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SERFE PLSS Component Lessons Learned from ISS

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NASA has been developing a new spacesuit, called the Exploration Extravehicular Mobility Unit (xEMU) for over a decade. This spacesuit is under development to support missions to the International Space Station (ISS) and also to the Moon. Improvements in the life and robustness of the Portable Life Support System (PLSS) has been a major objective of these efforts. The Suit Water Membrane Evaporator (SWME) was chosen as the technology to provide cooling to the xEMU and has undergone several iterations of development over this period. An ISS flight experiment centered around the SWME and other thermal control loop (TCL) technologies was developed and tested in an ISS EXpedite PRocessing of Experiments to the Space Station (EXPRESS) rack from November of 2020 to August of 2022. In addition to the SWME, the SWME EXPRESS Rack Flight Experiment (SERFE) contains several technologies from the xEMU project and demonstrated their performance in micro-gravity and over an extended duration. These included two dissimilar water pumps, custom check valves, custom bypass relieve valves, a custom thermal control valve, development pressure and temperature sensors, and the thermal loop controller. This paper presents PLSS component lessons learned after return of the SERFE flight unit in August of 2022. The SERFE team took the flight unit apart and handed hardware components over to hardware owners to see how parts of the TCL managed after almost 2 years on the ISS and 25 simulated EVAs (Exploration Extravehicular Activity) on orbit. The team performed inspection, testing, and analysis and provided lessons learned on PLSS components for NASA's prototype spacesuit. This analysis included how well SWME maintained its heat rejection capability, as well as looked at the robustness of the other TCL hardware.

I. Introduction

THE SWME EXPRESS Rack Flight Experiment (SERFE) is an integrated experimental system equipped with some of the latest technology of the Exploration Extravehicular Mobility Unit (xEMU), which is NASA's prototype of the next-generation spacesuit. This flight experiment and the technologies within were flown and tested aboard the ISS for 22 months. A second unit, the Ground Unit, was tested in parallel at the Johnson Space Center (JSC). Following this extended testing profile, during which 25 simulated Extravehicular Activities (EVAs) were performed, the SERFE Flight Unit was disassembled at JSC and inspected for signs of material and performance degradation. This document summarizes the final performance of the SERFE test article and also the findings of that tear-down, including materials analyses, post-flight component performance, and discusses the lessons learned through those findings. These results should be compared to earlier SERFE papers and analyses.[1, 2, 3] Table 1 summarizes the testing profile of each SERFE unit. Ultimately, the SERFE experiment and related project activities provide a useful reference for development of future spacesuits and demonstrate the strength of some of those technologies in their current or very recent design iterations.

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Table 1. Testing profiles for SERFE Flight and Ground Units.

SERFE FLIGHT UNIT (SN 1001)				
EVA series	**Dwell (days)**	**Dates**	**# of EVAs**	**Total EVAs**
Ground Test Series				
1	18	3/10/20-3/13/20	4	4
Functional	32	4/14/2020	1	5
2	27	5/11/20-5/14/20	4	9
3	25	6/8/20, 6/10/20	2	11
Flight Test Series (ISS - US Lab)				
Functional	150	11/10/2020	1	12
1	N/A	11/11/20-11/14/20	4	16
2	92	2/22/21-2/25/21	4	20
3	30	4/5/21-4/8/21	4	24
Tel/Comm check	N/A	8/3/2021	--	--
Tel/Comm check	N/A	10/18/2021	--	--
4	211	11/15/21 - 11/19/21	4	28
Tel/Comm check	N/A	12/27/2021	--	--
5	45	1/4/22 - 1/7/22	4	32
6	91	4/11/22 - 4/15/22	5	37

SERFE GROUND UNIT (SN 1002)				
EVA Series	**Dwell (days)**	**Dates**	**# of EVAs**	**Total EVAs**
Ground Test Series				
Functional	50	9/8/2020	1	1
1	7	9/15/20-9/18/20	4	5
2	38	10/27/20-10/30/20	3	8
3	39	12/8/20-12/11/20	4	12
Flight Test Series (PLSS Development Lab)				
1	44	1/25/21-1/28/21	4	16
2	5	2/2/21-2/5/21	4	20
3	47	3/24-3/26/21, 3/29/21	4	24
4	210	10/25/2021 - 10/28/21	4	28
5	46	12/13/21 - 12/16/21	4	32
6	81	3/7/22 - 3/14/22	5	37

II. Final Testing Results

A. Thermal/Fluids Performance

Previous papers documenting the performance of SERFE were published prior to receipt of testing results for the final test series of both the Flight and Ground Units.[1, 2, 3] The following section provides details closing out this story on the thermal performance side and discusses their meaning for the project in its entirety.

The primary thermal performance measures tracked in SERFE testing were the maximum capable SWME heat rejection as well as the temperature of water exiting the SWME, recorded by temperature sensor TS-439. The maximum heat rejection capability was typically tested twice per test series when a heat input of 600 Watts was provided to the water loop. In combination with ambient heat gains, this would provide a heat input beyond what the SWME could handle while still maintaining an exit water temperature of 50 °F. Both variables were averaged over the last minute of these 600-Watt heat input tests and are plotted for both the Flight and Ground Units in Figure 1. Generally, the heat rejection would remain in the range of 600-650 Watts with an outlet temperature of 53-55 °F. It should be noted that problems related to temperature sensor drift (discussed in a later section dedicated to disassembly observations) affected both the Ground and Flight Units. Fortunately, the sensor drift did not impact the maximum heat capability testing at 600 Watts of heat input. TS-439 provides a control signal to the CON-450 thermal loop controller to open and close the SWME backpressure valve. However, at the 600 W test point, the valve would stroke to the full open position, regardless of the temperature reading from TS-439. The sensor drift was accounted for in the data analysis, necessary offsets were applied to telemetry, and these changes are reflected in the values appearing in Figure 1.

