SERFE PLSS Component Lessons Learned from ISS

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Agenda

- Introduction
- Final Testing Results
  - Thermal/Fluids Performance
  - Water Quality
- Flight Unit Post-Testing Operations
- Conclusion
- Acknowledgements
- References

SERFE Flight Unit installation on ISS.

Introduction

- **Our payload is evaluating a new cooling technology to keep astronauts cool in eXploration Extravehicular Mobility Unit (xEMU)**
  - Key component is Suit Water Membrane Evaporator (SWME)
  - SWME EXPRESS Rack Flight Experiment (SERFE) is the name of our payload
  - Additional technology demonstrations to help test new PLSS Thermal Control Loop (TCL):
    - Water pumps
    - Pump check valves
    - Pump bypass relief valves
    - Thermal Loop Controller
    - Thermal Control Valve
    - Pressure Transducers/Temperature Sensors
    - Titanium backplate
  - ➢ Show decreased sensitivity of TCL to water quality issues, reduced maintenance, increased life over EMU

#SuitUp Gallery | NASA

CWC-I

SERFE Flight Unit installed on ISS.[1]

Introduction

- **Analysis showed SWME maintained its heat rejection capability, as well as robustness of other TCL hardware**
- **Summarized final performance of SERFE Flight test article & findings of that tear-down, including:**
  - Materials analyses
  - Post-flight component performance
  - Lessons learned
- **Results should be compared to earlier SERFE papers & analyses (see References)[1,2,3]**

SERFE Flight Unit and Ground Unit at JSC.[1]

Introduction

- **Plan**
  - Over 1 year on ISS
  - 25 simulated EVAs
- **Start of testing**
  - Final flush with new water
- **Ground test phase**
  - Performance baseline
- **Flight operations**
  - 6 weeks of simulated EVAs
  - Water samples
  - Test Modes
  - Various dwell times
    - 90 day
    - 210 day

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

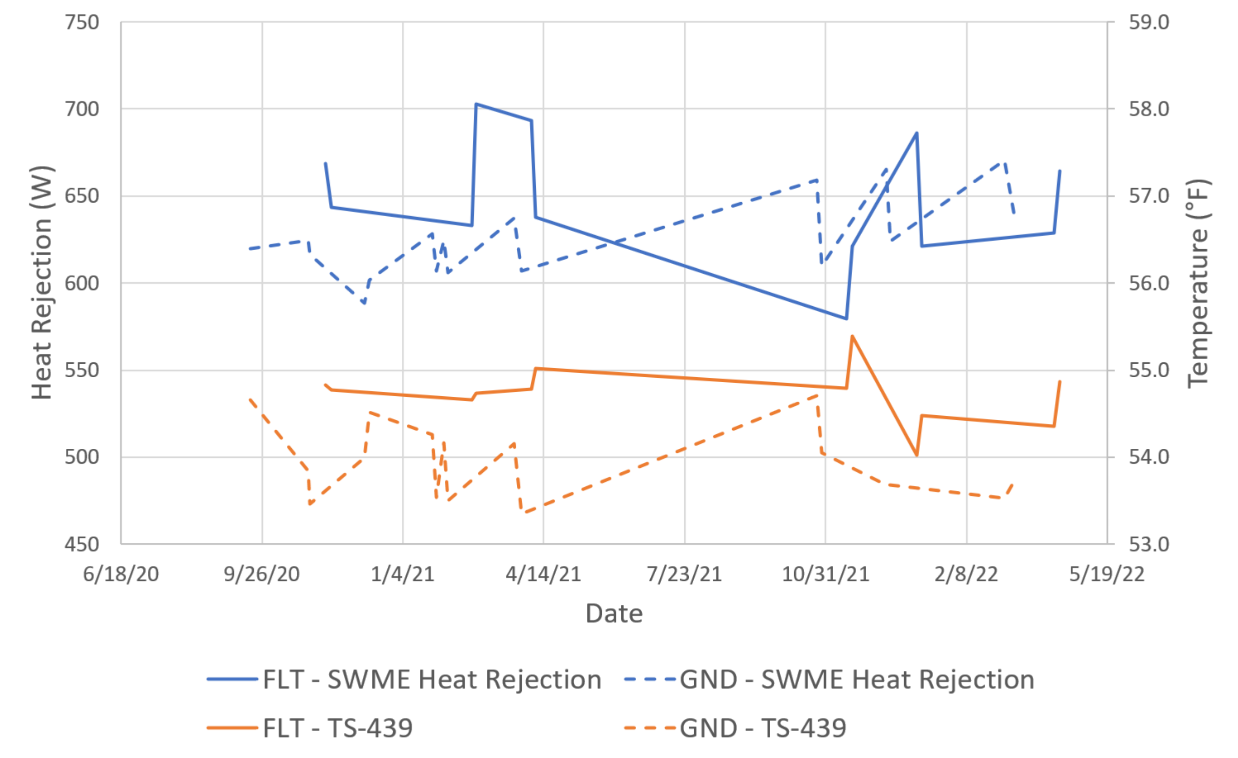
Note: Quiescent duration based on pump circulation, Which is typically the water sample taken before or after Each EVA series shown.

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

Testing schedule.

