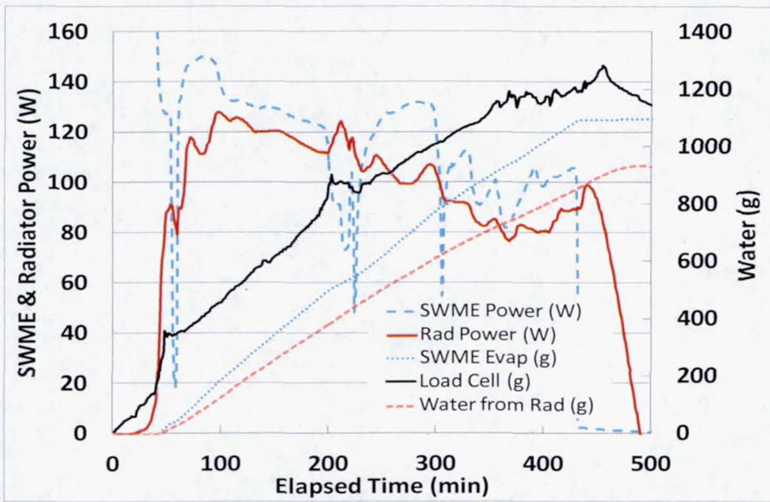

Figure 15. Run 2, SWME Power and Water Accumulation

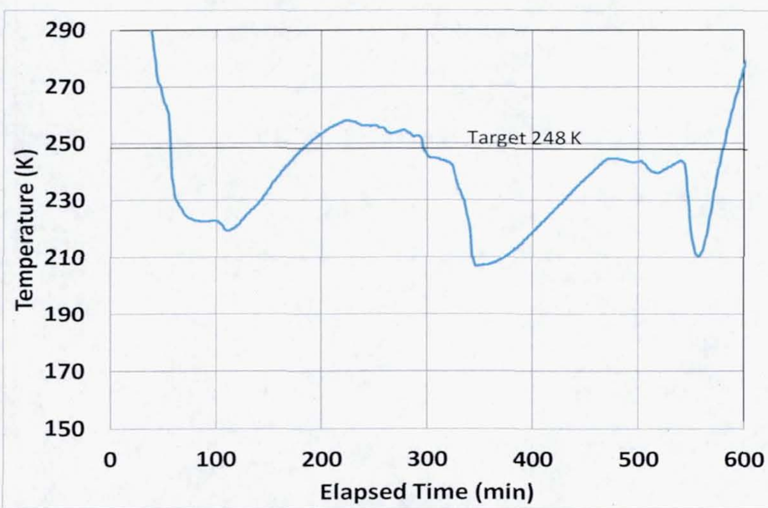

Figure 16. Run 3, Average Shroud Temperature

powers (SWME and radiator) along with water accumulation based on SWME temperatures, radiation temperatures, and the load cell. The values calculated from the SWME and LCAR temperatures agree well at the end of the test.

Run 4 was performed at various valve conditions to test two operational modes not captured by the previous runs. The first was to test excess venting conditions alternating with the IVV and the RVV. This mode of operation would occur when cooling demands exceeded SEAR heat rejection capability. The goal was to show at different excess venting conditions, which mode of external venting would result in the greatest absorption by SEAR. Unfortunately, the level of control the globe valves provided were not sufficient enough to produce results that was comparable. Both configurations resulted in radiation power between 160 W and 180 W during these operations (data not shown.

The second mode of operation test was to show low heat rejected, for low cooling demands in a 173 K environment. In this mode the IVV and RVV were fully closed and the SWME exit valve was nearly fully closed. Again the valve manipulation was difficult but SWME heat rejection rates of 7W, 10 W, 20 W and 48W (data not shown). The 48 W case was maintained stably for 40 minutes before ending Run 4.

