Hollow Fiber Space Water Membrane Evaporator Flight Prototype Design and Testing

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The spacesuit water membrane evaporator (SWME) is being developed to perform thermal control for advanced spacesuits and to take advantage of recent advances in micropore membrane technology. This results in a robust heat-rejection device that is potentially less sensitive to contamination than is the sublimator. The current design was based on a previous design that grouped the fiber layers into stacks, which were separated by small spaces and packaged into a cylindrical shape. This was developed into a full-scale prototype consisting of 14,300 tube bundled into 30 stacks, each of which is formed into a chevron shape and separated by spacers and organized into three sectors of 10 nested stacks. The new design replaced metal components with plastic ones, eliminated the spacers, and has a custom built flight like backpressure valve mounted on the side of the SWME housing to reduce backpressure when fully open. A number of tests were performed in order to improve the strength of the polyurethane header that holds the fibers in place while the system is pressurized. Vacuum chamber testing showed similar heat rejection as a function of inlet water temperature and water vapor backpressure was similar to the previous design. Other tests pushed the limits of tolerance to freezing and showed suitability to reject heat in a Mars pressure environment with and without a sweep gas. Tolerance to contamination by constituents expected to be found in potable water produced by distillation processes was tested in a conventional way by allowing constituents to accumulate in the coolant as evaporation occurs. For this purpose, the SWME cartridge has endured an equivalent of 30 EVAs exposure and demonstrated acceptable performance decline.

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I. Introduction

The National Aeronautics and Space Administration (NASA) is currently developing a spacesuit Portable Life Support Subsystem (PLSS) technology unit that is human-rated for long duration microgravity or planetary missions, a thermal vacuum environment, and vacuum or low pressure environments. A critical component of extravehicular activity (EVA) suits is heat rejection, which cools the crewmember and the electrical components in the PLSS. The current PLSS uses a sublimator for heat rejection. While the current PLSS sublimator can effectively cool the crewmember and electronics, it has a number of limitations, including sensitivity to contaminants, and uses a separate feedwater supply. Because of these limitations, the current PLSS sublimator is only certified for 25 EVAs—critically limiting current EVA capability. Additionally, sublimators do not have the capability of rejecting heat in pressure environments above the triple point of water, such as the atmospheric conditions of Mars.

The Hollow Fiber (HoFi) Suit Water Membrane Evaporator (SWME) have been selected as the heat rejection technology in the next generation of spacesuits. The HoFi SWME cools the circulating water through in-line evaporation. The coolant is then circulated to the liquid cooling garment (LCG), and also to PLSS components. The SWME takes advantage of recent advances in micropore membrane technology to provide robust heat rejection with a high tolerance for contamination. Hollow fibers are thin-walled, porous, tubes made from polypropylene, approximately 300 microns in diameter. This HoFi membrane technologies yields a low mass and volume system that is durable and reliable. The HoFi geometry allows a high membrane surface area to be contained in a compact module; therefore, large volumes can be filtered with low power consumption, while utilizing minimal space. The design has about 14,300 tubes providing about 0.6 m^2 of open pore area, that contributes to the SWME's resistance to contaminants that accumulate in the coolant loop over the planned 800 hour operational life.
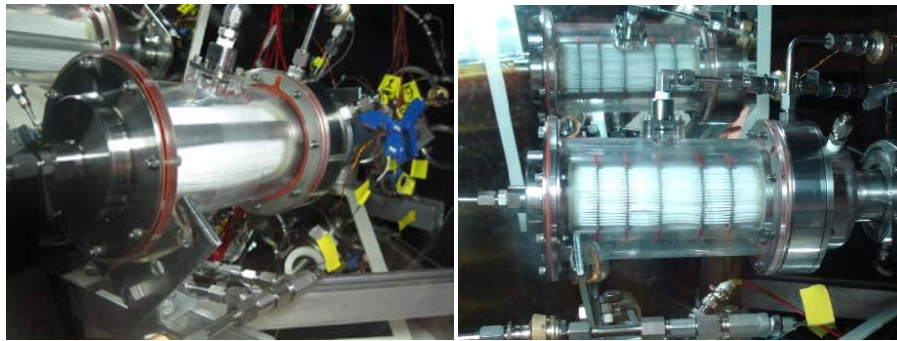
Figure 1. HoFi Gen1 SWME prototypes: a) HoFi#1 (no combs); b) HoFi#2 (five comb layers).

The first sheet membrane SWME prototype was designed and tested at JSC in 1999 and showed promise for the next generation heat rejection subsystem.[1] In 2009, a full-scale version of the sheet membrane prototype was built,[2] together with two full-scale HoFi prototypes, see Fig. 1, one with spacers for venting (Gen1 HoFi #2), one without (Gen1 HoFi #1).[3] These three prototypes underwent a series of tests to characterize the membrane performance, including the determination of the cooling water heat rejection rate, backpressure results, and contamination sensitivity. In 2010, a new prototype SWME, based on the Gen1 HoFi #1 was created (Gen2). Gen2 is built mostly of plastic and has
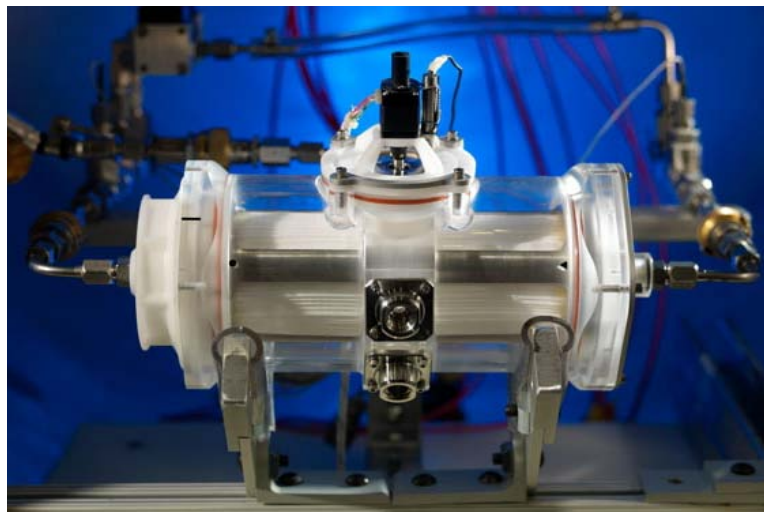
Figure 2. Gen2 SWME Test article

a flight like valve built into the housing, see Fig. 2. Gen2 incorporates a stronger formulation of polyurethane in the header to meet higher proof pressure requirements. Gen2 is also equipped with a quick-release end for rapid manual replacement of HoFi cartridges without tools. Gen 2 underwent a series of tests similar to the Gen 1 testing.[3] Additional testing was also performed that included rigorous metabolic testing to simulate actual EVA use, more rigorous bubble tests and freeze tests, and characterization of the backpressure valve. The contamination tests differed from the previous testing in that no attempt was made to conservatively project water constituents over the course of 100 EVA's, but rather the circulating coolant was allowed to accumulate contaminants in a flight-like manner, with evaporated coolant begin replace with baseline water.