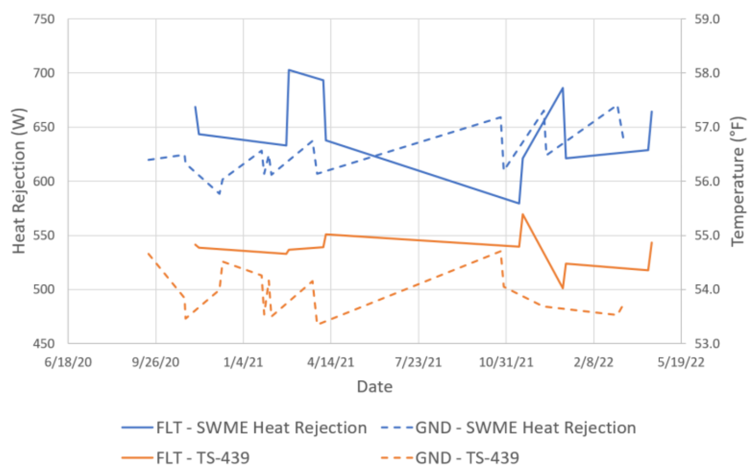

Figure 1. SWME Performance of Flight and Ground Units.

Beyond some fluctuations in value, there does not appear to be an overall trend in the heat rejection values for either unit. There seems to be a small positive slope for the Ground Unit data, however the increase from start to finish is near in value to the uncertainty of the heat rejection calculation. Regarding uncertainty, heat rejection values were estimated to have uncertainties of 30-40 Watts in most cases; however, the use of offsets on temperature values (due to sensor drift) introduced a complexity to the uncertainty formulation that could not feasibly be accounted for. Thus, we may conclude that the increase in heat rejection of the Ground Unit over 1.5 years is well within the bounds of uncertainty for its estimation. Heat rejection was calculated based on flow rate and temperature difference across the SWME[2]. The outlet temperature, TS-439, also did not change significantly over time for either unit. Section III documents standalone SWME tests after the Flight Unit was disassembled. The standalone performance is in agreement with the on-orbit data in showing that the SWME performed without degradation through the life of the experiment.

In addition to the thermal markers for performance, test points to evaluate the degassing performance of the SWME were also performed twice per test series. The ability of the SWME to remove air from the water loop is a required function as the Liquid Cooling Garment (LCG), the 48 feet of tubing that is in contact with the astronaut in the integrated xEMU to provide cooling, will not be wetted initially. Thus, 1L of air was injected at the beginning and end of each test series to assess this requirement of the technology. Beyond that, the speed at which the SWME is able to remove that gas can also provide a measure of performance since fiber degradation may impact the degassing performance of the membrane. Ultimately, degas performance did not change significantly in the final tests performed for the SERFE Flight and Ground Units. Detailed results can be found in Reference 2.

The SWME and other SERFE technologies which contributed to fluid flow and heat exchanges appear to have maintained their performance over the course of nearly 2 years of life and hundreds of hours of operation on both units.

B. Water Quality

As covered in previous papers related to the SERFE project[3] the water quality degraded over time. Some constituents continually increased through the end of the project and some stabilized at levels not normally acceptable in a spacesuit. The final water quality data is presented in this section.

The water quality analysis performed for each test series of both SERFE units tested for many contaminants and chemicals. The most important of these were: iodine, iodide, silicon, and chloride concentrations; water conductivity; Total Organic and Inorganic Carbon (TOC/TIC); and the microbial count. These are shown in a collection of plots appearing in Figure 2. Note that the time axis is in test days, which normalizes the time scale of both units to the number of days after the final pre-test water flush performed on each SERFE unit.

Many of the measured variables very clearly increased over time for both SERFE units. In general, the trends accompanying these increases were similar between the two units, however there are some discrepancies worth noting. Beginning with the iodine and iodide concentrations, there is very little change in iodine compared to iodide, which is expected as the former converts to the latter following interaction with other wetted materials in the system. There is an initial sharp increase in iodide for the Flight Unit, followed by a sharp decrease to about half the initial peak concentration value. This is likely due to large volumes of water being sampled in the first few ground tests performed on the Flight Unit (represented by the first 8 points on the plot). Large samples likely removed much iodide-heavy water and replaced it with unused, iodinated water. A similar peak followed by a drop is not seen on the Ground Unit as it did not experience the same water sampling as the Flight Unit in those early tests. The maximum value seen on the Flight Unit for iodide concentration, which was also the final value recorded, was about 7.3 ppm. Fresh water was added to the system with iodine between 1 and 4 ppm. This is the active biocide for the water in the loop. Unfortunately, the iodine reacts quickly with the wetted materials in the system (like the polypropylene SWME fibers) or evaporates across the SWME membranes. Iodine readings are effectively 0 ppm, or below the detection level throughout the life of both SERFE units.

The water conductivity displayed very similar behavior to the iodide concentration, with a large peak followed by a drop in the first few tests, giving further credence to the theory that this is the result of incidental water loop flushing. The maximum value seen for conductivity was also on the Flight Unit, and was approximately 21 mS/cm. The Ground Unit conductivity appears to have increased very well in tandem with the Flight Unit. The gradual increase in conductivity is certainly expected, as the buildup of non-volatile contaminants is inevitable in a water loop where water is continually evaporated.

Concentrations of TOC and TIC rose to much higher values than expected. The causality has been discussed at some length in previous papers, however in summary the source was likely epoxies and adhesion promoters used on various components. Following the peak value of the Flight Unit, TOC did decrease in the last 300 days of testing, but was marked at a value of about 13 ppm in the final water sample prior to disassembly. The largest increases in TOC appear to occur after long quiescent periods, but the values appear to stabilize once the system is operated more regularly.

