Spacesuit Evaporator-Absorber-Radiator (SEAR)

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For decades advanced spacesuit developers have pursued a regenerable, robust non-venting system for heat rejection. Toward this end, this paper investigates linking together two previously developed technologies, namely NASA's Spacesuit Water Membrane Evaporator (SWME), and Creare's Lithium Chloride Absorber Radiator (LCAR). Heat from a liquid cooled garment is transported to SWME that provides cooling through evaporation. This water vapor is then captured by solid LiCl in the LCAR with a high enthalpy of absorption, resulting in sufficient temperature lift to reject heat to space by radiation. After the sortie, the LCAR would be heated up and dried in a regenerator to drive off and recover the absorbed evaporant. A engineering development prototype was built and tested in vacuum conditions at a sink temperature of 250 K. The LCAR was able to stably reject 75 W over a 7-hour period. A conceptual design of a full-scale radiator is proposed. Excess heat rejection above 240 W would be accomplished through venting of the evaporant. Loop closure rates were predicted for various exploration environment scenarios.

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
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

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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 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.

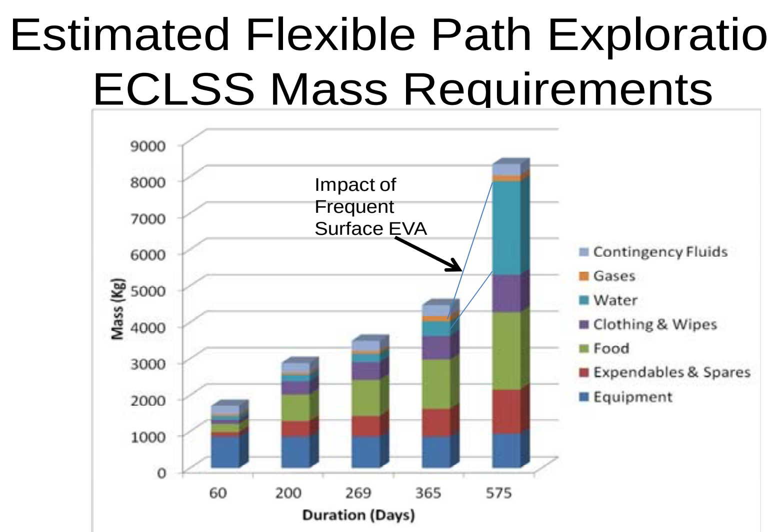

Figure 1. EVA water use for expendable cooling can lead to significant exploration mission mass penalties.

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. This concept and current evaluation studies by a NASA / industry team are described in this paper.

II. Concept Description

EVA thermal management with dramatically reduced water loss penalties can be achieved by combining the current liquid cooling garment with a water membrane evaporator and absorption heat pump radiator as depicted in Figure 2 [To be added later]. This arrangement provides effective cooling to the crew person over widely varying EVA work rates by controlling the cooling water temperature within proven thermal comfort control bands and allows the membrane evaporator to operate at flow rates and vapor discharge pressures proven during its development as a venting thermal control component. Delivery of the water vapor through a pressure control valve to an absorption heat-pump radiator--the LCAR--mounted on the outside surface of the EVA portable life support system allows it to be reabsorbed and retained for recovery after the EVA is completed. As the vapor is reabsorbed, the heat of vaporization removed from the circulating cooling water in the membrane evaporator is released as absorption heat and rejected to space in the radiator. The affinity of the LiCl chemical sorbent in the radiator for water vapor allows absorption and consequently radiator operation at substantially higher temperature than the crew person's skin, circulating water in the liquid cooling garment and membrane evaporator. This allows rejection of the full system waste heat load through the radiator over most system operating conditions, a dramatic gain over past efforts to implement a spacesuit radiator thermal control system. The addition of a normally closed control valve capable of venting water vapor to space vacuum ensures thermal control capability under extreme conditions where radiator heat rejection capacity falls below the system load providing a truly robust system design.

Preliminary system sizing estimates and performance analyses discussed later in this paper indicate that with demonstrated capabilities of the base technologies, liquid cooling garment, membrane evaporator, and heat-pump radiator, most of the water currently lost during an EVA can be retained and returned to the host vehicle under representative EVA activity profiles and operating environments. The system can be implemented within expected PLSS volume constraints, adds very little to the PLSS power requirement, and imposes modest on-back mass penalties.

III. Membrane Evaporator

The sublimator is the state-of-the-art heat rejection device of the space suit thermal control systems proven in the Apollo, Shuttle and ISS programs. Heat from the crew, the portable life support system and the environment is transported via circulating coolant and conducted through a cold plate into a sublimator. The current sublimator is a 50 square inch porous stainless steel plate, supplied by a feedwater loop. Feedwater passes into the sublimator, freezes in the pores of the plate, and the ice sublimates into space. It is a compact demand system for rejecting heat, but the performance tends to decay within about 25 EVA's due to fouling from contaminants in the feedwater circuit. Sublimation is physically limited to work at pressures below the triple point of water and therefore cannot function in the atmospheric pressures of Mars.