II. Design and Development

The basic HoFi structure selected for the prototype is the Celgard X50-215 fiber sheets of the previously tested Membrana minimodules.[4] Details of the fiber structure are shown in Fig. 3. The porous polypropylene HoFi's are stitched together in a regularly spaced parallel array about 21 per cm; see Fig. 3a. The tubes have a 300-μm outer diameter and a 40-μm wall thickness, yielding a burst strength of 2,760 kPa (400 psi); see Fig. 1b. The tube walls are 40% porous and consist of typically slit-shaped openings with widths up to 0.04 μm and lengths up to 110 μm. The hydrophobicity of the polypropylene and the pore geometry result in a water bubble point of greater than 276 kPa (40 psi). Fiber arrays were obtained from the manufacturer in 9-in.-wide sheets.

a)

b)

c)

Figure 3. Magnified details of Celgard X50-215 HoFi's: a) sheets of parallel array of tubes 52-53 per inch; b) tube cross section, c) micrograph of pore structure.

The SWME is required to reject 810 W (2164 BTU/hr) at 91 kg (200 lbm/hr) flow with an coolant outlet temperature of 10 °C (50 °F).[3] Prior efficiency studies showed that as the number of layers increased, evaporation on a per-tube basis decreased.[4-6] To minimize the prototype volume and mass, an optimal design element consisting of stacks of five layers of sheets separated by gaps of 0.89 mm (0.35 in.) was adopted. Originally, the cartridge assembly contained chevron-shaped HoFi segments separated by spacer combs to allow vapor to flow radially away from the center of the cartridge; see Fig. 2a. It was later determined that SWME performance was only marginally affected by the absence of these spacer combs in the fiber assemblies.[3] The cartridge assembly contains the chevron-shaped HoFi segments that are separated by spacer combs to allow vapor to flow radially away from the center of the cartridge; see Fig. 4a. Ten chevron stacks are within each of the three 120-deg sections of the cartridge assembly. Major HoFi water and vapor flow passages are designed into the cartridge assembly, as shown in Fig 4b, to promote radial outflow of the water vapor to the peripheral space between the fiber perimeter and the housing. Water vapor then flows around the perimeter and out the centrally located back pressure valve; see Fig 2c. A detailed description of the potting and assembly process, is detailed elsewhere.[3]

After successful testing of the Gen1 SWME, a Gen2 SWME was designed in 2010. Four significant design changes were made: 1) the addition of a more compact, flight-like backpressure valve, 2) a tool-less cartridge replacement capability, and 3) reduced system mass and volume, and 4) improved strength of polyurethane in headers.

The new backpressure valve is a smaller, more compact unit that incorporates a stepper motor to control backpressure valve position, and ultimately the amount of cooling provided by the SWME, see Fig. 2. Additionally, the position of the valve provides a less constrained path for gas to escape—thereby reducing the fully open backpressure and improving of the cooling potential.

The tool-less cartridge replacement capability was deemed necessary to allow crew members to perform maintenance to the SWME on-orbit during future missions. The ability to change the cartridge and make any other repairs during a mission will not only ensure mission success, but also prolong the overall lifetime of the SWME.
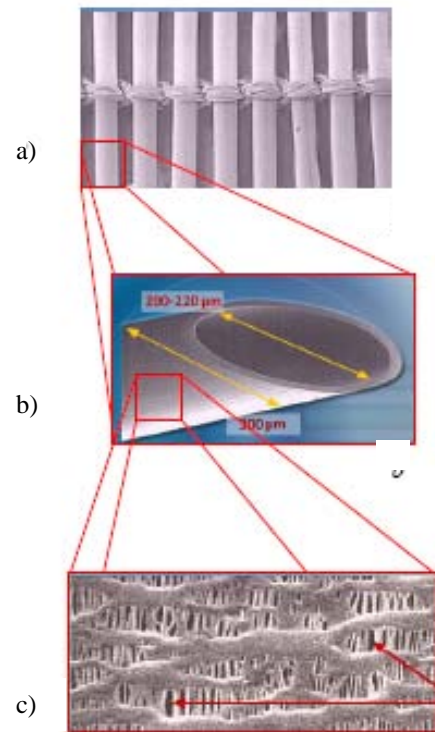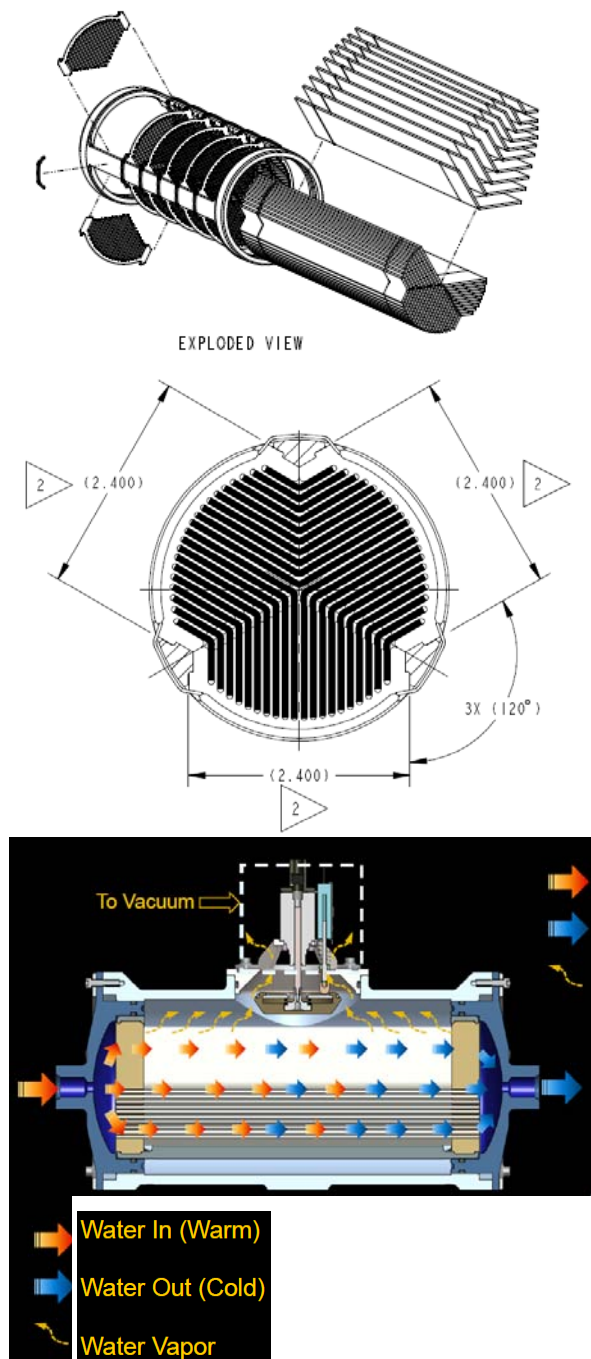
EXPLODED VIEW

Figure 4. Selected components of HoFi SWME assembly: a) exploded view of cartridge showing chevron stacks; b) view of three-comb layer showing slots for 30 chevrons; c) section of FY10 SWME showing flow paths of coolant and evaporant.

Reduced system mass was achieved by replacing many stainless steel parts of the SWME with plastic materials in the housing. Most notably, the stainless steel cage was replaced with an identical cage made out of Delrin (acetal), which was surface treated by corona discharge. Lightweight alternatives to the Delrin cage material are being considered for the next design.