The presence of silicon and chloride in the water loop were of particular concern as the presence of the former is likely indicative of degradation of the approximately 600 sq-in of Ethyl-Vinyl Acetate tubing present in the water

Figure 2. Various final water quality results of the SERFE Flight and Ground Units.

loop, while the presence of the latter can contribute to metal corrosion. Both constituents rose in concentration over the life of both units, however the Flight Unit appears to have had a much larger increase in silicon than the Ground Unit. The maximum silicon concentration in the Flight Unit water was seen in the final sample at approximately 5.8 ppm. This is higher than typical EMU water which is in the range of 1-2 ppm. Chloride concentration on both units rose to a level of 1-2 ppm in the first 500 days of testing and remained in that range for the remainder of testing (with the exception of the final sample of the Flight Unit).

The final noteworthy contaminant are microbes. Both SERFE units showed values typically in the range of 1x 10^5 to 1x 10^6 CFU/mL, however the Flight Unit did rise above this range and remained near 1x 10^6 for the last four samples taken. For comparison, EMU water is typically in the range of 7.5x 10^1 to 2.9x 10^5 with an average of around 1.0x 10^3 CFU/mL. Thus, SERFE water ended near and above the high end of this range, and well above the average value[3].

Overall, the water quality data for SERFE shows that the water loop in both units had a significant buildup of contaminants, especially TOC and microbes, that remained high in value through the end of testing. Relative to typically EMU water, SERFE water was quite dirty. Despite this, the life-support technologies (e.g., the SWME) continued to perform well over the course of the experiment, and this is the mantra that we carry to conclusion for the SERFE experiment.

Table 2. Post-testing disassembly water sample collection summary.

Water Sample Collection Totals	Volume Collected (mL)
MiniPLSS Chemistry	225
MiniPLSS Micro	50
Misc Chemistry	100
Misc Micro	25
Special	100
Total	**500**

Misc Sample Collection Breakdown	Volume Collected (mL)
LCVG	15
Tubing	50
Gas Injection Assy	30
Heater Assy	30
Total	**125**

III. Flight Unit Post-Testing Operations

Upon receipt of the SERFE Flight unit following its stay on ISS, the flight experiment was put through a systematic disassembly procedure that allowed observations to be made about the hardware on a materials and processes level. The payload was initially removed from the payload locker. After locker removal, side panels were removed to provide access to the lower level payload assemblies: the heater assembly, LCVG Simulator Assembly, vacuum chamber assembly, etc. Accessible water lines were drained and sub-assemblies were removed for closer inspection. The drained water was collected for chemistry analysis in the lab as noted in Table 2. It is notable that SERFE has a wetted volume of approximately 1.7 L, however only approximately 500 mL of water was able to be collected for water analysis. Part of this disparity is due to the difficulty in getting the water out of some of the different components. In addition, several of the components were unexpectedly dry. The heater assembly had very little water remaining in it by the time of disassembly. The LCVG simulator was difficult to remove water from due to the large number of small diameter tubes that were only partially wet. Continued evaporation across the SWME membranes and permeation through the ethyl vinyl acetate tubing in the LCVG simulator are potential sources of water loss from the experiment during the storage period between the last test in April 2022 and the disassembly in September the same year.

As sub-assemblies came apart, the interior wetted surfaces were found to be clean, especially the vacuum chamber which contains the MiniPLSS and provides a vacuum for SWME heat rejection, as shown in Figure 3. The lack of rust and buildup of contaminants on wetted components indicate that the wetted surfaces were processed and machined properly and that the materials were selected properly. It is possible, however, that the iodine present in the water caused some staining and discoloration on a few components. After pulling apart the HX-440 assembly, which is the SWME, the closeout plate and plug plate were found to have slight discoloration. Whether or not the iodine in the water is actually the culprit, the discoloration was deemed inconsequential to operation and component health.

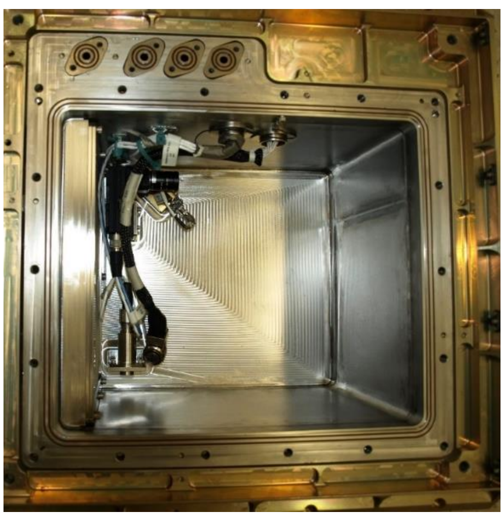

Figure 3. SERFE vacuum chamber interior.

Beyond slight discoloration of a few components, the interior of the HX-440 housing, which contains the actual SWME fiber cartridges, was found to be clean and clear of foreign materials and debris. One of the three fiber cartridges did display slight yellow/purple discoloration near the epoxy headers holding the fiber bundles in place at their ends. Despite this, the epoxy headers themselves showed no signs of damage or deterioration. The exterior surfaces were found to be generally clean. When the SWME was removed from the MiniPLSS backplate, a puddle of water was observed underneath the SWME housing, shown in Figure 4. This is believed to be due to water continually evaporating across the membranes during long periods of storage and is a commonly seen occurrence.

Following SERFE disassembly, the SWME was removed from the MiniPLSS and tested to assess post-flight performance including cartridge leakage, capacity for heat rejection, and component pressure drop. Testing was performed at incremental steps of the SWME disassembly. This included leak test and heat rejection performance tests at the full assembly level and the individual cartridge level. The full assembly and cartridge stack are shown in Figure 5.