Final Testing Results

- **Thermal/Fluids Performance:**
  - Primary thermal performance measures:
    - Max capable SWME heat rejection
    - Temp of water exiting SWME (TS-439)
  - Max heat rejection capability was tested
    - Heat input of 600 W + ambient heat exchanges => maintained exit water temp near 50 °F
      - Heat rejection: 600-650 W
      - Outlet temp: 53-55 °F
  - No overall trend in heat rejection values
    - Heat rejection calculated from flow rate & temp difference across SWME
  - TS-439 did not change significantly over time
  - ➢ SWME/other SERFE technologies that contributed to heat rejection maintained performance over ~2 years of life & hundreds of hours of operation on both units

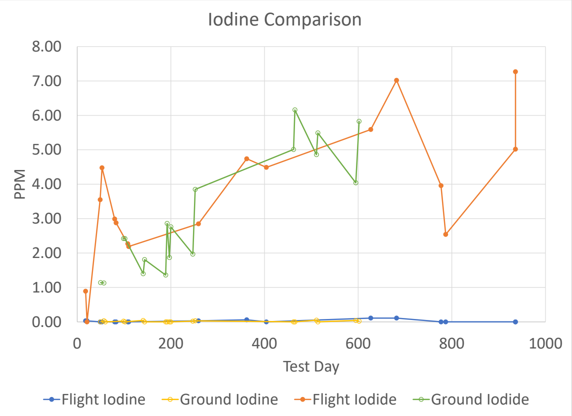


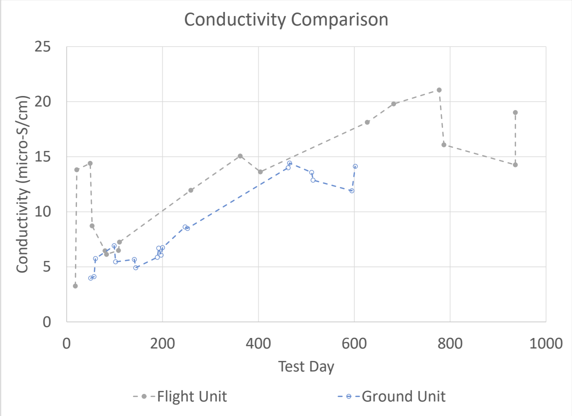
SWME Performance of Flight and Ground Units.

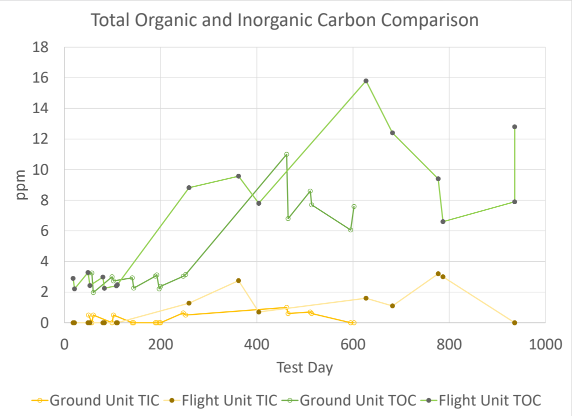
Notes: Heat rejection and TS-439 are averaged over last minute of 600-Watt heat input tests. Temperature sensor drift affected both units but accounted for in data analysis. Necessary offsets applied to telemetry.

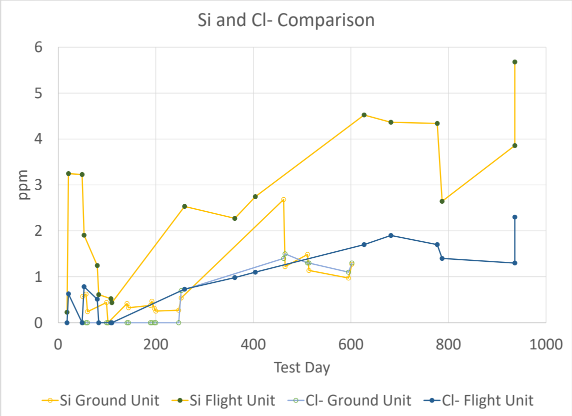
Final Testing Results

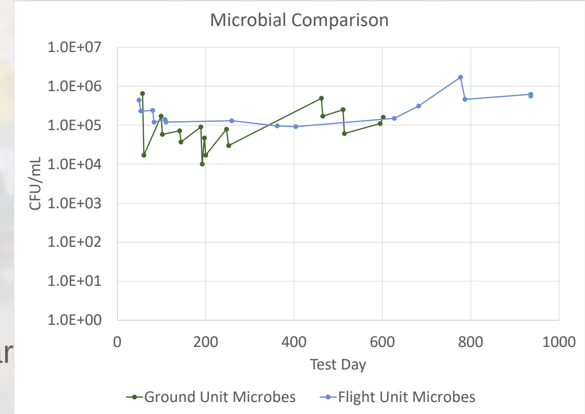
- **Water Quality:**
  - Tested for many contaminants & chemicals, including:
    - Iodine & iodide
    - Water conductivity
    - Total Organic & Inorganic Carbon (TOC/TIC)
    - Silicon & chloride
    - Microbial count
  - Water quality data shows water loops had significant buildup of contaminants, especially TOC & microbes
    - ➢ Relative to typical EMU water, SERFE water was dirty but life-support technologies (e.g., SWME) continued to perform well









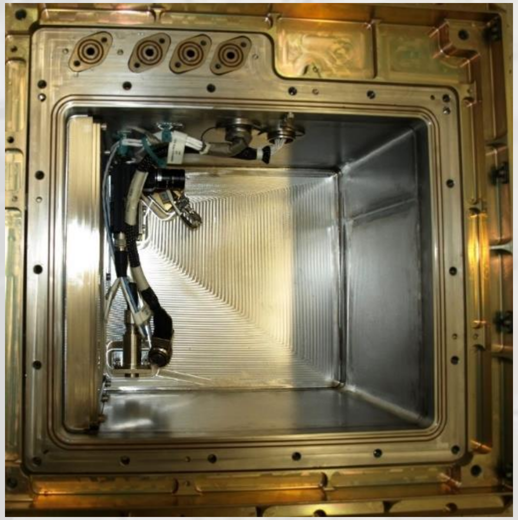


Various final water quality results of the SERFE Flight and Ground Units.