Contingency use of SWME required cooling system pressures about three times as high as the nominal pressure. At this pressure there was significant bulging of the polyurethane that distorted the chevron folds between the headers. Additionally untreated Delrin cages did not bond sufficiently with the polyurethane to meet the proof pressure requirements. Accordingly a study was undertaken, detailed in the next section, to improve the strength of the polyurethane header.

III.   Polyurethane Header Study

A potential contingency use for the SWME is to provide cooling during decompression sickness treatment that result in elevated cooling system pressures of 190 kPa (27.7 psid). Proof pressure requirements call for a factor of safety of 1.5, requiring the SWME header to hold without leaking at a delta pressure of 285 kPa (41.6 psi). Methods of improving stiffness and increase bond strength of the polyurethane were explored. The polyurethane used is GS 1526-1 (GS Polymers, Inc.).

A. Hardness Tests

Stiffness had been shown in preliminary bending tests to correlate with hardness. In order to investigate the hardness of the polyurethane, an study was conducted consisting of various cure times, cure temperatures, and hardener. A total of 23 samples were poured, each of which had different cure times, heat treatment temperatures and amount of hardener. The hardness of the samples were measured at 1, 2, 5, 8, and 14 days after pouring. During the hardness measurements, it was observed that the samples were measuring at the maximum of the Shore A hardness scale, which prompted the use of both Shore A and Shore D hardness measurements. A response surface analysis was performed on these measurements, and it was determined that the hardest, polyurethane mixture consisted of 41.73% hardener, a cure temperature of 80 degrees Celsius, and a cure duration of 24 hours. It was also determined that hardness of the polyurethane did not increase notably after cure duration of 24 hours. Details of this study are presented in Appendix A.

B. Plug Pressure Tests

Following the hardness test, a plug pressure test was designed to prove that the best polyurethane formulation could withstand SWME pressure requirements. A cage simulator was designed to represent the cage of the SWME. This cage simulator has the same dimensions and design features as the actual SWME cage. Cages were produced out of stainless steel (primed with GSP 268), untreated Delrin, chromic acid etched Delrin and corona discharged Delrin (primed with GSP 268). Each of the cage simulators was then potted with the ideal formulation polyurethane, determined by the hardness testing. No hollow fibers were potted within the polyurethane. The cage was inserted into a plug pressure test stand, which consist of a closed fluid loop filled with water and an electrically powered pump. Pressure of the system was measured using gauges installed in the stand. The polyurethane-potted cage simulators were then stepped through a series of pressurization schemes. The maximum expected operating pressure of the SWME is 190 kPa (27.7 psi), which may be incurred during crew decompression sickness treatment. The nominal SWME operating delta pressure is 68.7 kPa (10 psi). First, the cage simulator was pressurized above ambient to 144 kPa (21 psi) in 34 kPa (5 psi) increments. Then, the cage simulator was pressurized above ambient between 34 kPa (5 psi) and 68.7 kPa (10 psi) for 100 cycles simulating 100 EVA operational cycles. Then each cage simulator was then pressurized in 34 kPa (5 psi) increments up to 495 kPa (72 psi) above ambient. The stainless steel, corona discharged Delrin, and the chromic acid etched Delrin cage simulators maintained system pressure at 495 kPa (72 psi) for 7 hours. The untreated cage simulator failed at 4 hours at a delta pressure of 423 kPa (61.5 psi), when the polyurethane plug began to peel away from the Delrin cage simulator. The nominal polyurethane formulation in the untreated Delrin cage, failed after a few minutes at 172 kPa (25 psi) delta pressure. This study shows that the polyurethane formulation developed in the hardness study has sufficient strength to withhold the proof pressure of 285 kPa (41.6 psi) whereas the nominal formulation does not.

IV. Test Methods

A series of four tests was conducted to assess the performance, contamination sensitivity, freeze sensitivity, and Mars atmosphere performance simulations. These tests were performed in the Building 220 vacuum chamber at the NASA Johnson Space Center.

A. Key Instrumentation

The most important measurements for the four test series were the inlet/outlet temperatures, SWME water loop mass flow, and vapor backpressure; the instrumentation scheme was common to the different tests. Calculations of SWME heat rejections and instantaneous vapor mass flow rates were based on being able to accurately measure mass flow and temperatures. Inlet and outlet temperatures were measured with Fluke Hart Scientific 5611T Teflon® thermistor probes that have an ±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 components have an accuracy of ±0.003°C. The JLC International Inc. (New Britain, Penn.) type 1 flow meter sensor has an accuracy of ±3% of measured value and is monitored by the Precision Digital Corporation (Holliston, Mass.) PD693 flow indicator. SWME backpressures were measured by a Baratron® 690A 100-mmHg series, which has a worst-case accuracy of 0.12% of reading.
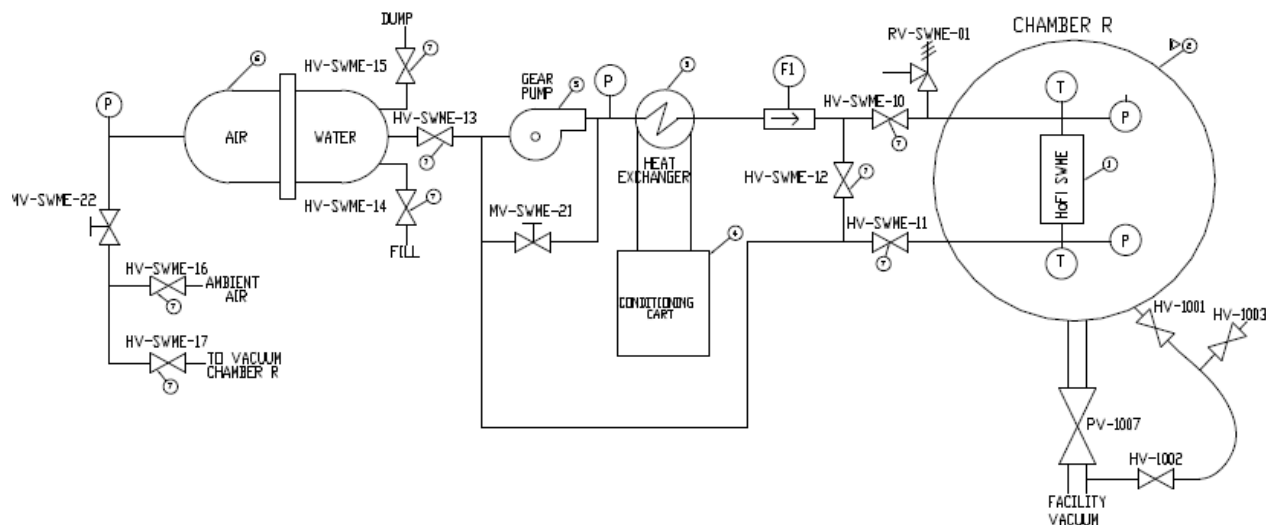
B. Test Setup

A similar test setup was used for the four tests. Figure 5 is a schematic of the test loop illustrating the SWME water loop, thermal conditioning water loop, and key instrumentation. The SWME water inlet temperatures were controlled by the chiller cart via a liquid-to-liquid heat exchanger (HX). The chiller cart also had an 800-W heater that had to be supplemented with immersion and line heaters to match higher SWME heat rejection rates. Makeup water was continuously supplied from the reservoir feedwater tank as the SWME evaporated water.