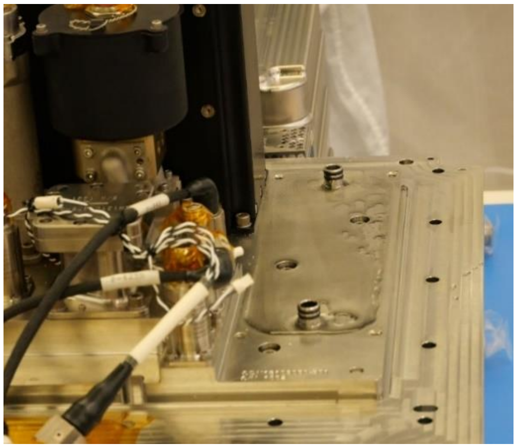

Figure 4. Water puddle beneath HX-440.

Leak testing was performed on a proof and leak test rig where cartridges were pressurized to 35 psig and held at that pressure for 30 minutes. This represented the Maximum Design Pressure (MDP) test. A proof pressure test at 1.5x MDP, or 52.5 psig, was done following the MDP test and held for 5 minutes on each cartridge. All three cartridges passed both levels of leak testing. Prior to the test, cartridges were flushed with iodinated water. During the test, the fiber portion of the cartridges was inspected for any sign of leakage. This is evidence that the designed fiber cartridges retained their robustness following a long stay in microgravity and hundreds of hours of operation with water flowing through them.

Thermal testing provided further evidence of the robustness of SWME performance following flight testing. This testing was performed using the Leak Test Vacuum Chamber (LTVC) which provides vacuum conditions and flowing water pass-throughs for small test articles such as the individual SWME fiber cartridges. The SWME cartridges were exposed to vacuum between 0.1 and 1.0 torr with water flowing internally at approximately 90 kg/hr and heat input from the heater in the test stand. Heat input was increased to the maximum setting where the SWME outlet temperature could still be maintained at 50 °F. The average estimated heat rejection, based on the temperature drop from inlet to outlet, is shown in Table 3 for each cartridge, the stack of three together, and the full HX-440 assembly. SWME acceptance data taken before SERFE integration is also shown with the percent change from pre- to post-flight values. An average was taken due to noise and minor fluctuations in the sensor value. These heat rejection tests show that these SWME cartridges did not degrade noticeably during the life of the SERFE Flight Unit.

Table 3. Heat rejection estimates of SWME cartridges before and after flight testing.

Cartridge/Unit	Pre-Flight Average Heat Rejection (W)	Post-Flight Average Heat Rejection (W)	% Change
1010	281	306	9%
1011	288	262	-9%
1012	276	308	12%
3 Cartridge Stack	941	914	-3%
HX-440 Assembly	812	779	-4%

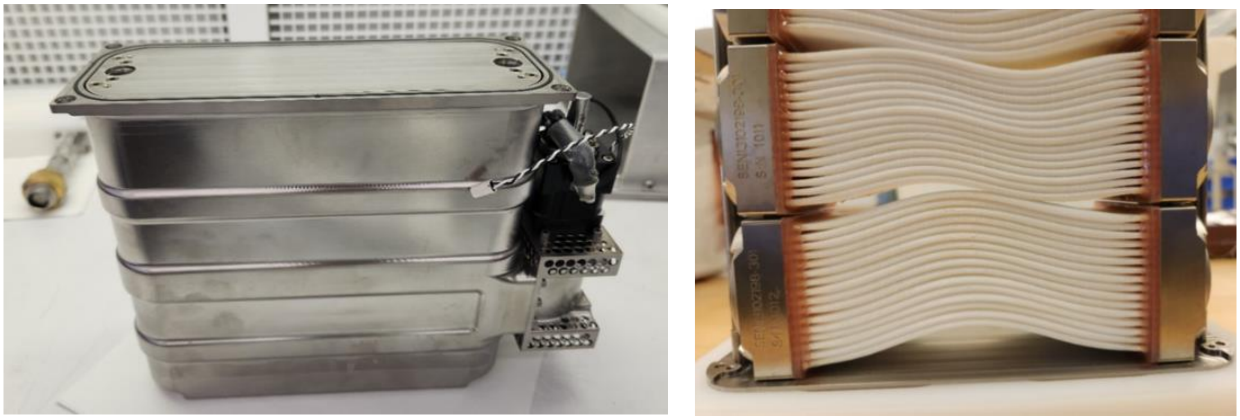

Figure 5. HX-440 assembly (left) and fiber cartridge stack (right).