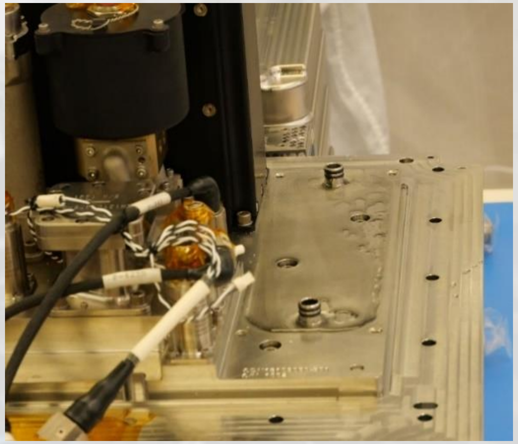
Note: Time axis in test days = # of days after final pre-test water flush

Flight Unit Post-Testing Operations

- **After SERFE Flight unit returned from ISS:**
  - Systematic disassembly procedure to observe hardware on M & P level
    - Payload locker => payload => side panels => lower level payload assemblies
    - Accessible water lines drained => sub-assemblies removed for closer inspection
  - Interior wetted surfaces were clean (ex. Vacuum chamber)
    - ➢ Lack of rust/buildup of contaminants on wetted components showed wetted surfaces processed/machined properly & materials were selected properly
  - Slight discoloration of few components but interior of the HX-440 housing was clean & clear of foreign materials/debris
    - Epoxy headers showed no signs of damage/deterioration
    - Exterior surfaces generally clean
  - After SWME removed from MiniPLSS backplate, a puddle of water was observed underneath SWME housing
    - ➢ Water continually evaporates across membranes during long periods of storage (commonly seen occurrence)



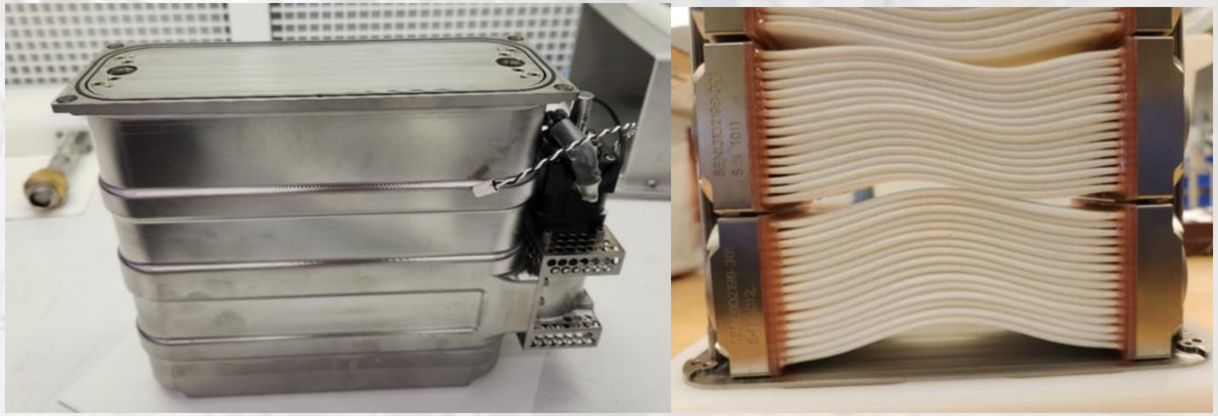
SERFE vacuum chamber interior.



Water puddle beneath HX-440.

Flight Unit Post-Testing Operations

- **SWME post-flight performance:**
  - Assessed cartridge leakage, capacity for heat rejection, & component pressure drop
  - Passed Leak testing on proof and leak test rig
    - MDP test: 35 psig
    - Proof pressure test: 1.5x MDP (52.5 psig)
    - Fiber portion of cartridges did not show leakage
    - ➢ SWME fiber cartridges retained robustness following long stay in microgravity & hundreds of hours of operation with flowing water
  - Passed Thermal testing using Leak Test Vacuum Chamber (LTVC)
    - Vacuum: 0.1 - 1.0 torr
    - Water flowing: 90 kg/hr
    - Heat input from heater in test stand increased to max setting where SWME outlet temp still maintained 50 °F
    - ➢ Heat rejection tests showed SWME cartridges did not degrade during life of SERFE Flight Unit



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

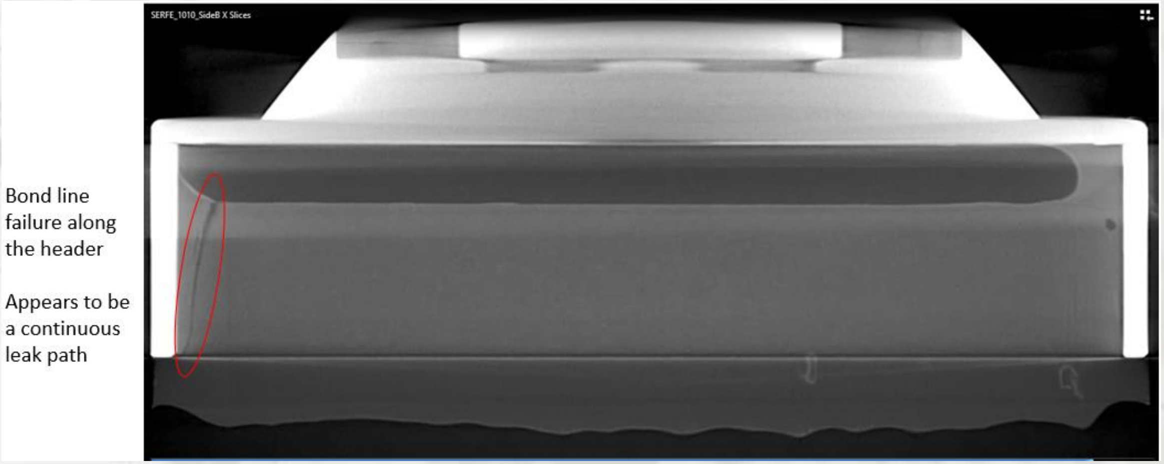
Heat rejection estimates of SWME cartridges before and after flight testing.