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 utilization determinations. Air injections were done at the sample port during bubble testing with a 50-cm³ plastic syringe fitted with small flexible tubing. A valve controlled (not shown) at the base of the port would be opened prior to air injection and then closed immediately afterwards. The SWME water flow rate will be adjusted by adjusting the pump motor speed controller. The water flow rate was monitored by micro-motion Coriolis flow-meters, on the inlet and outlet sides of the SWME. SWME heat rejections rates were controlled by the backpressure valve, which, when adjusted, would change the SWME vapor side pressure—this is also called backpressure. Backpressure valve adjustments were done via the National Instruments Corporation (Austin, Texas) LabVIEW data acquisition (DAQ) system. Backpressures ranged from

water saturation pressure corresponding to inlet temperatures, when the valve was closed, to values less than the water triple point pressure, when the valve was fully opened.

The supply water, and the water initially circulating in the test loop is found in Table 1. The circulating water was allowed to accumulate contaminants in the water as evaporation occurred, and evaporant lost was always resupplied with the same fill water.

Figure 5. Test setup.

C. Performance Tests

The HoFi SWME performance tests consisted of a set of tests characterizing the fundamental performance of the HoFi SWME. Deionized water was used for all performance tests.

Backpressure performance tests used backpressure control to examine performance at the nominal and maximum coolant loop pressures, 68.7 kPa (10 psi) and 190 kPa (27.7 psi), and six backpressure settings to control outlet temperatures ranging from fully open to fully closed. Inlet temperatures were controlled to 16, 20, 24, 28, 32, and 36°C. Coolant flow rates of 91 and 60 kg/hr were tested. A total of 72 test points were conducted to map performance with respect to the four variables.

D. Contamination Tests

The contamination test series was designed to probe for sensitivities in the HoFi SWME element to ordinary constituents that are expected to be found in the potable water source. For these tests, based on the long-term performance of the International Space Station (ISS) water processing assembly (WPA), a level was set for each impurity found that the system could comfortably meet by a factor of 2 to 5.[7] While these levels are more concentrated than those found in the ISS's potable water, they are well below the limits set for human consumption by NASA. This worst-case potable water was selected as the baseline water quality

Table 1. SWME Fill Water Table

ITEM	Amount (mg/L)
Chemical	
Barium	0.1
Calcium	1
Chlorine	5
Chromium	0.05
Copper	0.5
Iron	0.2
Lead	0.05
Magnesium	1
Manganese	0.05
Nickel	0.05
Nitrate	1
Potassium	5
Sulfate	5
Zinc	0.5
Organic Constituents	
Total Acids	0.5
Total Alcohols	0.5
Total Organic Carbon	0.3

to be supplied to the feedwater tank (Table 1). Some ordinary potable water impurities, such as the organics, are volatile while others, such as the metals and inorganic ions, are more or less nonvolatile. The nonvolatile constituents are expected to concentrate in the HoFi SWME as evaporated water from the loop is replaced by the

feedwater. At some point in the HoFi SWME mission lifecycle, as the concentrations of the nonvolatile impurities increase, the solubility limits of one or more of the constituents may be reached. The resulting presence of precipitate in the coolant water may begin to plug pores and tube channels, ultimately affecting HoFi SWME performance.

Unlike previous contamination testing where contaminant concentrations found in Table 1 were conservatively projected to simulate contaminated water for specific levels, e.g. 0, 33, 66 and 100 EVA's,[2-6] the philosophy of this test series (0-30 days) and future test series (31-100 days and beyond) is to accumulate contaminants in a flight-like manner The heat rejection rates for most of these test days exceeded the expected EVA average.

Between tests, the SWME were stored wet with a sealed water loop, and with the backpressure valve closed. For long durations between tests (> 14 days) the SWME was drained and cleared of coolant with a nitrogen gas purge.

Metals testing, ion chromatography testing, total organic carbon testing, and colony forming units (CFU) was assayed every 5 test days.

E. Freeze Tests

Freeze tests analyzed the Gcn2 SWME vulnerability to freezing conditions. For the intermittent freeze tests, water flow was stopped for 15 minutes while keeping the backpressure valve open to freeze the water contained in the water passages. After the freeze period the valve was closed. When the membranes thawed, the pump was then gradually turned back on and the Gen2 SWME was inspected for leaks, and other damage indications due to ice formation. This intermittent freeze test was repeated as many cycles as possible during a 7-hour test period.

A long duration freeze test was conducted on the last day of testing with a new, unused cartridge. In order to limit heat leak, the housing was wrapped with multilayer insulation. For the freeze test, the Gen2 SWME was fitted with 6 (six) thermocouples that monitored SWME temperature in the following locations:
To monitor hollow fiber temperature, thermocouples were located:

- axially in the center of the fiber chevron
- axially on the circumference of the fibers
- near the outlet manifold in the center of the fiber chevron
- near the outlet manifold on the circumference of the fibers.

 To monitor polyurethane header temperature, thermocouples were located:
- Inside of the SWME water outlet, on the polyurethane
- On the periphery of the polyurethane header on the outlet side of SWME.

In an extended freeze test Gen2 SWME back pressure valve was fully opened and the water flow to the inlet halted for 6.0 hours.   After 6 hours, the backpressure valve was closed and the unit allowed to thaw. This required a repress/depress cycle to remove the multilayer insulation. Once thawed, the pump was then turned back on and the Gen2 SWME was inspected for leaks and the performance was monitored.

F. Bubble Tests

Bubble performance tests analyzed the FY10 SWME for vulnerability to air bubbles. After a dry start-up of the system, air or nitrogen bubbles was injected into the sample port, first at the rate of 1 cubic centimeter (cc) per second and then at 5cc per second. These rates were maintained for a period of 10 minutes, during which performance was monitored. Each 10 minute bubble streaming period was followed by a 1 hour no-bubble period to monitor the response of the system after stopping the bubble stream. After the 10 minute bubble streaming tests, bubble streams at 1cc per second and 5cc per second were streamed for 1 hour. After each of the hour long bubble streams, there was another 1 hour no-bubble period. Clear tubing segments allowed viewing of the inlet and outlet coolant streams to verify the presence of circulating bubbles.