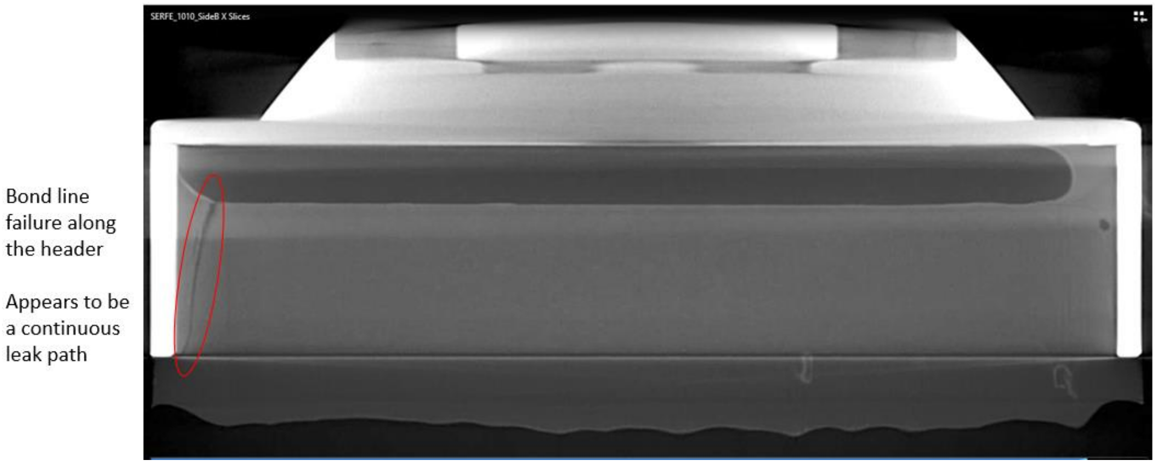

Figure 6. SWME Cartridge Bond Line Failure

In spite of this outstanding long duration performance of the SWME, an interesting discovery was made after these performance tests were completed. Two of the cartridges were dried and then scanned using computerized tomography (CT). An example of one of these CT scans is shown in Figure 6. Several cartridges in the overall SWME cartridge inventory, not used for SERFE, have begun to develop leaks inside the epoxy headers where the membrane tubes are bonded into a bundle and then the bundle is bonded into the titanium end caps. The assembly process uses two different epoxy pours for these two operations, creating an epoxy to epoxy bond line. CT scans of these dried cartridges indicated several cracks or failures that occurred at this bond line. After observing these cracks in the CT scans, these cartridges were leak tested again. This second round of leak tests failed to even hold 3 psig and leaks at the headers were clearly visible. The hypothesis for this failure is that while wetted, the epoxy swells. When it is dried, it shrinks and cracks and this bond line appears. This phenomenon is an important risk to influence manufacturing processes and hardware storage plans for this type of membrane evaporator. The team has learned that SWME cartridges need to be kept wet to maintain their integrity. The SERFE Flight unit was wetted prior to flight during ground processing and launched to ISS still wetted. On the ISS, the thermal loop always contained water. It was after the SWME cartridges returned from flight and dried out that they developed cracks in epoxy bond lines.

The xEMU thermal control loop uses titanium as the primary wetted metal. Titanium has excellent strength, density, and corrosion resistance properties that make it desirable for aerospace applications. However, machining titanium parts proved to have some challenges. The primary issue found during the fabrication and assembly of SERFE components was unexpected rust spots that were often found on the titanium parts. This ranged from parts that used traditional cutting operations to 3-D printed titanium manifolds on PMP-422. In each case it was determined that the titanium was not actually rusting and that it was due to process control issues which left iron deposits on the parts. This could have been from a dull tool on a mill or poor cleanup in between runs on the laser sintering machine. These experiences led to better control of manufacturing processes when xEMU thermal loop components were made.

Figure 7. Various SERFE components following removal, including RV-424A/B (top-left), heater assembly (top-right), TCV-421 shuttle (middle), and F-2048 (bottom).

Most of the SERFE Flight unit titanium parts looked pristine during posttest inspections, Figure 7. Disassembly of the TCV (thermal control valve) provided observations that the wetted titanium components held up well during the SERFE mission and the shuttle inside of the valve did not show significant wear. Relief Valves RV-424A/B appeared to be in excellent condition when they were removed from the MiniPLSS. Component disassembly also showed that the wetted titanium components were still in excellent condition. The Heater (HTR-2060) is a titanium heat exchanger with adhesive backed strip heaters attached to provide heat input for the SERFE water loop. Again, upon disassembly, the wetted passages appear to be in excellent condition. Filter F-2048 from the Feedwater Recharge Assembly looked good under inspection. No contamination was found after more detailed inspection of the filter element. It appears the use of titanium as the primary wetted metal in the xEMU thermal control loop was a good choice once the team learned how to overcome machining challenges.

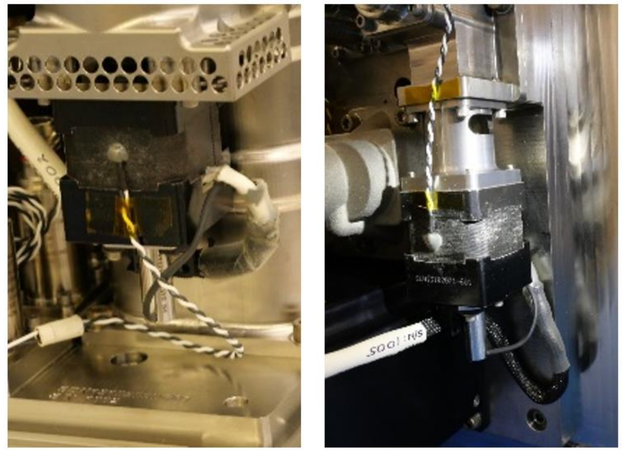

Figure 8. Body rust on linear actuators of SWME BPV (left) and TCV-421 (right).

Linear actuators are a common sub-component that are spread across the PLSS. SERFE has one on the SWME backpressure valve (BPV) and one on the TCV that are the same as the current xEMU PLSS hardware. These linear actuators have a history of sticking, however the two units on the SERFE Flight Unit have been in operation for over two years and have never jammed due to procedural controls that avoid leaving either of the valves at a hard stop position for any extended period of time and current reductions as the motors approach the ends of travel. The TCV actuator, after disassembly from the valve, was tested for force output and evaluated for jamming. The results were then compared with linear actuators that were removed from the xEMU PLSS that have had more difficult operational histories with sticking to see if there are any visible differences in the internal threads on the motor. Some body rust was observed on both actuators, as shown in Figure 8. These steel parts were painted but were also exposed to a humid environment inside of the SERFE vacuum chamber for several years. It is likely that condensation formed on these pieces of hardware inside the SERFE vacuum chamber after test points were completed.

Figure 9. Presumed rust spots on secondary pump manifold.