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%

Note: Average estimated heat rejection, based on temp drop from inlet to outlet is shown for each cartridge, the stack of three together, and full HX-440 assembly

Flight Unit Post-Testing Operations

- **Long term SWME storage:**
  - Two of the cartridges were dried & scanned using computerized tomography (CT)
  - Leaks inside epoxy headers where membrane tubes are bonded into bundle & then bundle is bonded into titanium end caps
    - Assembly process uses 2 different epoxy pours to create an epoxy to epoxy bond line
    - Several cracks or failures occurred at bond line
    - 2nd round of leak tests failed to even hold 3 psig & leaks at headers clearly visible
  - While wetted, the epoxy swells => when it is dried, it shrinks & cracks & bond line appears
    - ➢ Important risk to manufacturing processes & hardware storage plans for this type of membrane evaporator



SWME Cartridge Bond Line Failure

➢ SWME cartridges need to be kept wet to maintain their integrity
- SERFE Flight unit was wetted prior to flight during ground processing & launched to ISS wetted
- TCL loop always contained water on ISS
- After SWME cartridges returned from flight & dried they developed cracks in epoxy bond lines

Flight Unit Post-Testing Operations

- **Use of titanium in xEMU thermal control loop as primary wetted metal:**
  - Titanium: excellent strength/density/corrosion resistance properties but poses a challenge with machining titanium parts
  - Primary issue during fabrication/assembly: unexpected rust spots on parts using traditional cutting operations to 3-D printed titanium manifolds
    - Titanium doesn't rust => process control issues left iron deposits
      - Dull tool on mill or poor cleanup between runs on laser sintering machine?
  - ➢ Led to better control of manufacturing processes when xEMU thermal loop components were made

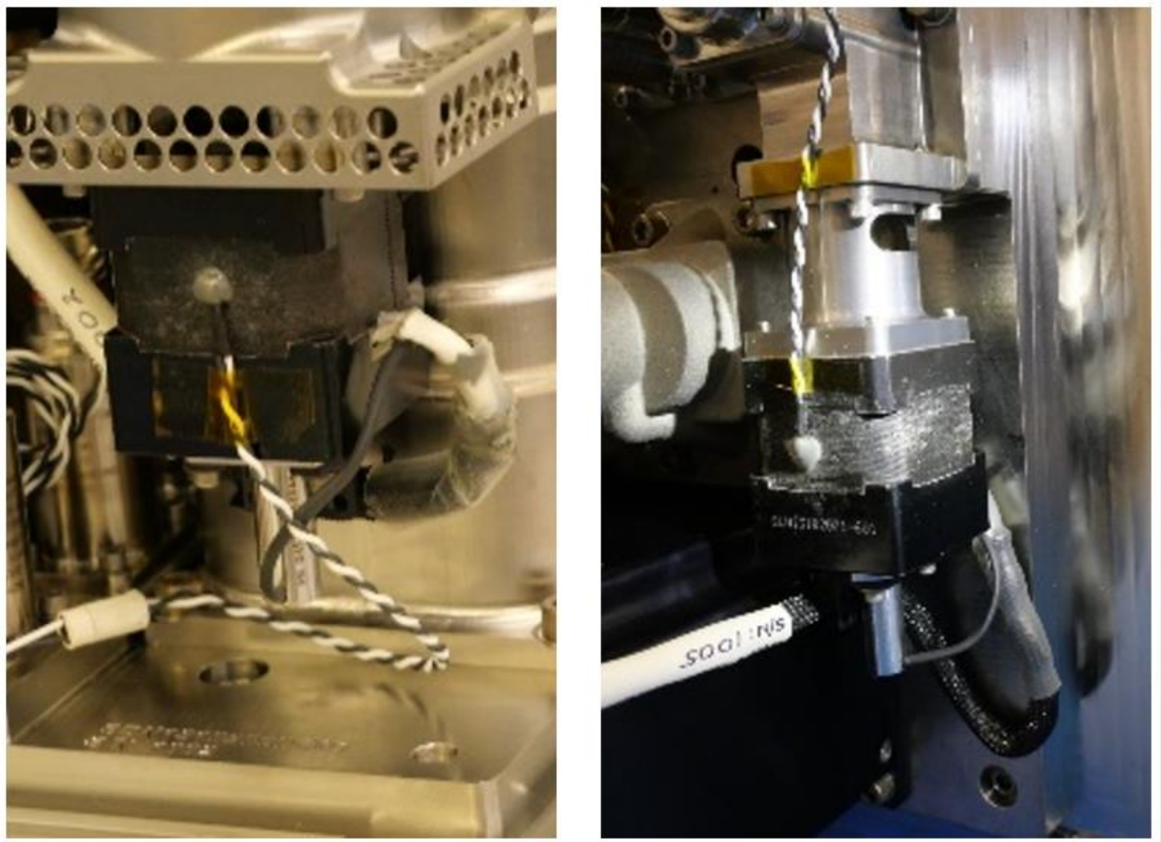
Various SERFE components following removal, including RV-424A/B (top-left), heater assembly (top-right), TCV-421 shuttle (middle), and F-2048 (bottom).