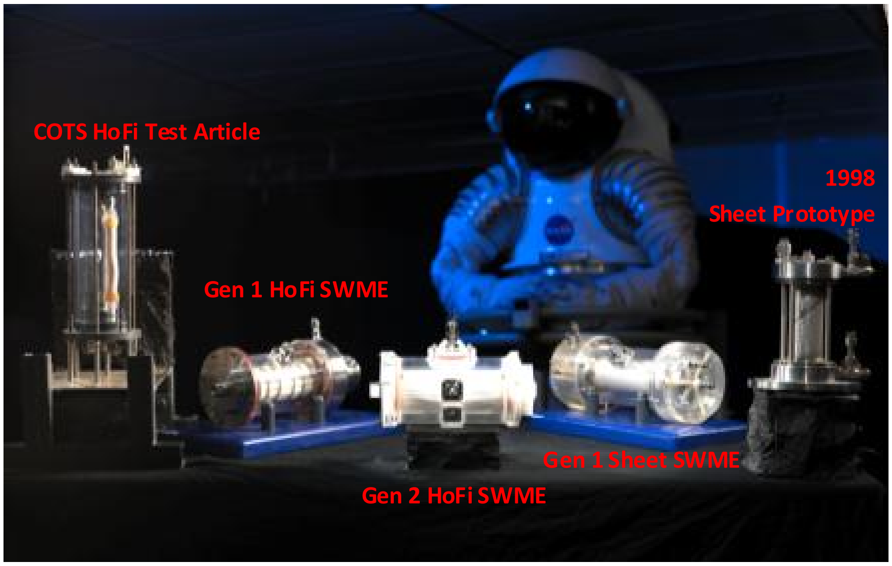

Figure 3. Spacesuit Water Membrane Evaporator Development at JSC

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 in-house resources (see Fig. 3). A design built and tested in 1998 using a pair of concentric cylindrical membrane sheets supported by stainless steel screens, demonstrated feasibility.[1] 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.[2] Small scale tests of similar membranes made self-supporting of hollow fibers showed that this alternate geometry was promising.[3,4] 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.[5] Testing of the sheet and hollow fiber prototypes proved that both types could meet the system requirements.[5,6] The Gen1 SWME is the membrane evaporator component of the SEAR engineering evaluation (see Fig. 4).

A second generation hollow fiber system (Gen2), built with light weight materials and a flight-like backpressure valve, is currently being tested.[7,8] Gen2 SWME (hereafter referred to as the evaporator) 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 lb/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.

IV. Lithium Chloride Absorber Radiator

LCAR contains a powerful LiCl desiccant that enables the SWME to generate cooling without venting water from the PLSS. The desiccant absorbs water vapor produced by the SWME while operating at a temperature more than 30°C higher than the SWME. High-temperature operation enables heat rejection by radiation at a heat flux nearly 50% greater than normal suit temperatures, 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 rare periods when it is overloaded, but will be much smaller than an LCAR designed to absorb all water vapor under all conceivable heat loads. Because the desiccant absorbs water during the course of an EVA mission, the modules must be regenerated prior to

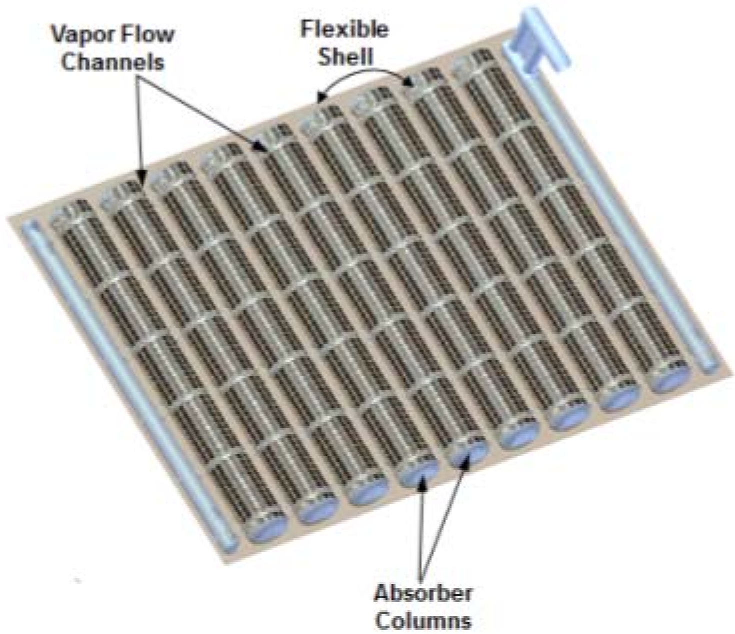

Figure 5. Overall Design Concept for the Absorber Radiator. Module Dimensions 12 in. × 17 in. × 1.1 in.

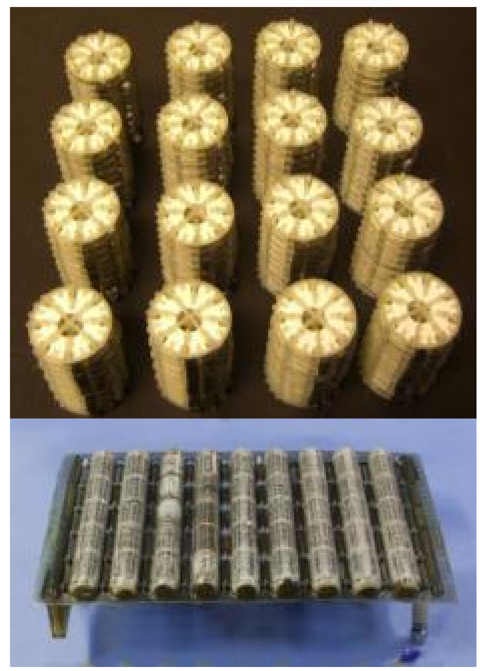

Figure 6. Absorber Elements and Assembled Module

the next mission by heating to moderate temperatures (120°C) and drying out the desiccant. The basic process and the absorber/radiator panel technology have been demonstrated in the laboratory. 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). Earlier papers describe the process in more detail. [9,10]

- **Description**

A single PLSS will typically need four absorber/radiator modules for an 8-hour EVA mission. Each module comprises an array of nine absorber columns installed in a lightweight, flexible, plastic shell (see Fig. 5). The absorber columns are assembled from stacks of sponge disks, spacer elements, and heat spreaders (see Fig. 6). 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.

- **Prototype Hardware**

We have assembled two complete absorber/radiator panels. Figure 6 shows absorber sub-stacks prior to assembly into complete stacks, and a top view of an assembled radiator module. Since the modules will be mounted on the PLSS, only one side will be radiating heat to the environment. 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. Flexibility simplifies integration with the PLSS and ruggedizes the modules.