Primary Pump PMP-423 worked very smoothly throughout the SERFE testing profile. The pump was removed from the Mini-PLSS and looked to be in good condition. The pump inlet filter (423C) was found to be clean. Pump Check Valve (CKV-426) at the pump outlet also looked good. This pump was stored wet for return to OEM for evaluation. Component level testing agreed with SERFE testing in showing that no pump performance degradation occurred throughout the SERFE mission.

PMP-422 also worked well and did not have any issues during testing operations. Some materials and processing issues were noticed during assembly of the pumps, which included rust spots on the 3-D printed titanium manifolds and "tarnishing" of the nitrided (gold colored) titanium pump body parts. The pump manifold can be seen in Figure 9. This pump was disassembled and inspected. During disassembly from the Mini-PLSS, the pump inlet filter (422C) was examined for contamination. Similarly to the inlet filter on PMP-423, it was examined at 50x magnification and did not contain any FOD (foreign object debris). Pump Check Valve (CKV-427) at the outlet looked good.

Once all the MiniPLSS components had been removed, the backplate was inspected. Visual inspection of the backplate and all the fluid ports for the PLSS components was performed to look for evidence of particles, corrosion, or biological activity. Additional visual inspections of the internals were performed with a borescope. Areas of interest within the backplate were the TCV LCG outlet, TCV inlet, TCV pump outlet, PMP-422 inlet, and HX-440 inlet. Borescope images of these areas are shown alongside a diagram with their locations in Figure 10.[4]

Finally, sectioning the backplate to further inspect the weld joints of the fluid passages was performed per engineering discretion. "Areas of interest" were cut out to better locate anomalies (surface finish/mineral deposits in inlet ports) and create samples for further sectioning. Then straight lengths of backplate channel were cut out for inspection with a rigid borescope to identify other areas to take sections. Results are still pending from M&P. These areas will undergo additional analysis. These may be residual markings from electron beam welding close out plates to make the water channels, reactions between the backplate and water, left over water droplets reflecting off the light

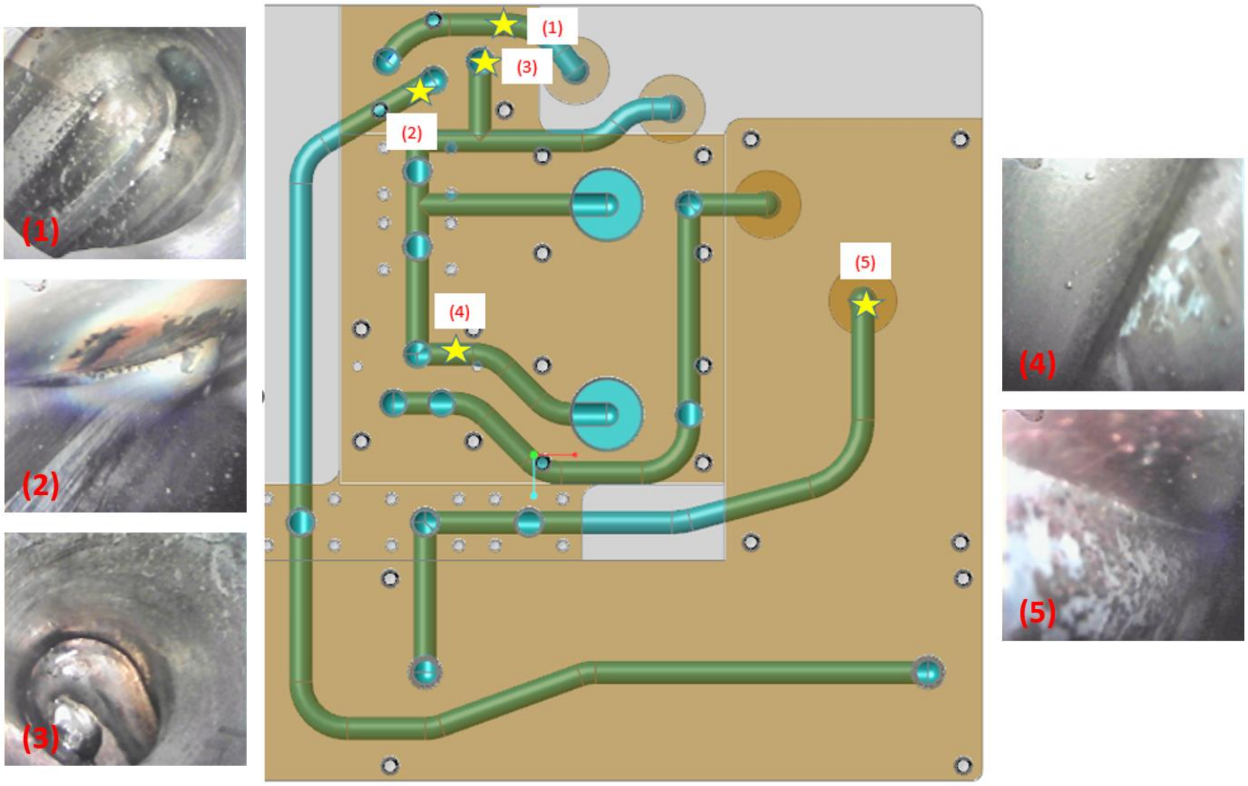

Figure 10. Areas of interest on backplate including the TCV LCG outlet (1), TCV inlet (2), TCV pump outlet (3), PMP-422 inlet (4), and HX-440 inlet (5).

on the borescope, or something currently unknown.[4] For information on M&P results and lessons learned from the backplate, reference ICES paper titled “xPLSS Structural Backplate Design, Manufacture, and Test Overview.”[4]

During disassembly, it was discovered that the assembly paperwork had not correctly captured serial numbers for all the sensors that were installed. This was a lesson learned in configuration management. An assessment of these serial number differences was done by evaluating the differences in the calibration coefficients implemented in the SERFE Ground Station software and the post processing analysis spreadsheets. Several temperature and pressure sensors were affected, however the resulting change in calibration did not significantly impact data and does not invalidate any conclusions made about the SERFE project from previous analysis.