Water transfer measurements based on SWME power, LCAR mass change, and integrated radiation heat transfer are generally consistent (see Fig. 19). Load cell data are also roughly consistent, but were transiently perturbed by shroud temperature fluctuations and changes water vapor flux due to valve operations. Water transfer calculated based on radiation from the LCAR has probably the second greatest error due to uncertainties in the actual sink temperature and

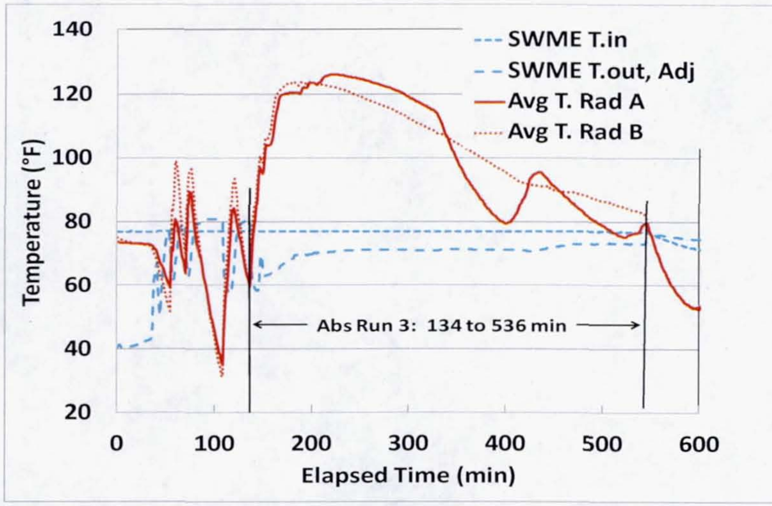

Figure 17. Run 3, LCAR Panel and SWME Temperatures

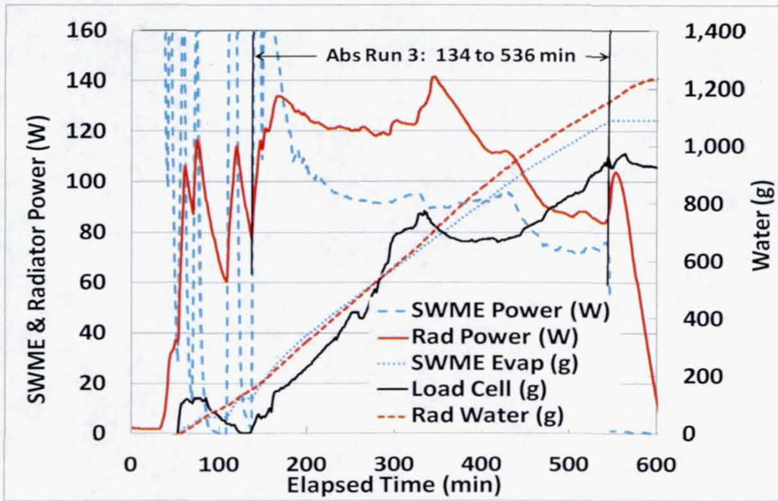

Figure 18. Run 3, SWME Power and Water Accumulation

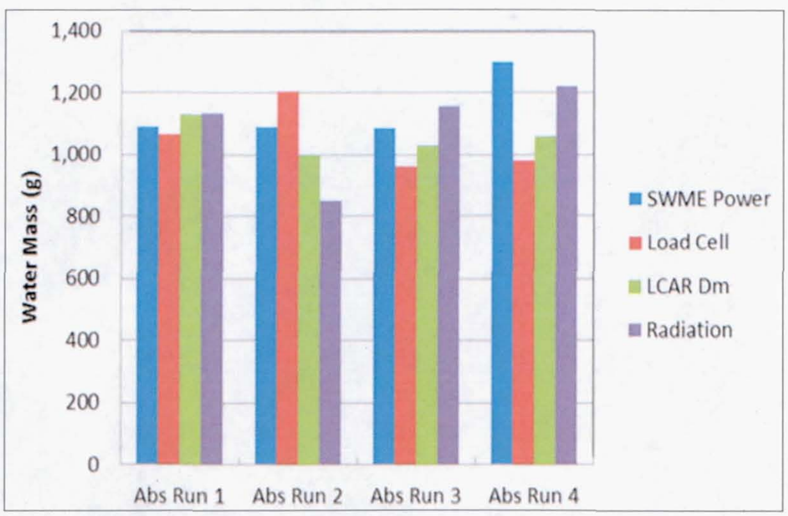

Figure 19. Comparison of Water Transfer Measurements

view factors. SWME power and LCAR mass change (before and after a test) represent the best measurements. Note that the water evaporated from the SWME could include significant amounts of water vented from the LCAR if operating at very high power. A close match between the SWME power and LCAR Δm values is only expected when the vented water mass is small. For example SWME power exceeds LCAR Δm in Run 2, when the RVV was opened to vent NCG build-up and compensate for a plugged capillary, and in Run 4, when the RVV and IVV were opened to test excess venting operations.

VII. Conclusions

The SWME and LCAR technologies can be integrated to produce a SEAR system that can dramatically reduce the amount of water vented by a space suit PLSS. A performance model of the SEAR system was developed based on SWME, LCAR and LCG performance characteristics, that predicted cooling capabilities consistent with PLSS thermal management requirements. The prototype SEAR was assembled and integrated with SWME and tested in a thermal vacuum chamber