- **Benchtop Performance Demonstration**

We demonstrated operation of the absorber module by coupling with a microchannel, capillary evaporator and cooling it with a temperature-controlled circulating loop. Figure 7 illustrates the test setup. We measured the cooling capacity of absorber radiator by calorimetry of both circulating loops (absorber cooling and evaporator warming) and validated these measurements by weighing the absorber before and after the test. Thermocouples on the radiator surface and in the evaporator recorded temperatures continuously during the test. Figure 8 shows typical data from an absorption test. During this nearly ten-hour test, the evaporator temperature remained less than 19°C while the absorber temperature was 49°C. Total heat transfer was about 275 W-hr, for an average of 30.6 W absorption averaged over the entire run.

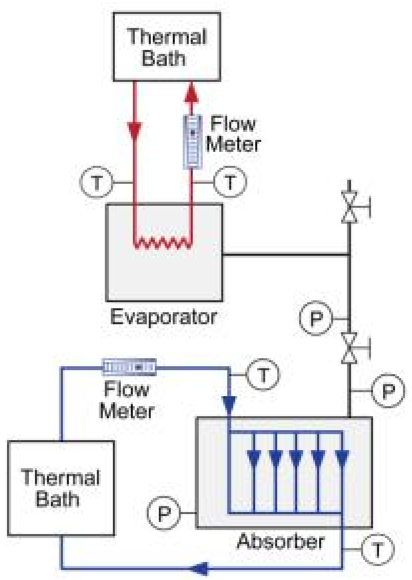

Figure 7. Benchtop Test Setup

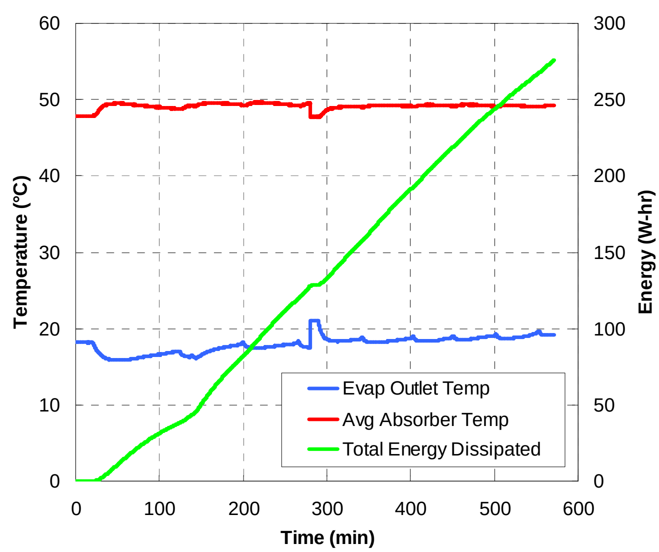

Figure 8. Absorber Performance Measured in Benchtop Tests. 30.6 W Average Power Dissipation

- **Regeneration** After an EVA mission, the absorber elements have absorbed roughly 1 kg of water per panel and the LiCl concentration in the desiccant solution is low. The absorber elements must be dried out before the panel can be used for another EVA mission. We demonstrated regeneration by coupling the absorber to a condenser and heating it in the same facility shown in Figure 7 using a propylene glycol/water solution heated to 115°C. The absorber was installed in an aluminum fixture equipped with liquid circulating plates to provide a uniform, elevated temperature. The condenser was a clear glass vessel containing a pool of water that was cooled by a copper coil coupled to the low temperature circulating bath. We maintained the condenser temperature at about 5°C for regeneration, corresponding to about 6.6 Torr vapor pressure. We stopped regeneration once we could observe no further, appreciable water transfer, which typically took about four hours. Most of the water was driven out of the absorber at the early stage of the regeneration process.

V. Analytical Assessment Modeling

The SEAR concept involves the interaction of several complex subsystems, human thermo-regulatory systems, a spacesuit liquid cooling garment, a membrane evaporator heat sink, and an absorber heat pump radiator. An analytical model linking those subsystems has been assembled in order to better understand its performance. In the model:

- A human thermal comfort model based on historical performance data with the existing spacesuit liquid cooling garment relates crew work rate to circulating water temperatures at the liquid cooling garment inlet and outlet. (Figure 9)

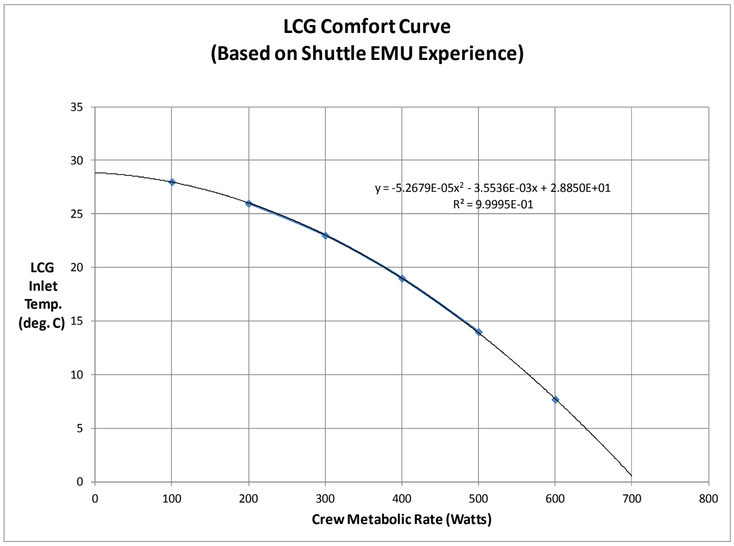

Figure 9. LCG crew comfort experience defines the circulating coolant temperature required from the system.