- Most of SERFE Flight unit titanium parts looked pristine during posttest inspections
  - Thermal control valve (TCV-421)
  - Relief Valves (RV-424A/B)
  - Heater (HTR-2060)
  - Filter (F-2048)
- ➢ Titanium as primary wetted metal in xEMU thermal control loop was a good choice once team learned to overcome machining challenges

Flight Unit Post-Testing Operations

- **Linear actuators (same as current xEMU PLSS hardware):**
  - SWME backpressure valve (BPV)
  - TCV-421

- SERFE Flight Unit in operation for over 2 years & never jammed due to cautious procedural controls
- SERFE TCV actuator tested for force output/evaluated for jamming: compared to linear actuators from xEMU with sticking history
  - Body rust observed on both SERFE actuators
    - Steel parts painted but exposed to humid environment inside of SERFE vacuum chamber
    - ➢ It is possible condensation formed on hardware after test points were completed



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

Flight Unit Post-Testing Operations

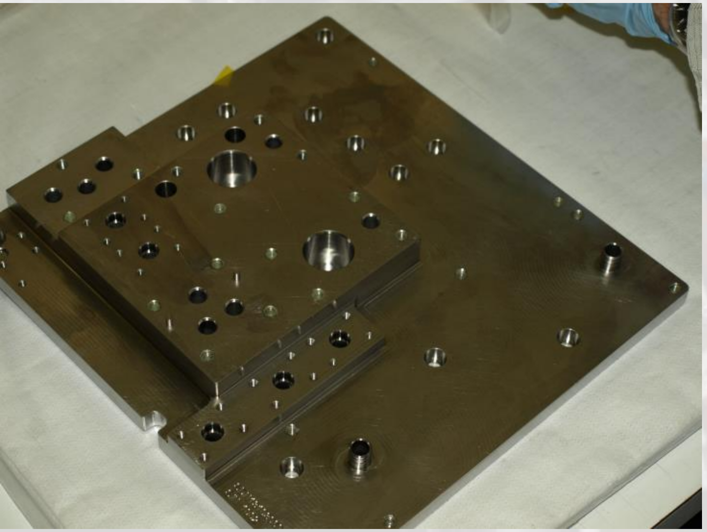
- **Primary Pump PMP-423:**
  - Pump inlet filter (423C)
  - Pump Check Valve (CKV-426) at pump outlet
  - Pump worked well on ISS
  - Disassembly: good condition
    - 423C: no FOD
    - CKV-426: looked good
  - Component level testing => no pump performance degradation occurred

Presumed rust spots on secondary pump manifold.

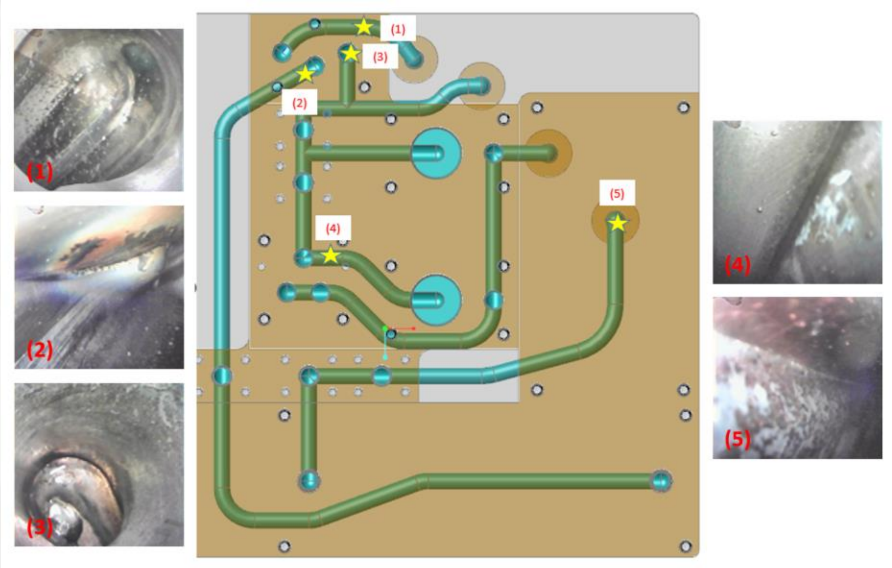
- **Secondary Pump PMP-422:**
  - Pump inlet filter (422C)
  - Pump check valve (CKV-427) at pump outlet
  - Pump worked well on ISS
  - Disassembly: rust spots on 3-D printed titanium manifolds/“tarnishing” of nitrided (gold colored) titanium pump body parts (M&P issues during assembly of pumps)
    - 422C: no FOD
    - CKV-427: looked good
  - No component level testing performed at this time

Flight Unit Post-Testing Operations

- **Backplate/fluid ports inspection:**
  - Borescope used for visual inspection
  - Sectioned backplate to inspect weld joints of fluid passages
    - "Areas of interest" cut to locate anomalies (surface finish/mineral deposits in inlet ports)/create samples for further sectioning
    - Residual markings from electron beam welding close out plates to make water channels, reactions between backplate and water, left over water droplets reflecting off light
  - ➢ M&P results/lessons learned from backplate
    - Reference 2023 ICES paper: "xPLSS Structural Backplate Design, Manufacture, and Test Overview."[4]