G. Mars Atmosphere Performance Simulations

Martian atmosphere testing was performed with a perforated sweep gas delivery tube place at the center space between the three chevron sectors, see Fig. 6. The delivery tube is fitted with a mid-axial tee attached to a sweep gas supply line. The Gen2 SWME was stepped through a series of test points in which the chamber pressure, outlet water temperature, and or dry gaseous nitrogen (GN2) sweep gas mass flow rate was varied. Martian atmospheric pressures (4.5 torr and 7.5 torr) was simulated by operating the chamber vacuum pumps simultaneously while

bleeding air into the chamber at a controlled rate. GN2 sweep gas was utilized to prevent the buildup vapor at the elevated Martian atmospheric pressures. Water flow was set to 91 kg/hr during these tests.
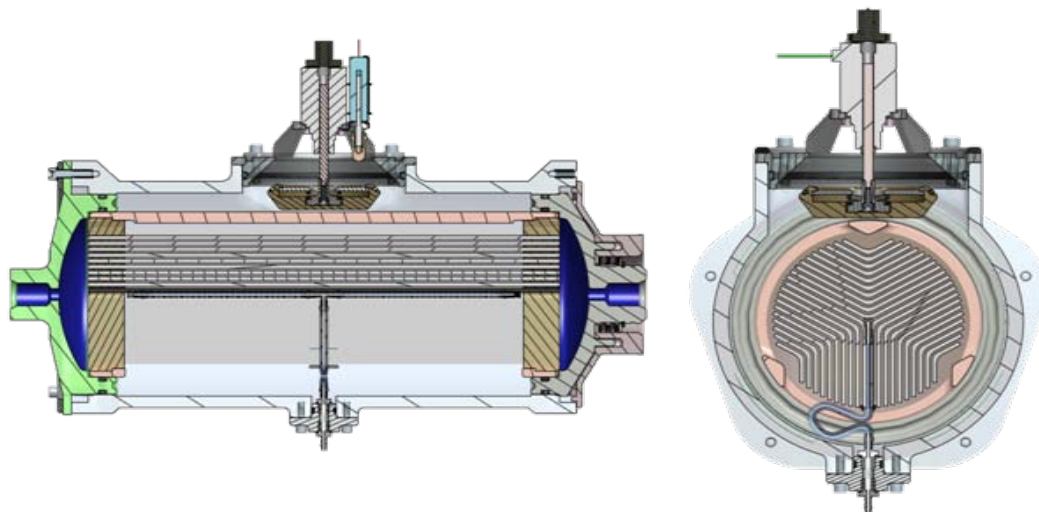
Figure 6. Gen2 SWME with Sweep Gas Tee-Tube for Martian Atmosphere Test

H. Nominal Use Tests

Fifteen days of testing (7 hours each, 105 hours of testing total) was performed with an alternating series of four Nominal Use heat rejection profiles, which simulate potential EVA heat rejection scenarios. Each Nominal Use profile begins and ends with a fully open valve for an hour, with intervening heat rejection rates that provide an overall heat rejection rate for the test day of 470 W, to exceed expected EVA average heat rejection requirements. Each of the four repeated profiles, was controlled to maintain an outlet temperature of 50°C to mimic the intended control scheme of the advanced PLSS.

V. Results

A. Performance Tests

The extensive performance-mapping test regime provided for many distinct evaluations, including varying the inlet water temperature, coolant pressure, coolant flow rate, and comparisons of the Gen1 HoFi 1(no spacer combs), Gen1 HoFi 2 (with spacer combs) and Gen2 (no spacer combs). The heat rejection of Gen1 and Gen2 SWMEs with a fully open backpressure valve as a function of inlet temperature for the specification flow rate of 91 kg/hr is presented in Fig. 7. The specification heat rejection is 807 W, with an outlet temperature of 10°C and a corresponding inlet temperature of 17.7°C marked with a plus sign on Fig. 7. Heat rejection performance was linear with respect to inlet temperature for all three systems. The Gen2 test used highly accurate flow rate transducers were installed on both the inlet and outlet sides of the SWME. This allowed heat rejection basis to be more properly put on the outlet flowrate which was about 1.2% lower than the inlet rate in the 17.7°C region. When Gen1 test data are adjusted for the outlet flowrate, the heat rejection performance of HoFi 2 (with spacer combs) exceeds the specification by about 1.5%. The adjusted performance for Gen1 HoFi 1 (no spacer combs) is slightly below the requirement, about 5% lower than HoFi2. The Gen2 SWME (no spacer combs) has almost identical performance compared to Gen1 HoFi 1, but much higher performance was expected. The active region of the hollow fibers was increased by about 4%. Also, the valve performance was expected to reduce the backpressure thereby increasing the driving gradient for evaporation. This is indeed indicated by the backpressure measurements of the Gen1 and Gen2 systems, see Fig. 7. Gen2 backpressure is 75 Pa lower than Gen1 at 17.7°C. This equates to a 7% increase in pressure gradient from the saturation pressure at the temperature of the water/membrane interface to the measured backpressure. The combined effect should result in close to a 10% performance increase compared to what was measured, see dashed curve on Fig. 7. There is some doubt that the valve controller is accurately repeating the fully
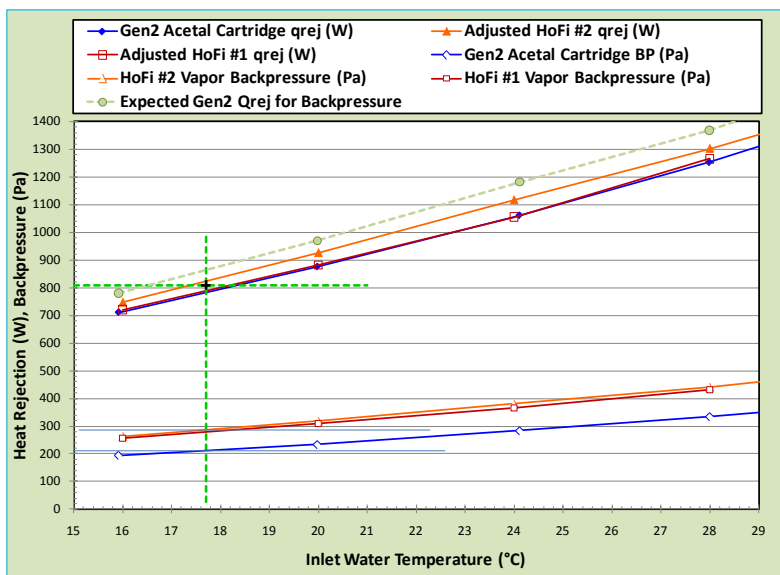
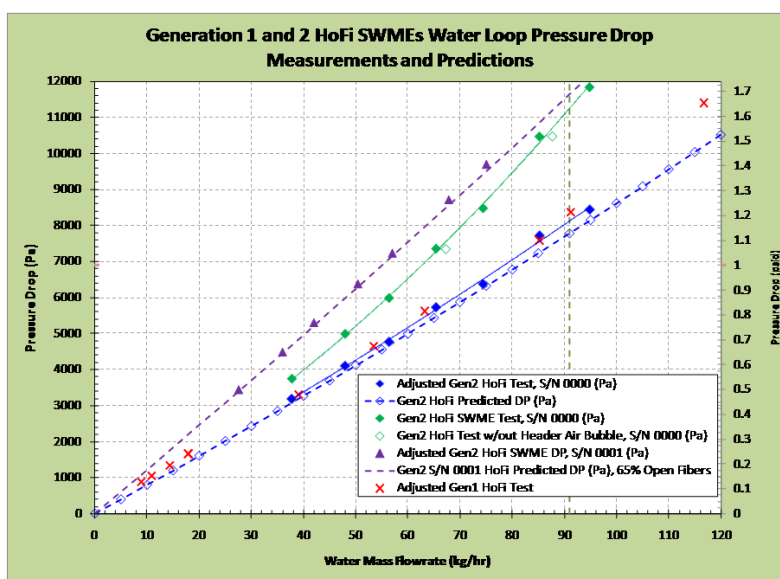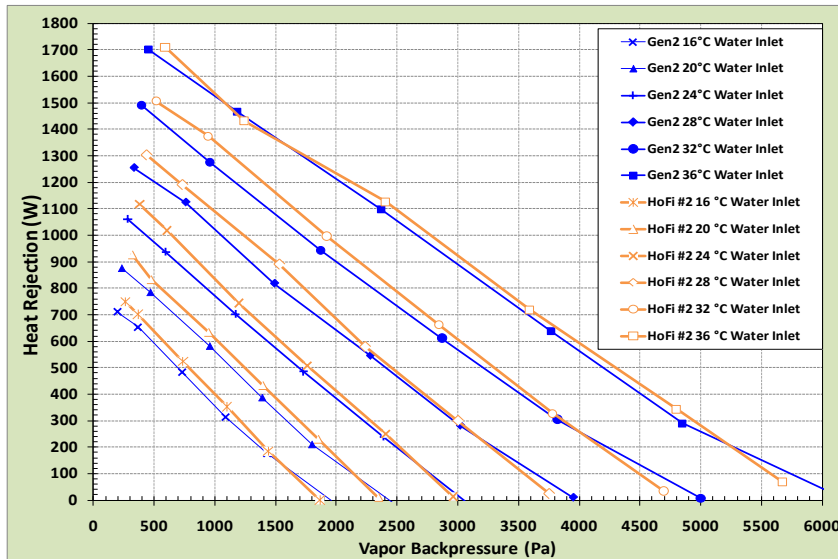**Figure 7. Gen1 and Gen2 fully open backpressure valve performance, 91 kg/hr inflow, 68.95 kPa inlet pressure**