- Historical models for the interaction of the liquid cooling garment and vent gas flow within a spacesuit and other predicted system heat loads (heat leak and equipment loads) are applied to relate the LCG water temperatures to those at the SWME outlet and inlet ports and to relate heat loads that must be rejected through the SEAR to the crew metabolic load. (Figure 10)

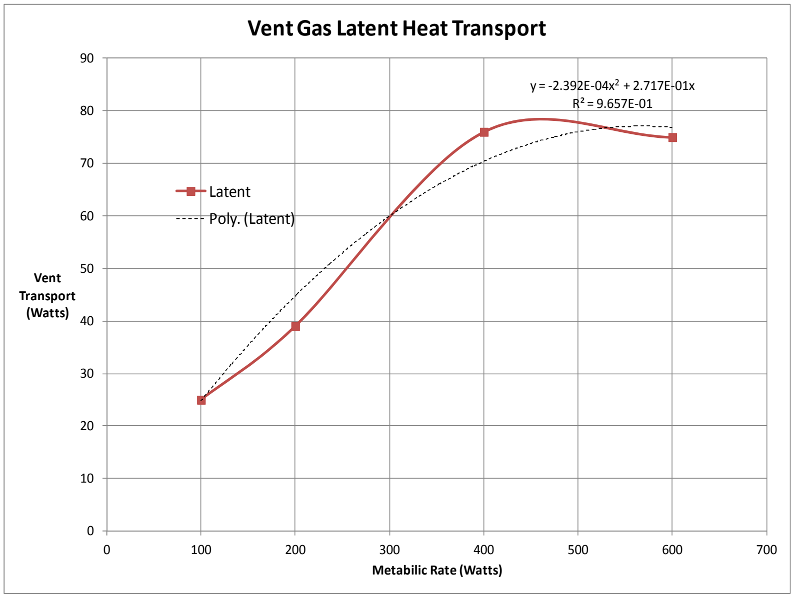

Figure 10. LCG crew comfort experience defines the circulating coolant temperature required from the system.

- Physical properties data establish the saturation vapor pressure within the SWME. (Figure 11)

- Empirical test data for the SWME are used to predict water vapor pressure loss from the saturation value during transport through the SWME membranes and within the assembly (Figure 12)

- A flow model for the SWME back pressure control valve is used to relate pressure loss through the valve in its fully open position, heat load transferred from the SWME as vapor, and steam back-pressure at the valve outlet. (Figure 13)

- An absorber model based on published data characterizing LiCl – water hydration states, solubility, and vapor equilibria is used to relate vapor pressure available from the SWME, the amount of water previously loaded in the absorber, and the absorber temperature. (Figure 14)

- Thermal conductive paths (heat spreaders) between the absorption sites and radiator surface are modeled to relate the absorber temperature and heat rejection rate to the radiator surface temperature.

- The radiator is modeled to relate the heat rejected to space to the radiator temperature and effective radiation sink temperature for the EVA. (Figure 15)

Together these elements allow the prediction of the integrated system performance under any selected combination of crew work rate , prior heat transfer during the EVA and operating thermal environment. The upper bounds for thermal control without venting water vapor can be estimated throughout an EVA or test sequence for both test scale and full scale systems. At heat loads below the predicted boundary, the SWME pressure control valve can be partially closed to maintain crew comfort and decrease the heat rejected by lowering the absorber and radiator temperatures. Above the

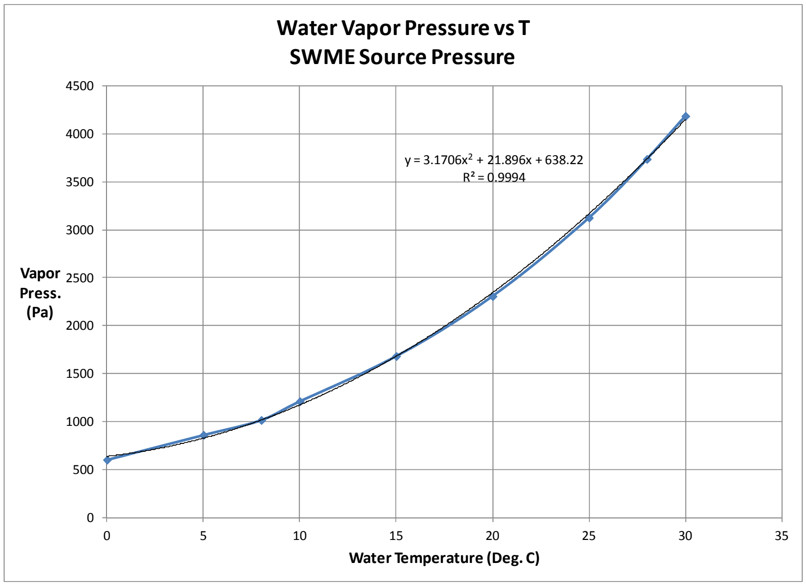

Figure 11. LCG coolant temperatures establish the source vapor pressure that drives SWME performance.