There was also an issue of temperature sensor drift during flight testing, which was documented in a previous paper related to SERFE[1, 2]. The affected sensors were the inlet and outlet SWME sensors (TS-441 and TS-439 respectively) and the pump inlet sensor (TS-400). Three different methods were employed to estimate sensor drift, each of which is detailed in previous papers related to the SERFE project. The final test series of flight-ops showed that drift had not worsened since the previous test series three months prior. The full evolution of sensor drift on the Flight Unit can be seen in Figure 11.

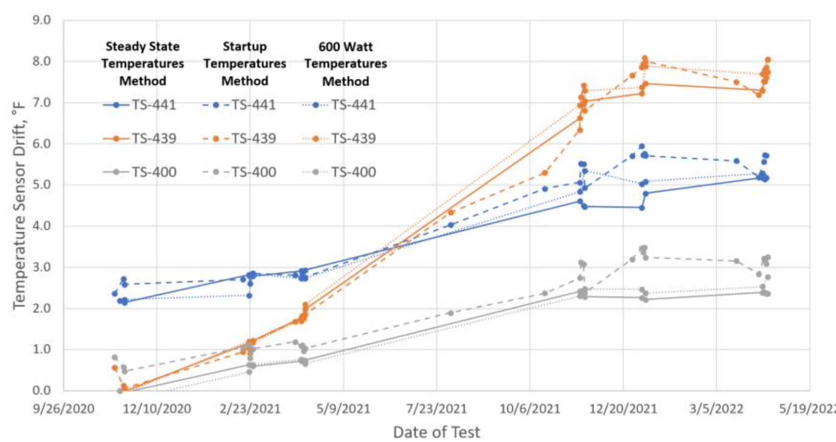

Figure 11. Estimated temperature sensor drift of three major sensors on the SERFE Flight Unit.

A series of troubleshooting tests was performed to isolate the cause of the temperature drift between the temperature sensors, harnessing, and the CON-450. The temperature sensors were 1000 Ohm resistance temperature devices (RTD), so this drift was theorized to be due to an increase in resistance in some portion of the integrated system or degradation in the circuit that was exciting each sensor. Each SERFE CON-450 was previously acceptance tested per a CON-450 Acceptance Test Procedure which utilizes a CON-450 test box and LabVIEW code to read the telemetry coming from the box. In order to evaluate the temperature sensor drift issue, the following test sequences were performed.

- Configured the CON-450 with the CON-450 to Instrumentation harness (SEN13103066-301) and the three temperature sensors: TS-400, TS-439, TS-441. Performed evaluation at multiple temperatures (room temperature and an ice bath).
- Configured the CON-450 with the CON-450 to Instrumentation harness (SEN13103066-301) and used a calibrator to simulate the RTD resistance while interfacing to the sensor end of the harness.
- Tested the CON-450 by itself with the test box using a calibrator to simulate the RTD resistance.

These tests indicated the source of the temperature sensor drift is in the CON-450, although more detailed inspections still need to been performed.

The LCVG assembly is a set of ethyl vinyl acetate tubes that simulate the wetted materials of a liquid cooling garment with titanium headers that are bonded to the tubes using EA-9313 epoxy, which is the same epoxy used in the SWME headers. However, the LCVG did not undergo a vacuum bake out as part of the hardware processing and the epoxy is believed to be the source of elevated total organic carbon readings that have been noticeable after long quiescent periods. Inspections included disassembling the titanium headers and performing visual inspections of the epoxy and tubes. The EA-9313 epoxy headers nor the tubes had noticeable degradation. One header was cut off of the LCVG assembly and the epoxy header was sectioned to perform lower level material property tests. Samples were subjected to Thermogravimetric Analysis, Differential Scanning Calorimetry, and Fourier Transform Infrared Spectroscopy. These analyses indicated that the epoxy, similar to that used in the SWME headers, was relatively unchanged, with the exception that it has absorbed water during years of testing.

Samples from the LCVG simulator tubing were removed to evaluate the mechanical properties after being in service since 2019. (LCVG was initially wetted in fall of 2019, had a final flush on 2/21/20, and was installed on ISS as part of SERFE payload on ISS on 11/4/20). Pull tests were performed on SERFE LCVG simulator tubing and