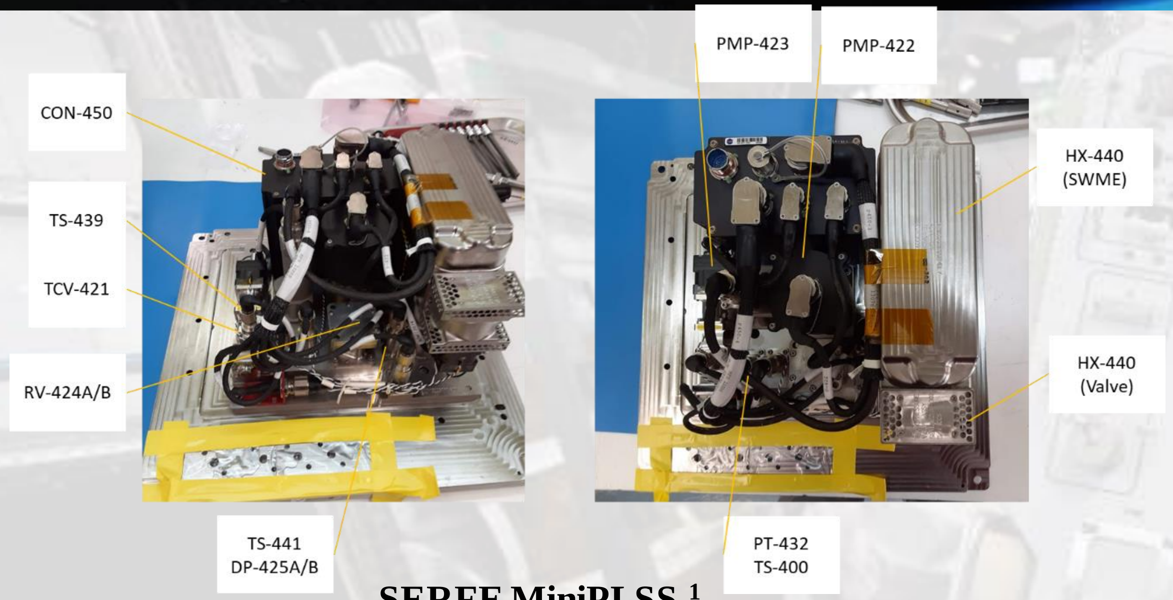


SERFE Backplate with Integrated Fluid Passages.[1]

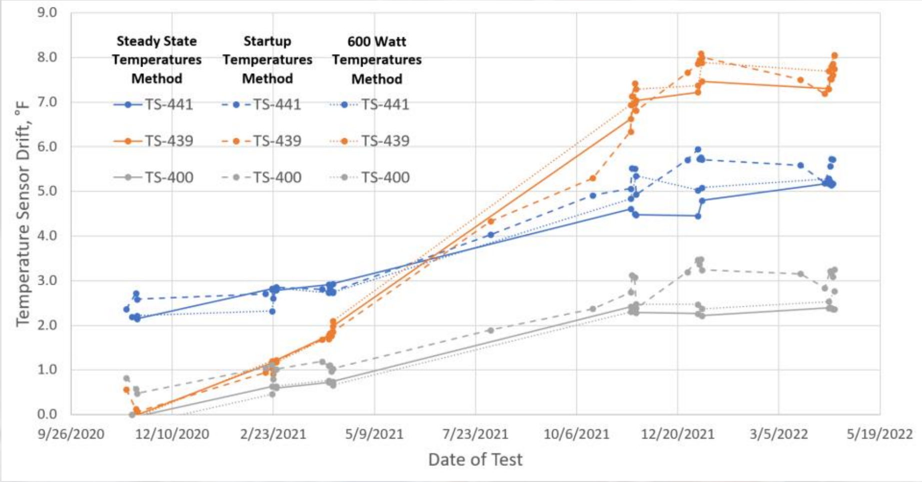


Areas of interest on backplate including the TCV LCG outlet (1), TCV inlet (2), TCV pump outlet (3), PMP-422 inlet (4), and HX-440 inlet (5).

Flight Unit Post-Testing Operations



SERFE MiniPLSS.[1]

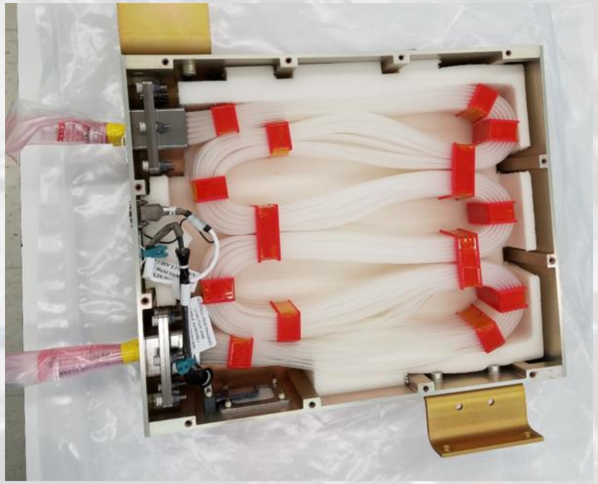


Estimated temperature sensor drift of three major sensors on the SERFE Flight Unit.

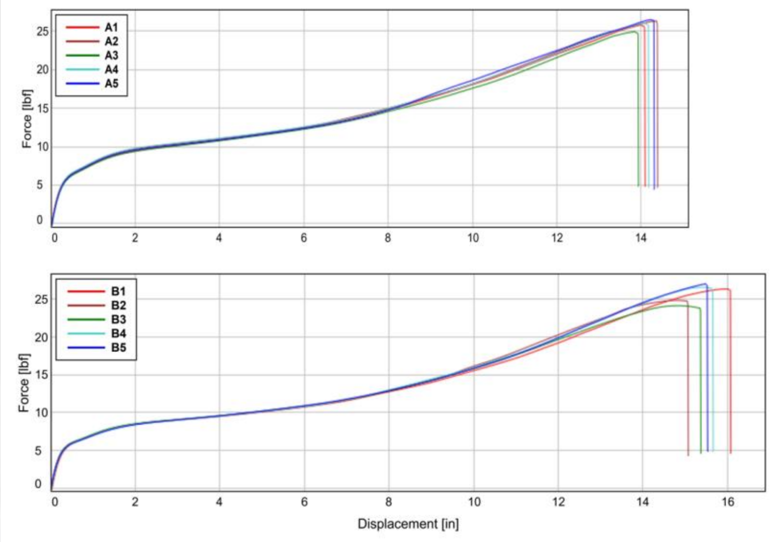
- **Temperature sensor drift during flight testing:**
  - Inlet SWME sensor (TS-441)
  - Outlet SWME sensor (TS-439)
  - Pump inlet sensor (TS-400)
  - 3 different methods to estimate sensor drift: see previous SERFE ICES paper[2]
  - Final test series of flight-ops showed that drift had not worsened since previous test series 3 months prior

➢ Troubleshooting tests to isolate cause of temp drift between temp sensors, harnessing, and CON-450 found that source of temp sensor drift is CON-450

Flight Unit Post-Testing Operations



SERFE LCVG Simulator.[1]