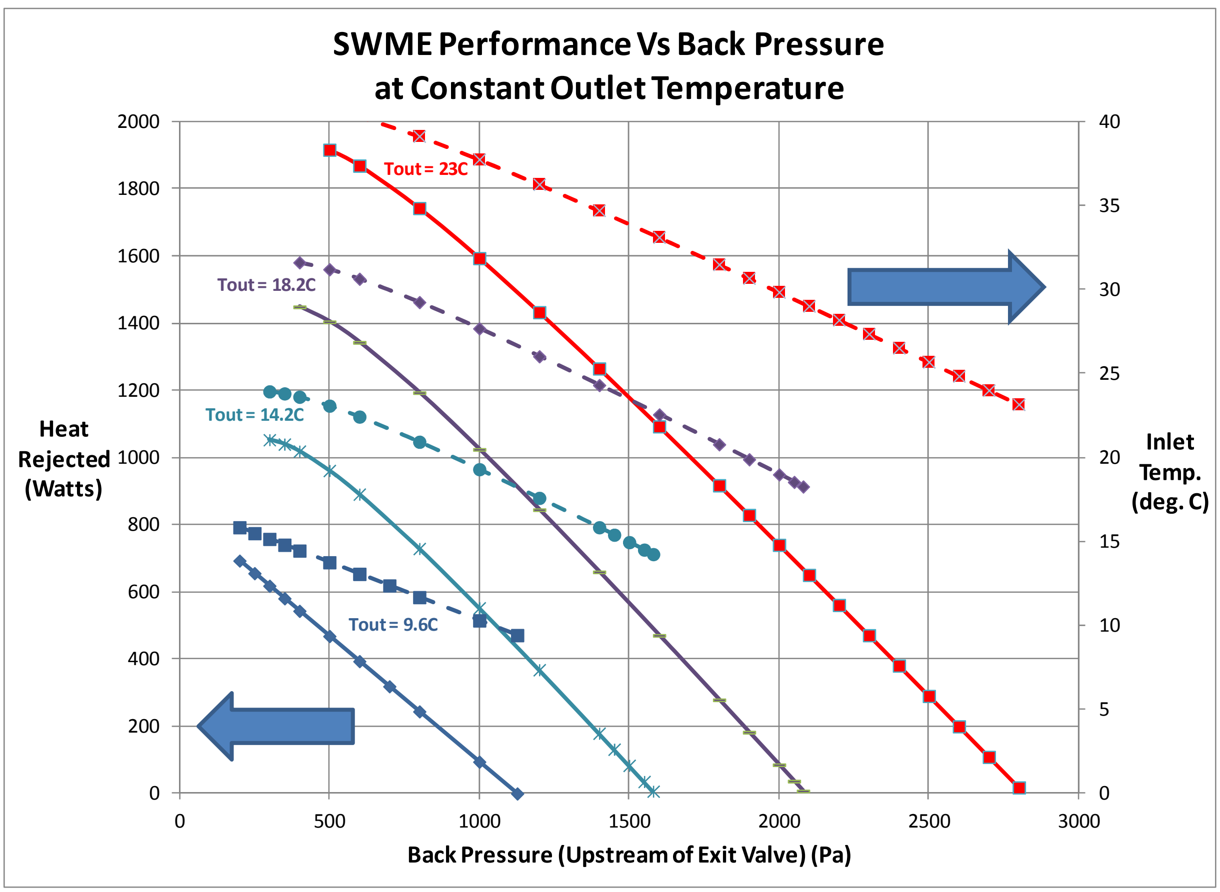

Figure 12. SWME internal back-pressure and heat rejection capability are related for any required coolant

boundary, the model allows the estimation of additional water vapor that must be produced in the SWME and vented to space to maintain the desired system thermal control, ultimately supporting estimates of system benefits in terms of EVA water loss reductions over individual EVA's and extended EVA campaigns. Salient points in the analysis are discussed in greater detail in the ensuing paragraphs.

Circulating coolant temperatures required to achieve heat transport from the astronaut's skin while maintaining thermal comfort is a primary driver for SEAR design and performance. Current modeling is based on historical data with existing flight systems and shows a demand for low coolant supply temperatures below 10C at high work rates.

LCG enhancements in next generation EVA systems including more effective LCG heat acquisition based physiology based designs under study by NASA and reduced heat transfer resistance through thermal comfort undergarments may raise these temperatures and significantly enhance potential SEAR performance at high work rates. [11-13] LCG performance characteristics and vent circulation patterns also influence both latent and sensible heat transfer in the circulating ventilation gas. While the vent loop sensible heat transport ultimately results in a heat load that must be rejected through the SEAR, vent loop latent loads are expected to leave the spacesuit system through a common carbon dioxide and humidity control pressure swing absorption system and will decrease the ultimate SEAR thermal load. This is reflected in the model with the amount of heat load reduction based on historical data for vent loop latent loads from current spacesuit and LCG systems. Future systems with enhanced LCG's that allow operation at increased coolant temperatures are expected to increase the latent loads rejected at high work rates somewhat further reducing the SEAR heat loads under those conditions. This presents an opportunity for model refinement in future work.

In current modeling, the SWME source vapor pressure from Figure 11 is based on the SWME coolant exit temperature (the lowest water temperature in the SWME) since this provides the most conservative estimate of system performance. This almost certainly understates vapor transport through the SWME membranes near the module entry, especially under high heat rejection rate conditions. Future refinement including more detailed evaluation of SWME internal vapor flow processes will support improved and less conservative estimates of this