in relevant environments. SEAR performance was measured across a range of simulated metabolic rates and environmental conditions. In an equivalent deep space environment, the system was able to reject 130 W of SWME power for more than five hours. In an equivalent constant ISS one-sun environment, the two panel SEAR was able to reject 100 W if SWME power for more than six hours. The results suggest that the two panel LCAR system has about one third of the capacity needed for a 7 hour EVA, and about one fifth of the radiation area needed for a full scale system.

The flexible panel design had been developed to be placed in a conformal way on the outside of the housing, making this a very bulky and impractical system. The system of parallel cylindrical stacks of absorber elements would be too bulky when scaled-up to capture all the water vapor from a typical EVA. As configured, the full scale system would add about an inch in depth to every flat panel surface of PLSS housing. While the system was useful in proving out the concept in a flight like environment, the team recognized from the outset of the project that the next prototype would need to be repackaged.

Furthermore, the flexible design called for a network of axial and transverse channels to distribute the water vapor to the cylindrical stacks of desiccant storage media. This led to performance inefficiencies and problems with NCG build-up in communicating channels that hindered absorption. Having a single capillary vent required water vapor and NCG to pass over a large portion of entire system to get to the distal capillary, which also may have resulted in temporary regional blocking. Condensation may have also blocked transverse flow channels resulting in temporary regional blocking of the panels.