Figure 8. Gen1 and Gen2 coolant pressure drop measurement and predictions

open position—this is currently being tested. Also the placement of the pressure transducer in the Gen2 system may bias the backpressure measurement lower relative to the Gen1 measurement. This might result in a higher performance for Gen2 than in Fig. 7. The fact that the Gen1 tests were with distilled water whereas the Gen2 tests were performed with baseline water (see Table 1) are not likely to be responsible for the performance differences because both coolant types showed no performance difference in the Gen1 system. Also the performance difference cannot be attributed to partial blocking of some of the fibers. Pressure drop measurements were taken across of range of flowrates by measuring the height of a water column on a pitot tube placed on the inlet side of the Gen1 and Gen2 SWME's, see Fig. 8. The measured pressure drop profiles of the system were adjusted for the expansion to ambient through a fitting on the outlets side of the SWMEs, a profile of the Gen2 pressure drop as measured before the expansion correction is shown in Fig. 8. The Gen1 SWME and the Gen 2 pressure drop profiles were essentially the same. These profiles were about 5% higher than theoretical. Since both systems behaved close to theoretical and were had essentially the same pressure drop profiles, partial blockage of the Gen2 does not account for the deviation of Gen 2 from it's expected performance, see Fig. 7.

The heat rejection of Gen2 and Gen 1 HoFi 2 as a function of the backpressure and for a range of inlet temperatures is presented in Fig. 9. Performance over six valve positions, from fully closed to fully open, was obtained for inlet water temperatures bracketing the range of inlet temperatures. Both Gen1 and Gen2 were able to reject 1700 W with a 36°C inlet water that brackets conceivable conditions of the spacesuit. This is an important feature of the evaporator technology in general. As heat is stored by the human body, skin temperatures rise, and coolant water temperatures rise, the ability of the unit to return the coolant loop to cooler temperatures increases. If the demand suddenly increases because of heat storage and/or metabolic rate, the unit can return the coolant loop to the colder specification temperatures for peak heat rejection by the liquid-cooled garment. Heat rejection of both units as a function of backpressure is nearly linear, having about the same slope regardless of inlet temperature. The backpressure at zero heat rejection reflects the saturation pressure at the water temperature. Some water vapor leaks occurred in Gen1 tests because the digital valve position slipped. Figure 10 compares the performance of the HoFi 2 at a reduced flow rate of 60 kg/hr and the specification flow rate 91 kg/hr. Both specification and reduced flow rates produce heat-rejection profiles that are nearly linear with backpressure. For a

Figure 9. Gen2 and Gen1 HoFi #2 Heat Rejection as a function of Vapor Backpressure, 91 kg/hr Water Mass Flow
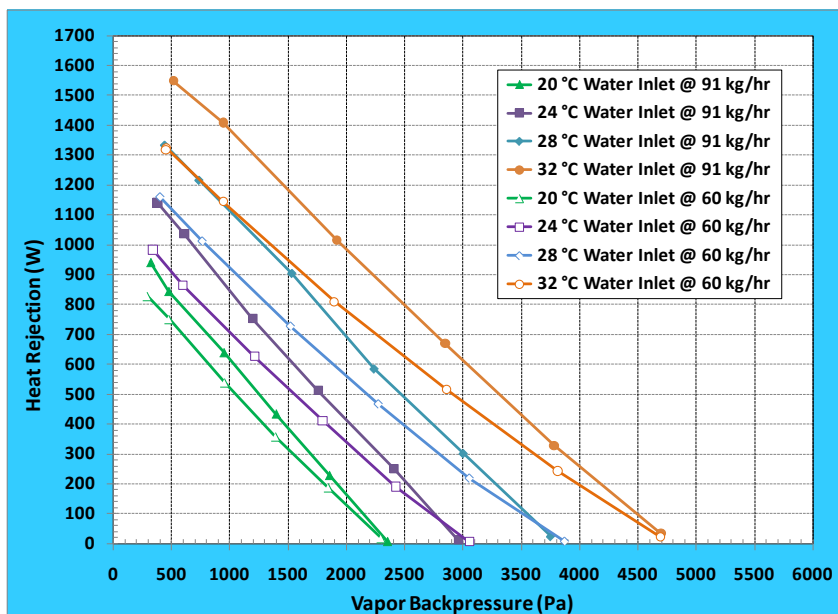
Figure 10. Gen2 heat rejection as a function of vapor backpressure and flow rates of 91 and 60 kg/hr.

given temperature, the heat rejection negative slopes of 91 kg/hr are always greater than those of the 60 kg/hr because, for a given inlet temperature, the mean temperature and the mean driving pressure are greater for the higher flow rate. As the water temperature increases, differences are exacerbated. In fact 32°C inlet temperature heat rejection at 60 kg/hr and the full-open valve position is 4°C less than the 91-kg/hr heat rejection at an inlet temperature of 28°C. The difference in the peak heat rejection at these two flow rates ranged between 18%, for an inlet temperature of 32°C, to 14% at an inlet temperature of 20°C.

The average difference in heat rejection across the backpressure range at the extremes of coolant pressure, 21 and 10 psia, is less than 0.5% at the specification flow rate (data not shown). This suggests the fibers do not deform significantly at the higher pressure.