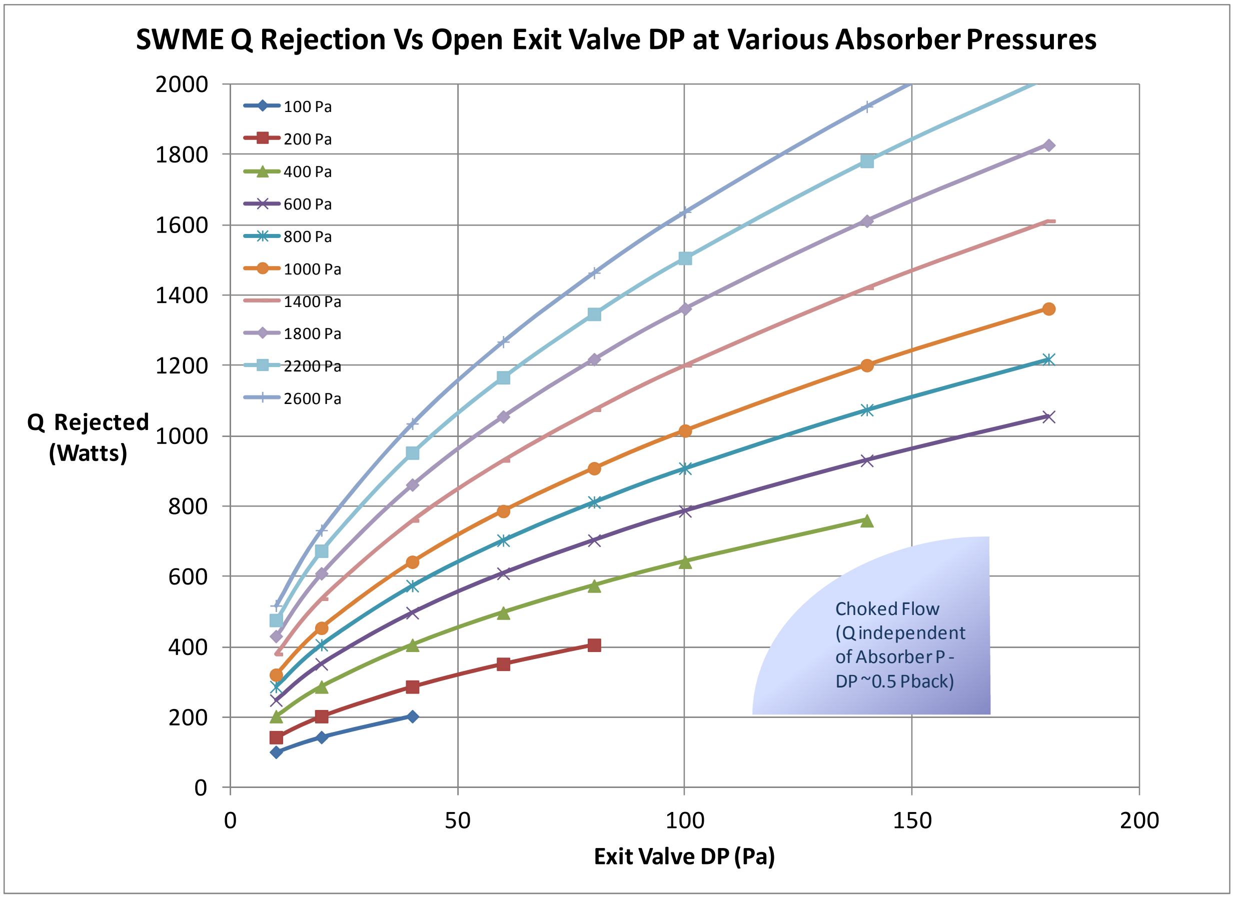

Figure 13. The SWME pressure control valve and exit aperture create pressure loss between the SWME and absorber radiator.

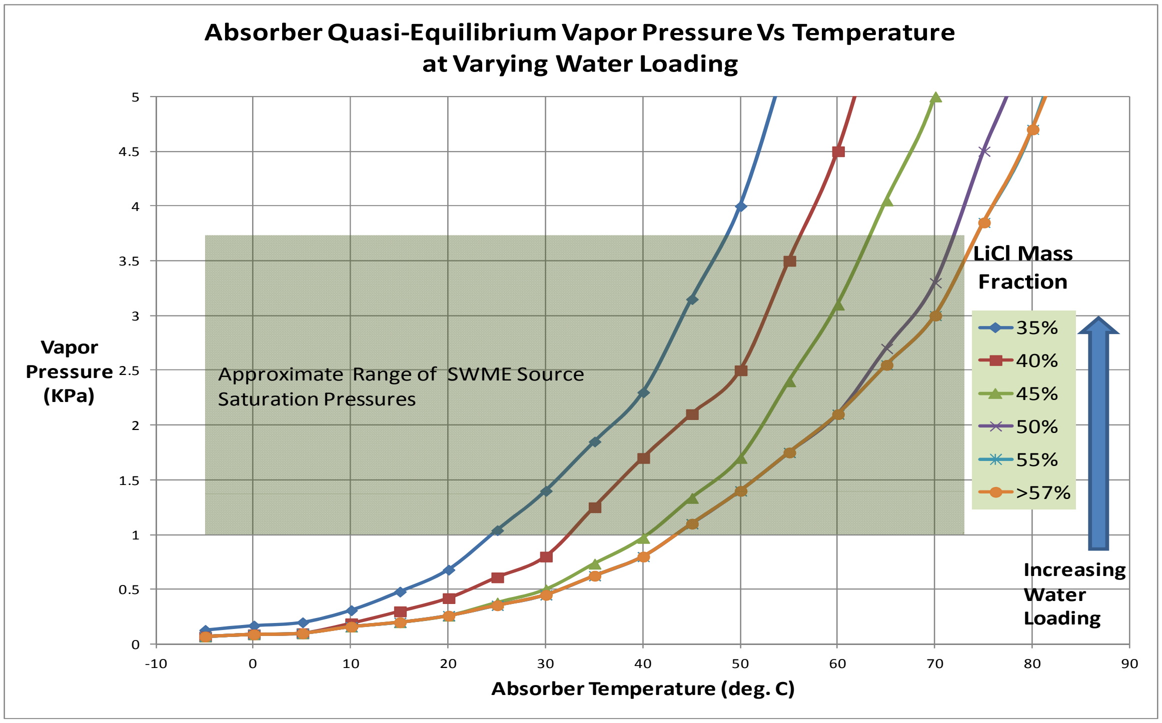

Figure 14. Absorber pressure equilibria allow operation high absorber temperatures.

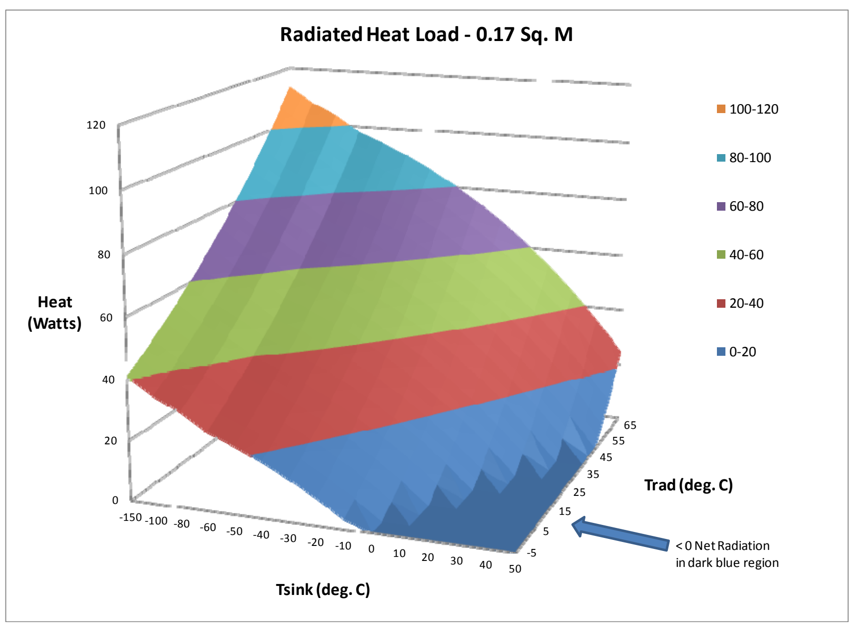

Figure 15. Test hardware radiator area is a limiting factor in concept testing.

value with corresponding improvements in estimates of SWME back pressure / heat transfer relationships shown in Figure 12 and consequently in system performance predictions. Analytical and test results reflected in Figure 13 indicate that pressure loss in the current SWME valve will have little effect in limiting system performance under most operating conditions, especially in proof of concept testing with subscale absorption radiator hardware.