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

- **LCVG:**
  - Ethyl vinyl acetate tubes simulate wetted materials of LCG with titanium headers bonded to tubes using EA-9313 epoxy (same epoxy used in SWME headers)
    - No vacuum bake out
    - ➢ Epoxy was source of TOC and elevated readings after long quiescent periods
  - Inspections:
    - Disassembled titanium headers and performed visual inspections of epoxy and tubes => EA-9313 epoxy headers nor tubes had noticeable degradation
    - Epoxy (similar to SWME headers) was relatively unchanged => absorbed water during years of testing
    - Pull tests on LCVG sim tubing & control samples of tubing (same lot but never wetted) => prolonged wetted usage of SERFE tubing increased elasticity of material slightly

Conclusion

- **SERFE project demonstrated key xPLSS technologies through long duration testing of Flight & Ground units:**
  - Testing successful & showed good overall performance in lab/in microgravity
  - Thermal loop technologies showed good performance without any water loop maintenance over long duration test
- **Major objectives of SERFE project successfully completed:**
  - Evaluated SWME heat rejection & degassing capabilities over extended duration/in microgravity
  - Demoed materials interactions between TCL/ISS EMU quality feedwater/microbial activity/biocide over an extended period of time with intermittent ops
  - Completed prelim requirements verification of xPLSS components in TCL

- **Ground unit**
  - 37 EVAs, 602 days of testing/dwell since final flush, two extended dwell periods lasting 210 & 91 days
- **Flight Unit**
  - 37 EVAs, 787 days of testing/dwell since final flush, four extended dwell periods lasting 211, 150, 92, & 91 days
- **Showed robustness to current ISS EMU & progress towards ability to meet challenging exploration requirements**
  - ISS PLSS: water loop maintenance: 90 days & refurbished: 25 EVAs or 174 hours of ops => SERFE exceeded these values & met longer 210-day storage requirement for beginning of lunar missions
  - Challenging exploration requirements: long term lunar presence with limited capability for hardware transport back & forth to Earth: 156 EVAs & 624 hours of ops => SERFE achieved ~1/3
- **Additional testing could be performed on Ground Unit in the future (currently simulating 2 year dwell)**

Questions

- GTS!

- For more information on SERFE:
  - https://www.nasa.gov/suitup

SERFE Flight Unit installation on ISS.

Acknowledgements

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  - Ryan Ogilvie
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References

- [1]Westheimer, D., Campbell, C., Greene, B., Baker, A., Korona, F., and Everett, S., "SERFE Project Overview," International Conference on Environmental Systems, ICES, Saint Paul, MN, 2022.
- [2]Sladek, C., Baker, A., Waguespack, G., Campbell, C., and Westheimer, D, "SERFE Thermal Performance Results," International Conference on Environmental Systems, ICES, Saint Paul, MN, 2022.
- [3]Westheimer, D, Campbell, C., Baker, A., and Steele, J., "SERFE Water Quality Results," International Conference on Environmental Systems, ICES, Saint Paul, MN, 2022.
- [4]Hargrove, S., and Miller, S., "xPLSS Structural Backplate Design, Manufacture, and Test Overview," International Conference on Environmental Systems, ICES, Calgary, AB Canada, 2023.

Backup: Additional Ops Data

- **Years of testing:** Flight (2) & Ground (1.5)
- **EVAs:** 37 (each unit)
- **210 day dwell:** Met initial storage requirement of spacesuit technology at start of a lunar mission
- **Usage times/evaporative water losses:**
  - Water evaporated: 140 kg
  - Pumps ran: 260-280 hrs
  - Vacuum chamber: 230-250 hrs

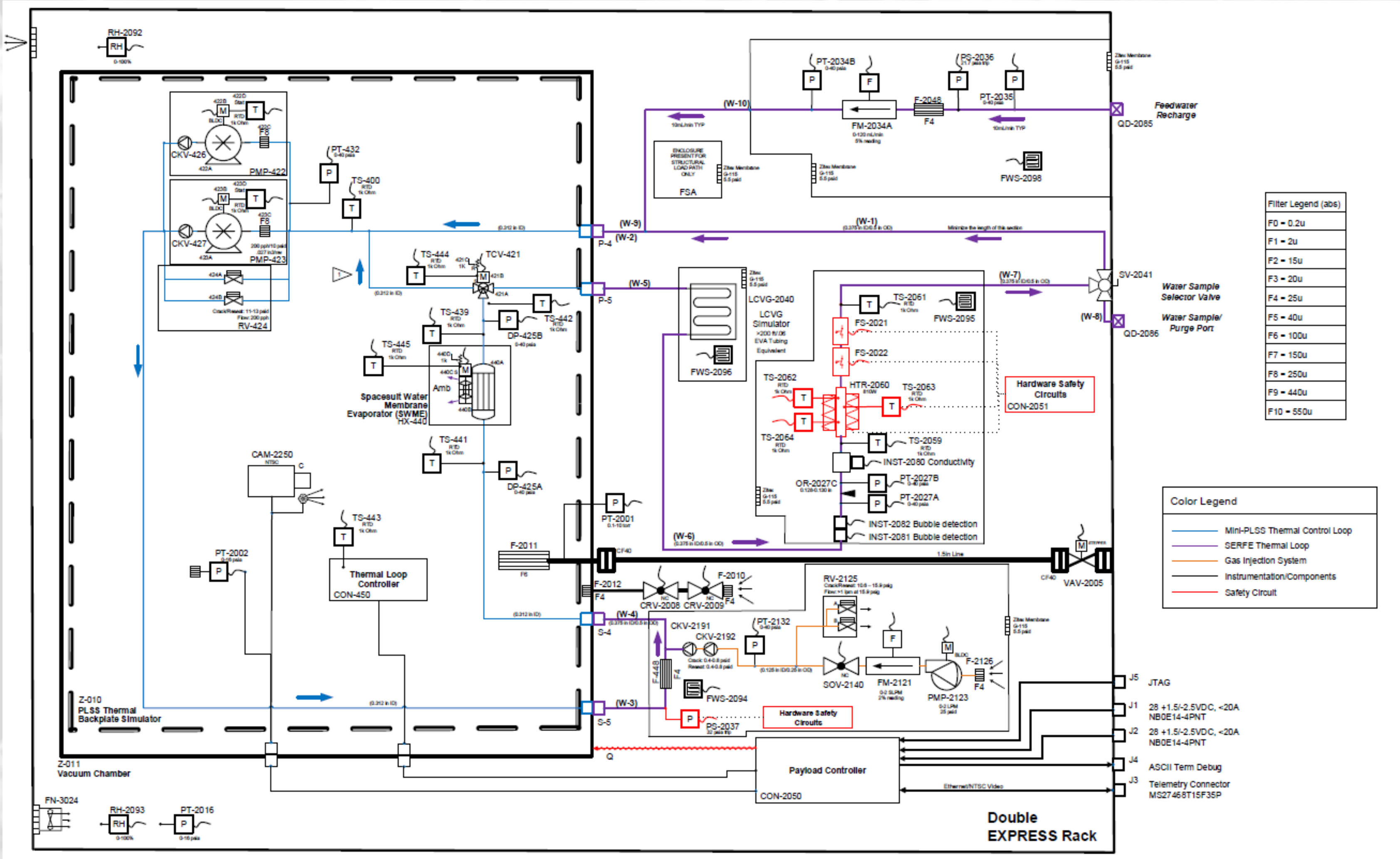
- **Besides temp sensor drift none of xPLSS technologies demonstrated significant degradation**
- **Water quality is not consistent with current ISS-EMU standards but no issues with SERFE hardware**
- **SERFE demonstrated robustness of new xPLSS technologies developed to improve reliability & decrease sensitivity**