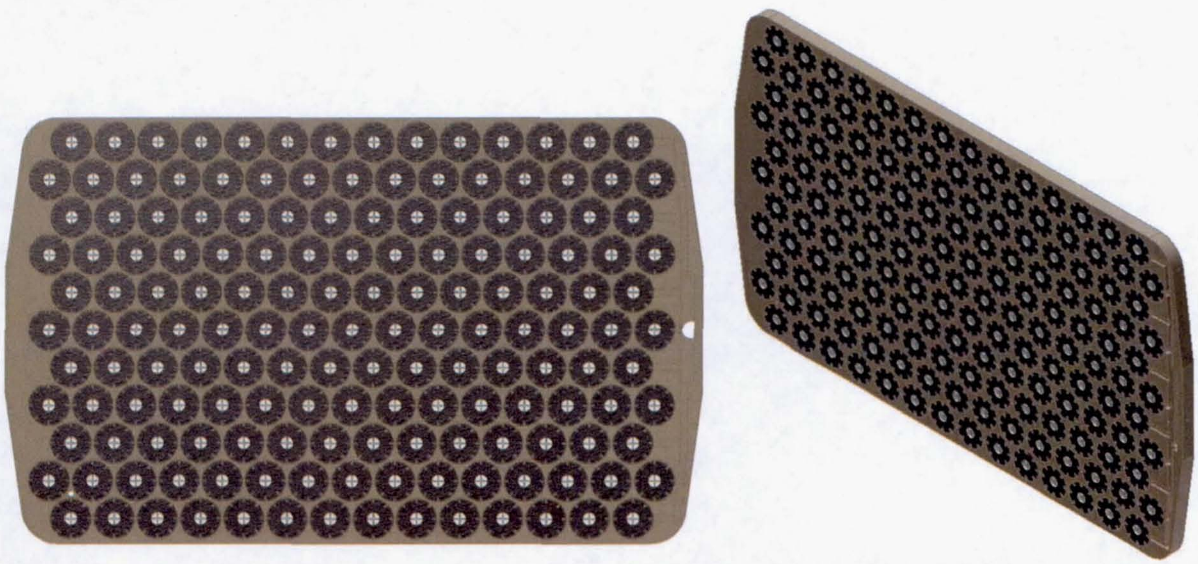

Figure 20. (left) Interior Face of Honeycomb Structure With Absorber Elements, (right) Radiating Face of LCAR (outer cover sheet not shown)

VIII. Forward Work

The storage bulkiness, condensation and NCG build-up problems inherent in the flexible panel LCAR could be solved by replacing the PLSS housing with a carbon fiber composite honeycomb, with the honeycomb cells packed with the stacks of desiccant sponges and grafoil interleaves (see Fig. 20). The entire stack would have a depth of ~12 mm, and include the storage stack honeycomb of ~8 mm in depth, an internal vapor header, and an external radiator face sheet. In this way, the housing multi-functionally provides the necessary housing protective structure, desiccant storage capacity and radiator surface to reject the heat. The 8mm depth of storage media suggests more efficient absorption resulting in a potential radiator temperature of 330K. the machined carbon composite plate that will simulate a honeycomb structure. The 11.4 mm (0.45 in.)-thick plate with overall dimensions of 30.5 x 50 cm (12.0 x 19.5 in.) is machined with a 14 x 11 array of 1 inch cylindrical holes, each of which can accommodate four absorber sponges. Each face of the plate will also be machined with an array of passages for water vapor (inward-facing side) and non-condensable gas (radiating side). This design enables the panel to be tested in either a continuous capillary venting or intermittent venting model. A thin sheet of conductive graphite will be bonded over each face to seal the internal volume and to spread heat over the radiating surface.

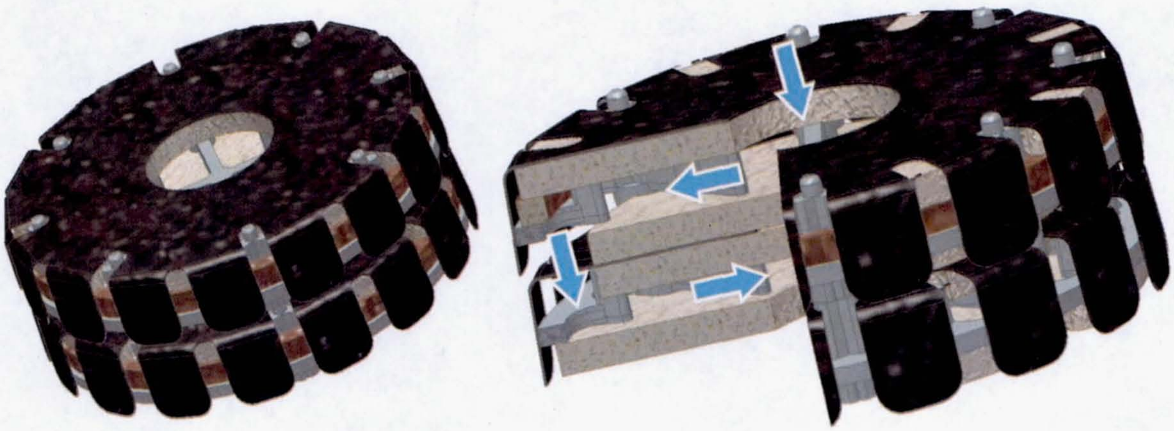

Figure 21. (left) Absorber Assembly for Single Honeycomb Cell, (right) Convoluted Flow Path Through the Module Promotes Efficient Use of the LiCl Absorber

A more complex concept is also being developed for providing a non-venting topping function for orbiting spacecraft during low lunar orbit where both heat rejection requirements and 290 K peak sink temperature are relatively high. Regeneration could be conducted during colder parts of the orbit where there is more available cooling for a condensing heat exchanger.

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