Modeling for the absorber in the absorber radiator was complicated by its operation through solid phase – solution transitions and over multiple salt hydration states. The planned range of water content and operating temperatures extends from a fully crystalline solid containing a mix of anhydrous salt and LiCl monohydrate through a liquid solution (see Fig. 14). Varying hydration states exhibit different equilibrium vapor pressure values at any given temperature. As a result, it is likely that absorber performance will vary depending on the rate of water transport within solid particles as exposed surfaces dominate vapor equilibria and are more hydrated than the average salt within particles. Initial modeling assumes that the equilibrium vapor pressure will be the value at the solution boundary for each operating temperature based on the belief that diffusion for equilibrium within solid particles will be comparatively slow and solid particle surfaces will be fully hydrated to equilibrium with a solution phase even when the total water content is well below the value for this hydration level on an average mass basis. Confirmation and refinement of this aspect of the model is important for system performance predictions and is a focus in the test program.

Radiated heat transport estimates are based on an assumed emissivity of 0.85 and an effective sink temperature (which combines solar and ambient IR spectral energy). This is expected to be conservative for the absorber radiator prototype hardware which is likely to provide an emissivity in excess of 0.9 and will be tested in a thermal vacuum chamber without any significant solar load. Based on historical experience, the model value is expected to be consistent with realistic performance of available low a/e coatings in solar illuminated space environments. As reflected in Figure 15, predicted performance with the absorber radiator prototypes is severely limited by radiator capability. Radiating surface area on the order of 1 square meter is reasonable on the surface of anticipated PLSS packages and would support anticipated total system heat loads under most operating conditions. This indicates an opportunity to enhance system level performance with modest weight increases through design optimization to increase the radiating surface area per unit of absorber mass and the likelihood that the optimized system can eliminate water loss over a wide range of operating conditions.

Early results from the model have been applied in defining test conditions for the feasibility study. Heat loads on the order of 100 W will be evaluated across a wide range of circulating coolant temperatures through the SWME and at varying radiation sink temperatures as described below.

VI. Experimental Assessment Plans

A. Key Instrumentation

Calculations of SWME heat rejections and instantaneous vapor mass flow rates were dependent upon the availability of accurate mass flow and temperature measurements. Inlet and outlet temperatures were measured with Hart Scientific (a division of Fluke Corporation, Everett, WA) 5611T Teflon® (DuPont™, E. I. du Pont de Nemours and Company, Wilmington, DE) thermistor probes that have a ±0.01°C accuracy. Thermistor sensors were monitored by the Fluke Hart Scientific Black Stack Thermometer Readout - Model 1560 via its Fluke Hart Scientific Model 2564 thermistor scanner. These scanners have an accuracy of ±0.003°C. The JLC International Inc. (New Britain, PA) type 1 flow meter sensor has an accuracy of ±3% of measured value and is monitored by the Precision Digital Corporation (Holliston, MA) PD693 flow indicator. SWME backpressures were measured by a Baratron® 690A 100-mmHg series (MKS Instruments, Andover, MA), which has a worst-case accuracy of 0.12% of reading.

B. Test Setup

A series of five tests were conducted to assess SEAR performance across the range of metabolic load conditions and EVA thermal environments. These tests were performed in Chamber N, a 5-foot thermal vacuum chamber in Building 33 at NASA Johnson Space Center. Figure 16 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 adjustable, allowing for variable pressures at the SWME water inlet. The reservoir was weighed continuously to calculate water evaporated for coolant use determinations. The SWME water flow rate was adjusted by regulating the pump motor speed controller. Water flow rate was monitored by micro-motion coriolis flow meters on the SWME inlet and outlet sides. 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 (see Fig. 16) [to be included later]. One end of LCAR is 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. The LCAR also includes a capillary tube that continuously bleeds a tiny flow of gas from the LCAR's internal volume to the external vacuum environment. 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