B. Contamination Tests

The contamination testing is in progress as the contaminated water continues to be tested in the PLSS breadboard test. The goal is to chart the degradation from testing until 1200 hours of testing have been reached, a margin 50% above the life cycle requirement. As of the completion of this test, the specification performance defined as the fully open heat rejection at 91 kg/hr flowrate with an outlet temperature of 10°C, degraded from 804 W to 783 W. This is a degradation rate of 0.09% per EVA. If this degradation rate remains constant for the next 70 EVAs then the performance would degrade to 735 W, about an 8.6% overall decline. In order to ensure that the flight unit meets the specification performance of 810 W rejection after 100 EVAs the initial performance should be designed to reject 880 W. This could be accomplished by adding an additional layer to alternate chevrons, increasing the fiber density by 10%. Analysis suggests that the fiber density can be increased by more than 10% without adversely affecting the fiber efficiency.[5] Such a cartridge with the same cage dimensions but with 10% more fibers is being produced and tested.

C. Freeze Tests

Gen2 was allowed to freeze by opening the backpressure valve fully and stopping flow. Freezing of the membranes, as measured by externally mounted thermocouples, occurred within 1 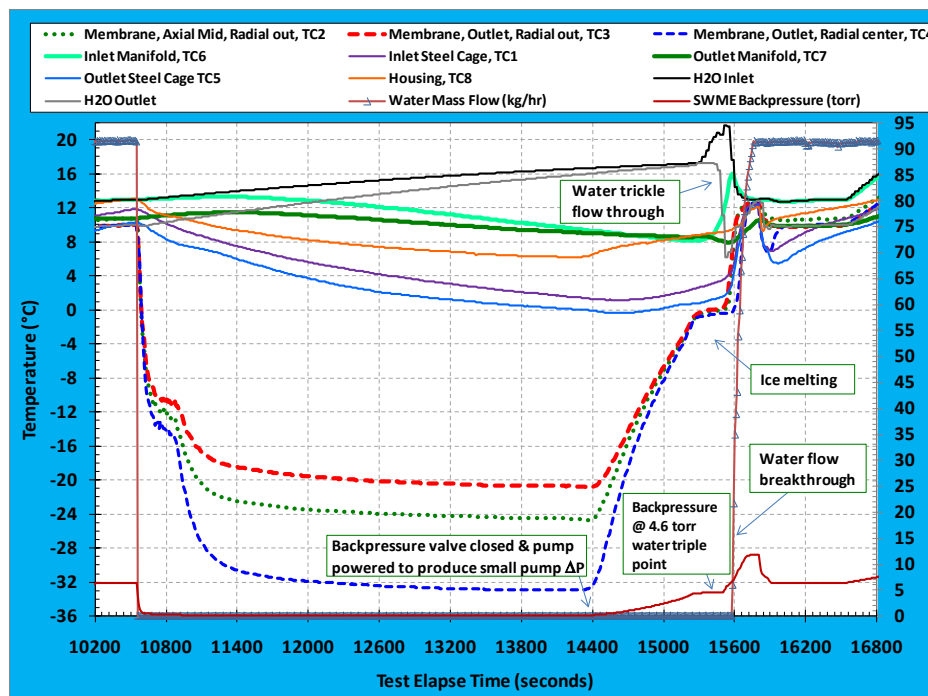min. Freezing was allowed to occur in four successively longer tests, for 1, 3, 6, and 12 min and for 1 hr, each test followed by closing of the backpressure valve until the unit warmed up and flow could be reestablished. Fully open heat rejection was then monitored to see whether performance had degraded.

Figure 11. One-hour freeze results for Gen 2

The 1-hr Gen2 freeze test results are plotted in Fig. 11. Membrane temperatures dropped quickly past 0°C, and then experienced a plateau or decreased cool-down rate a little more than 2 min after pump shutdown. The thermocouple located on the membranes at the core near the outlet reached the coldest temperature of -33°C while the thermocouples located on the membranes at the periphery reached a minimum of -21 and -25°C. These peripheral membrane warmer temperatures result from their view of the housing, which remained up to 31°C warmer. Given its proximity to the outlet header, the peripheral membrane near the outlet header was influenced by the warmer header and, not surprisingly, was 4°C warmer than its counterpart located at the axial middle. The HoFi cage (internal) structure near the outlet and inlet headers, which has a relatively strong conduction heat transfer path to the headers, reached 0 and 2°C, respectively. These temperatures demonstrate the potential of freezing occurring in the headers; in the room-temperature chamber, conditions such as these would start about 3 hrs after freeze conditions began. About 10 min after the backpressure valve had been closed, a 91-kg/hr flow was reestablished to the unit. At this point, a small leak (~1 ml total) was observed at the outlet header; this leak stopped a few minutes later upon header and water temperature rises. No further leaks were observed during testing performed the following day, the final day of HoFi 1 testing.

Freeze test results demonstrated significant membrane robustness. The HoFi membrane, sheet or HoFi, might be resistant to catastrophic failure because freezing water could expand through the pores and not be contained within a bounded volume. It is also possible that the plastic membranes are experiencing plastic deformation when subjected to water freezing cycles.
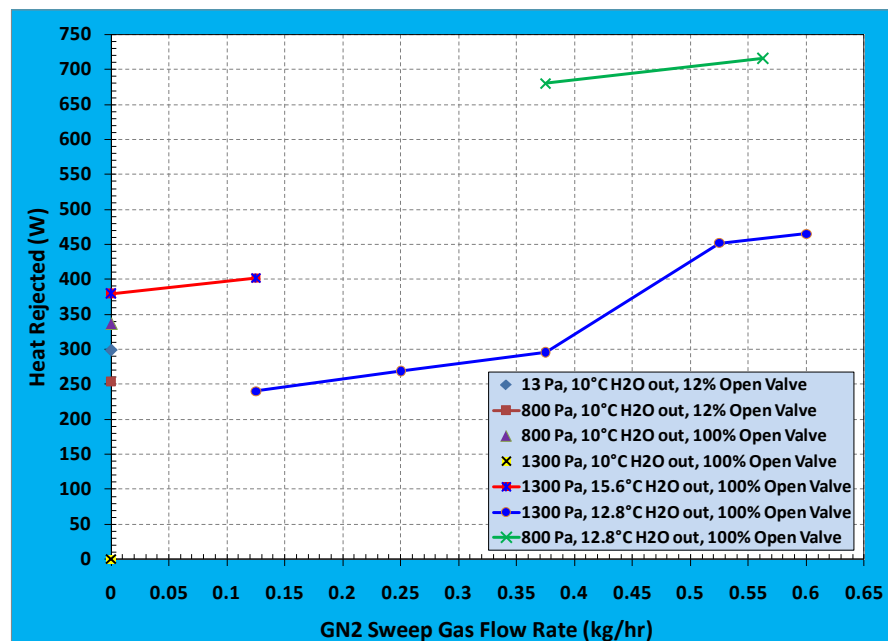
D. Bubble Tests

Bubble tests were conducted with Gen2 in which varying amounts of air were injected into the supply water line well upstream of the test article. The water supply and return lines each had a section of clear tubing near the test article so bubbles could be visualized going into the test article and also to determine whether bubbles exited or not. Gen2 was subjected to up to 50 cc of air injections into the 91-kg/hr water flow while maintaining the backpressure valve at three valve positions (fully closed, partially open, fully opened) for two different water inlet temperatures (20°C, 32°C). For all test points, no bubbles were seen exiting the test article. Each SWME effectively expelled all gas into the vacuum chamber via porous membranes. All air injections were completed within 5 sec or less.