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**

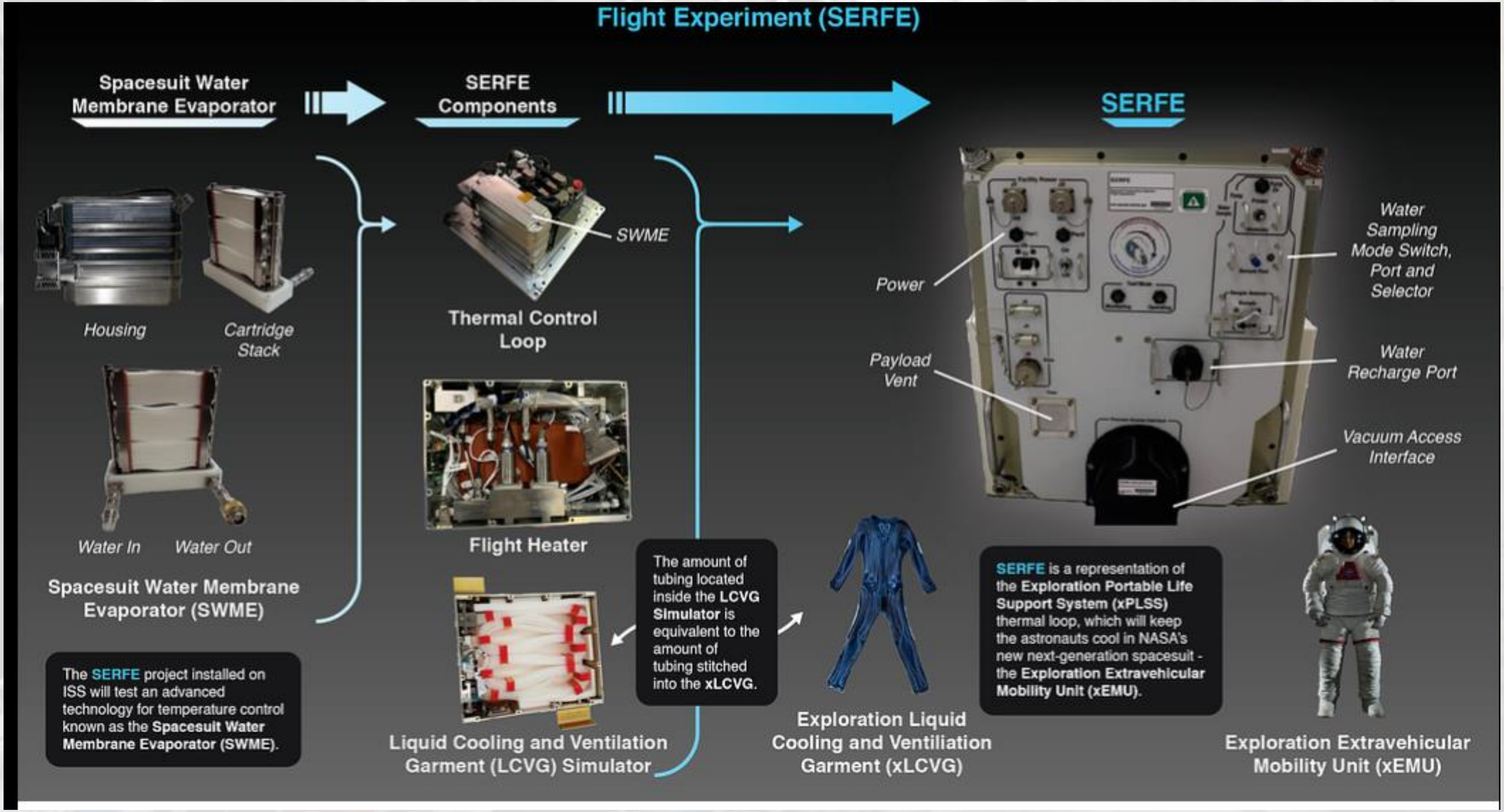
Summary tables of usage times and evaporative water losses for the SERFE Flight Unit (left) and Ground Unit (right).

Backup: Schematic



SERFE Fluid Schematic.[1]

Backup: Overview Graphic



Backup: SWME Overview