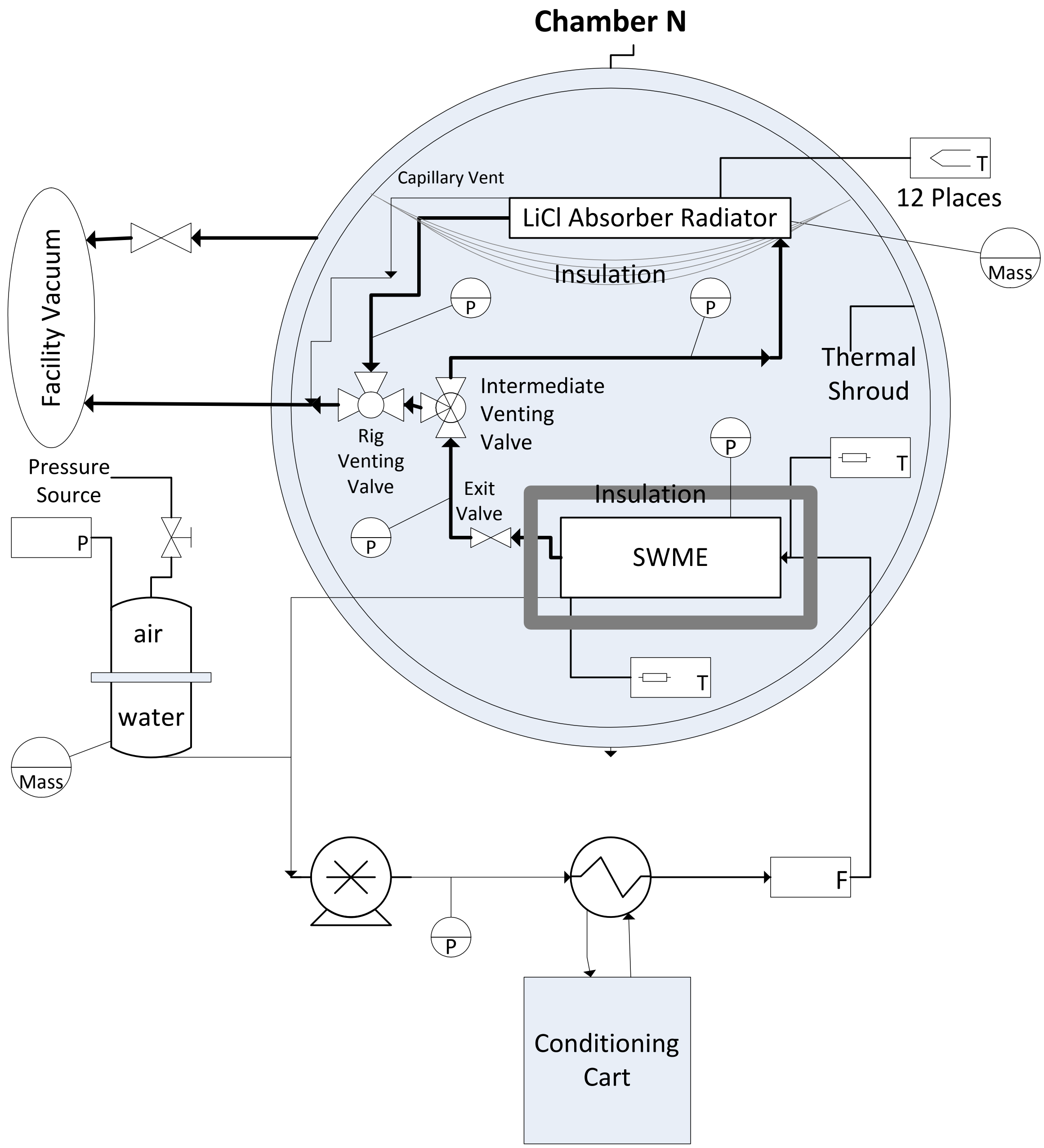

Figure 16. Schematic Thermal Vacuum Test Setup for SEAR.

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 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 above the insulation with four wire. Strain gauges were incorporated into the four wires so that Absorption rates of the LCAR could be monitored continuously. LCAR radiation surface temperatures were monitored with 12 surface mounted thermocouples. The shroud temperature above the radiating surface was monitored with 4 surface mounted thermocouples.

Water vapor flow to the Lithium Chloride Absorber Radiator (LCAR) was controlled through an Intermediate Venting Valve (IVV). The IVV is a three-way valve that can split flow between the LCAR and an external facility vacuum source. In four 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 require 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 five day thermal vacuum test series conducted in JSC Chamber N in Building 33. 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. Day 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. The SWME would produce a source pressure of about 2.3 kPa that would drive a radiator temperature of about 62 °C, which in this 1/5th scale radiator would reject at least 97 W. This is greater than the scaled portion of metabolic load plus 20% for the heat of absorption. This test point is run until the max 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.

Day 2 is similar to Day 1 but with a 1-sun non-planetary environment of -25 °C. At lower heat rate rejected from the radiator, longer time is need to get to the saturation limit of the LCAR.

Day 3 and Day 4 are designed to test the hysteresis of the LCAR performance with respect to the saturation of the LiCl. Like the first two days of testing these hysteresis test points have no external venting. Each series has six test points with a monotonic change in SWME outlet temperature. Day 3 begins the high SWME outlet temperature and ends with the low whereas Day 4 begins with the low temperature and ends with the high.

Day 5 explores 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. Each venting

Table 1 SEAR Testpoint Matrix

Duration (hours)	T_{Shroud} (°C)	Target T_{rad} (°C)	$T_{outlet,SWME}$ (°C)	IVV External Venting	RVV External Venting
Day 1	**Full Absorption Test, Deep Space**				
7	-100	66	20	None	None
Day 2	**Full Absorption Test, 1 Sun**				
12	-25	65	20	None	None
Day 3	**Full Absorption Test, Deep Space, Decreasing $T_{outlet,SWME}$**				
1	-100	Variable	28	None	None
1	-100	Variable	26	None	None
1	-100	Variable	23	None	None
1	-100	Variable	19	None	None
1	-100	Variable	14	None	None
1	-100	Variable	8	None	None
Day 4	**Full Absorption Test, Deep Space, Increasing $T_{outlet,SWME}$**				
1	-100	Variable	8	None	None
1	-100	Variable	14	None	None
1	-100	Variable	19	None	None
1	-100	Variable	23	None	None
1	-100	Variable	26	None	None
1	-100	Variable	28	None	None
Day 5	**Partial Absorption Test, Deep Space**				
0.5	-100	Variable	10	+++	None
0.5	-100	Variable	10	None	+++
0.5	-100	Variable	10	+++	None
0.5	-100	Variable	10	None	+++
0.5	-100	Variable	10	++	None
0.5	-100	Variable	10	None	++
0.5	-100	Variable	10	++	None
0.5	-100	Variable	10	None	++
0.5	-100	Variable	10	+	None
0.5	-100	Variable	10	None	+
0.5	-100	Variable	10	+	None
0.5	-100	Variable	10	None	+

type is tested in three degrees of venting: high, medium and low. For a given degree of venting, the two valve venting modes are alternated between each other twice to assess the effects of degradation.

VII. Test Results

[Placeholder for Test Results]

VIII. Forward Work

The results of these tests are currently being used to correlate the performance model of the system. Based on the predictions of the improved performance model a full scale design concept will be developed, one that optimizes radiator performance potentially though a broader area distribution of the LiCl, with a smaller standoff profile from the PLSS housing. Expected loop closure rates for SEAR will be determined for LEO, NEO and Mars environments.

IX. 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. The results suggest that the two panel LCAR system has about one half of the capacity needed for a 7 hour EVA, and about one fifth of the radiation area needed for a full scale system. The results are useful for correlating the performance model and optimizing the system for a full-scale design.

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