E.   Martian Atmosphere Simulation

Testing was performed to simulate operation within a martian atmosphere. Gen2 was stepped through a series of test points in which the chamber pressure, outlet water temperature, backpressure valve opening, and/or dry GN_2 sweep gas mass flow rate were varied. We simulated the martian atmospheric pressures by operating chamber vacuum pumps simultaneously while bleeding air into the chamber at a controlled rate. The GN_2 sweep gas, a test surrogate for carbon dioxide, was theorized as a necessary element for Mars operations to prevent the buildup of vapor at the elevated martian atmospheric pressures. Water flow was set to 91 kg/hr during these tests. At low elevations, the atmosphere on Mars ranges annually from 670 to about 1,000 Pa. This test used pressures that were close to the annual mean, 800 Pa, and 1,300 Pa—well above the martian extreme.

The result of this test is plotted in Fig. 12. Five test points were conducted with no sweep gas flow. At 1,300 Pa and an outlet temperature of 10°C, heat rejection was zero because the water vapor saturation pressure was 1,227 Pa, less than external pressure. The only evaporation in this case was due to diffusion and, thus, effectively no heat rejection occurred. With the valve 12% open, at 800 Pa external pressure, and with the water at 10°C, Gen2 rejected 254 W; 85% of the heat rejection occurred at near vacuum chamber pressure for that valve position. The unit was able to reject 337 W when the valve was opened completely. The mean saturation pressure was about 1,370 Pa and the external pressure (800 Pa) resulted in a positive pressure gradient between the Gen2 and the chamber of 570 Pa—sufficient to self-sweep the unit to some extent. Similarly with an inlet of 15.6°C and an external pressure of 1,300 Pa, the effective gradient due to the mean saturation pressure was about 700 Pa, resulting in 380 W.

Figure 15. Gen2 martian atmosphere heat reject with and without nitrogen sweep gas.

It was surmise that in the cold partial-pressure environment of Mars, more heat leak could be designed into the suit during high-metabolic-rate cases. If this is true, a higher outlet temperature could be used because the heat requirement through evaporation would be less; therefore, we investigated performance at an outlet temperature of 12.8°C. The solid blue line in Fig. 12 shows the effect of sweep gas at 1,300 -a external pressure on heat rejection, with a 12.8°C outlet temperature. The shift in apparent performance that occurred in changing GN_2 flow from 0.375 to 0.525 kg/hr was due to the better control that was obtained over the sweep gas flow, resulting in improved measurement accuracy. It is clear from the 800-Pa external pressure case (see green line in Fig. 12) that sweep gas had a secondary effect; i.e., extrapolating back to zero flow, the Gen2 would have rejected about 610 W. The sweep gas at 0.56 kg/hr only increased the rejection by about 17%. With this higher outlet temperature, most heat rejection needs could be achieved without a sweep gas, and the sweep gas could be employed intermittently to reject extreme heat loads.

VI.   Conclusion

Performance characterization testing showed that the Gen2 SWME was slightly under the heat-rejection requirement by 0.5%. As backpressure decreased in response to the valve releasing to the fully open position, the heat rejection increased linearly for a given temperature, suggesting that backpressure control would be useful for controlling outlet temperature to achieve heat rejection over the entire range of desired heat rejection rates. As inlet temperatures increased, a parallel linear response was obtained, but with higher heat rejection rates for equivalent

valve positions. The Gen2 design is freeze-tolerant, like the Gen 1 predecessor. Gen2 clears gas from the coolant loop without interrupting performance, and fails in a robust way should a leak occur from one or more of the tubes. The fabrication methods are flexible with respect to geometry, and can be adapted for other applications. The Mars atmosphere simulations were especially promising, achieving 716 W at a 0.56 kg/hr sweep gas flow test point, only 12% less than the 810-W requirement and only 25% less with no sweep gas at average low-elevation Mars external pressures. Another positive feature is the rising HoFi heat rejections in response to increasing sweep gas flow rates. This is especially encouraging given that HoFi sweep gas implementation was done quickly due to cost and schedule constraints, and is considered far from optimized.

Contamination tests showed little degradation throughout the entire series. In the final series, an apparent degradation of 0.09% per day through 30 days of testing. Further testing is recommended to determine whether this degradation rate is constant or progressive. This will determine how much margin should be built into the flight design.

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Acronyms

atm:	atmosphere
DAQ:	data acquisition
ETDP:	EVA Technical Development Program
EVA:	extravehicular activity
GN_2:	gaseous nitrogen
HoFi:	hollow fiber
HX:	heat exchanger
ISS:	International Space Station
MCL:	maximum contaminant level
PLSS:	Portable Life Support System
SWME:	suit water membrane evaporator
WPA:	water processing assembly

Appendix A

Experimental Design and Statistical Analysis for the Spacesuit Water Membrane Evaporator Polyurethane Hardness Study

The objective was to identify the values of important controllable factors that optimize the hardness of the polyurethane used to form the SWME headers, namely GSP 1526-1, a two-part adhesive/sealant made by GS Polymers, originally designed as a filter sealant with excellent resistance to water.. Based on considerations from materials science, three experimental factors were identified as important in controlling the experimental response, hardness. These factors are percent hardener, heat treatment temperature and heat treatment duration. An orthogonal central composite response surface design in 23 runs was used with the following values:

Percent Hardener	35.73	36.95	38.73	40.51	41.73
Heat Treatment Temperature (C)	22	34	51	68	80
Heat Treatment Duration (hrs)	16	25.73	40	54.27	64

Five repeat hardness measurements were taken on the same experimental units at 1, 2, 5, 8, and 14 days after the end of heat treatment.

Just one oven was available for heat treatment. Additionally, laboratory procedures required that the percent hardener not be varied arbitrarily from unit to unit. For these reasons, heat treatment duration was randomized within percent hardener which was randomized within heat treatment temperature. The 22°C heat treatment temperature was considered room temperature, and these units were aged under a laboratory hood.

Although every attempt was made to avoid having to take measurements on weekends and holidays, observations were not made on Christmas eve (a holiday) for follow-up day 2 on four units with the following treatment combinations:

Heat Treatment Temperature (C)	Heat Treatment Duration (hrs)	Percent Hardener
68	54.27	40.514
68	54.27	36.963
68	25.73	40.514
68	25.73	36.963

The resulting missing data did not seem to effect the conclusions.

Each of the five repeat measurements were averaged. A response surface analysis was performed on the averaged data for each of the five follow-up days. Each of the five repeat five Shore A hardness measurements made on each coupon at a given time were averaged. The similar 5 Shore D hardness measurements were also averaged, when they were present. If a Shore D hardness average was available, it was transformed to an estimated Shore A average by the following empirical formula.

$$A = \frac{1}{a + \dfrac{b}{D}},$$

Where $a = 0.0079875840$ and $b = 0.1154380923$. The corresponding Shore A average was replaced by the estimated Shore A average.

A response surface analysis was performed on the averaged data for each of the five follow-up days.

It was found that maximum hardness should be obtained at maximum percent hardener and maximum treatment temperature. The duration of heat treatment did not seem to make a substantial difference in hardness, and thus 16 to 24 hours of heat treatment should yield the same hardness as a longer treatment at the same high levels of hardener and temperature. Additionally, there did not appear to be a substantial increase in hardness with aging (curing), and thus the material seemed to reach its maximum hardness after one day of curing.

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