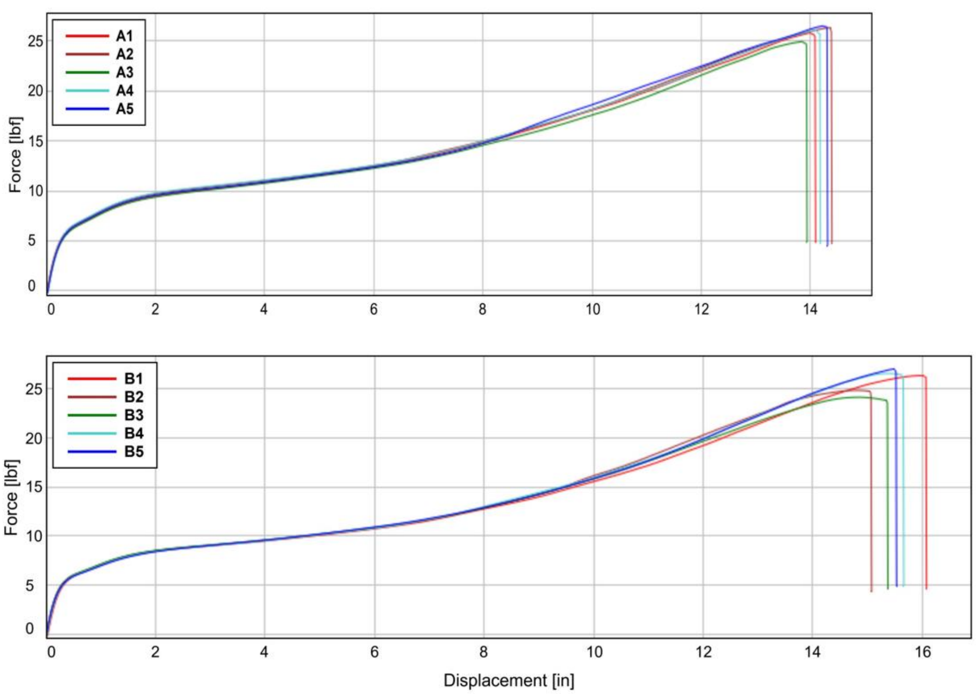

Figure 12. LCVG tubing mechanical testing results for a non-specific, untreated sample set (top) and a sample set from the SERFE Flight Unit following disassembly.

control samples of tubing that was part of the same lot but never wetted. The results of these tests are shown in Figure 12 and indicate that the prolonged wetted usage of the SERFE tubing increased the elasticity of the material slightly.

IV. Discussion

After 2 years of testing on the Flight Unit and 1.5 years on the Ground Unit, both SERFE experiments performed well overall through the final day of testing. These testing periods enveloped a total of 37 simulated EVAs on both units without any water maintenance. Both units also completed a long-term dwell of 210 days with successful operation following it. This satisfies the initial storage requirement of spacesuit technology at the start of a lunar mission. Some operational times for each unit are tallied by test series in Table 4, quantifying what was accomplished during these long testing periods. Both units evaporated close to 140 kg of water through the SWME, ran the pumps for 260-280 hours, and had the vacuum chamber depressed for 230-250 hours.

With the exception of apparent temperature sensor drift, none of the xPLSS technologies have demonstrated significant degradation in performance. Water quality is no longer consistent with current ISS-EMU standards, but this has not yet caused any issues with the SERFE hardware. In fact, SERFE appears to be demonstrating the robustness of the new xPLSS technologies that were developed to actually improve reliability and decrease sensitivity

Table 4. Summary tables of usage times and evaporative water losses for the SERFE Flight Unit (left) and Ground Unit (right).

Test Series	PMP-423 (hrs)	PMP-422 (hrs)	SWME Vacuum Time (hrs)	SWME Water Lost (kg)
Ground Series Total	59.7	18.8	66.1	44.7
Series 1	25.8	3.1	24.0	11.8
Series 2	25.9	2.5	26.3	14.0
Series 3	31.2	2.3	30.4	16.5
Series 4	30.1	2.2	29.5	15.7
Series 5	28.4	2.3	28.0	16.4
Series 6	31.2	2.3	29.1	17.1
TOTAL ALL	**232.3**	**33.4**	**233.3**	**136.1**

Test Series	PMP-423 (hrs)	PMP-422 (hrs)	SWME Vacuum Time (hrs)	SWME Water Lost (kg)
Ground Series Total	75.3	10.1	73.1	39.5
Series 1	27.0	2.3	26.1	12.9
Series 2	28.7	2.3	29.0	16.9
Series 3	30.0	2.0	30.0	16.0
Series 4	27.5	2.4	27.0	16.5
Series 5	28.6	2.0	28.9	15.6
Series 6	37.3	2.2	37.4	21.6
TOTAL ALL	**254.5**	**23.3**	**251.6**	**139.1**

to water quality issues.

There were some unexpected on-orbit events, but none produced significant impacts to the SERFE project objectives or brought to light concerns over the technologies under test.

V. Conclusion

The SERFE project has demonstrated key xPLSS technologies through long duration testing of the Flight (SN 1001) and Ground (SN 1002) units. Testing was very successful and showed good performance in the lab and in microgravity. Thermal loop technologies have also shown good performance without any water loop maintenance over a long duration test. The duration of testing, including the maximum length of a quiescent period exceeded the originally planned testing goals. Major objectives of the SERFE project were all successfully completed: evaluating SWME heat rejection and degassing capabilities over an extended duration and in microgravity; demonstrating materials interactions between thermal loop, ISS EMU quality feedwater, microbial activity, and biocide over an extended period of time with intermittent operation; and preliminary requirements verification of the xPLSS components in the thermal control loop.

At the completion of testing, the SERFE Ground Unit (SN 1002) had successfully completed 37 EVAs, 602 days of testing since the final flush, and extended dwell periods of 210 and 91 days. The SERFE Flight Unit (SN 1001) successfully completed 37 EVAs, 787 days of testing since the final flush, and extended dwell periods of 211, 150, 92, and 91 days. This performance was not only excellent with relation to the original SERFE project plan, but also showed excellent life and robustness as compared to the current ISS Extravehicular Mobility Unit (EMU) and made significant progress towards demonstrating the ability to meet challenging exploration requirements. As a point of reference, the ISS PLSS receives water loop maintenance at least every 90 days and is refurbished after 25 EVAs or 174 hours of operation. SERFE exceeded all of these values. NASA's prototype suit, the xEMU, has requirements for a demo mission of 25 EVAs and 100 hours of operation. Again, SERFE exceeded these values and was able to meet the longer 210-hour storage requirement for the beginning of lunar missions. The most challenging exploration requirements are based on a long term lunar presence with limited capability for hardware transport back and forth to Earth. These include 156 EVAs and 624 hours of operation. SERFE achieved approximately a third of these very challenging requirements during this testing phase. Due to the good performance of the technologies under test, additional testing could be performed in an attempt to demonstrate these very challenging life requirements with the Ground Unit.

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