44th International Conference on Environmental Systems Paper Number 128
13-17 July 2014, Tucson, Arizona

Performance of Water Recirculation Loop Maintenance Components for the Advanced Spacesuit Water Membrane Evaporator

Tony Rector[1], Barbara M. Peyton[2], and John W. Steele[3]
UTC Aerospace Systems, Windsor Locks, CT 06095

Janice Makinen[4], Grant C. Bue[5], and Colin Campbell[6]
NASA Johnson Space Center, Houston, TX 77058

Water loop maintenance components to maintain the water quality of the Advanced Spacesuit Water Membrane Evaporation (SWME) water recirculation loop have undergone a comparative performance evaluation with a recirculating control loop which had no water quality maintenance. Results show that periodic water maintenance can improve performance of the SWME. The SWME is a heat rejection device under development at the NASA Johnson Space Center to perform thermal control for advanced spacesuits. One advantage of this technology is the potential for a significantly greater degree of tolerance to contamination when compared to the existing sublimator technology. The driver for the evaluation of water recirculation maintenance components was to enhance the robustness of the SWME through the leveraging of fluid loop management lessons learned from the International Space Station (ISS). A patented bed design that was developed for a United Technologies Aerospace System military application provided a low pressure drop means for water maintenance in the SWME recirculation loop. The bed design is coupled with high capacity ion exchange resins, organic adsorbents, and a cyclic methodology developed for the Extravehicular Mobility Unit (EMU) Transport Water loop. The maintenance cycle included the use of a biocide delivery component developed for the ISS to introduce a biocide in a microgravity compatible manner for the Internal Active Thermal Control System (IATCS). The leveraging of these water maintenance technologies to the SWME recirculation loop is a unique demonstration of applying the valuable lessons learned on the ISS to the next generation of manned spaceflight Environmental Control and Life Support System (ECLSS) hardware.

[1] Staff Engineer, Engineering Specialists, Hamilton Sundstrand Space Systems International, (HSSSI), A UTC Aerospace Systems Company, 1 Hamilton Road, M. S. 1A-2-W66, Windsor Locks, CT 06096-1010
[2] Staff Engineer, Engineering Specialists, Hamilton Sundstrand Space Systems International, (HSSSI), A UTC Aerospace Systems Company, 1 Hamilton Road, M. S. 1A-2-W66, Windsor Locks, CT 06096-1010
[3] Technical Fellow, Engineering Specialists, Hamilton Sundstrand Space Systems International, (HSSSI), A UTC Aerospace Systems Company, 1 Hamilton Road, M. S. 1A-2-W66, Windsor Locks, CT 06096-1010
[4] Aerospace Technologist, 2101 NASA Parkway, Houston, TX, 77058, Mail Stop EC6, nonmember
[5] Aerospace Technologist, 2101 NASA Parkway, Houston, TX, 77058, Mail Stop EC6, nonmember
[6] Aerospace Technologist, 2101 NASA Parkway, Houston, TX, 77058, Mail Stop EC5, nonmember

Key Words

Advanced Space Suit
Biocide
Ion Exchange bed
Recirculation Loop
SWME
Water

Nomenclature

ACTEX	=	Activated Carbon/Ion Exchange Unit
AEMU	=	Advanced Extravehicular Mobility Unit
ALCLR	=	Airlock Cooling Loop Recovery
DI	=	deionized
ECLSS	=	Environmental Control Life Support System
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
HoFi	=	Hollow Fiber(s)
IATCS	=	Internal Active Thermal Control System
ISS	=	International Space Station
MF	=	multifiltration
OGA	=	Oxygen Generation Assembly
ppm	=	parts per million
LCVG	=	Liquid Cooling and Ventilation Garment
OPA	=	Orthophthalaldehyde
NiRA	=	Nickel Removal Assembly
SWME	=	Spacesuit Water Membrane Evaporator
TOC	=	Total Organic Carbon
TCS	=	Thermal Control System
VRA	=	Volatile Removal Assembly
WPA	=	Water Processor Assembly
WRLMD	=	Water Recirculating Loop Maintenance Device

I. Introduction

NASA is currently developing an Advanced Extravehicular Mobility Unit (AEMU) under the Advanced Exploration Systems Program. A key part of this is the spacesuit portable life support subsystem (PLSS) technology unit that is human-rated for long-duration microgravity or planetary missions, and vacuum or low-pressure environments. A critical component of extravehicular activity (EVA) suits is the thermal control system (TCS), which rejects heat from the crew member and electrical components in the PLSS. The current PLSS uses a sublimator for heat rejection. While the current PLSS sublimator can effectively cool the crew member and electronics, it has a number of limitations, including sensitivity to contaminants, and the need for 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 that are above the triple point of water, such as the atmospheric conditions of Mars. The operational goal for the AEMU is for 100 EVAs at 8 hours each amounting to 800 hours of TCS use. The useful life of the AEMU PLSS is set at 10 years without refurbishment.

To meet these challenging requirements, the spacesuit water membrane evaporator (SWME) was developed for the AEMU. The SWME cools circulating water (which acts as the coolant in the system) through in-line evaporation. The water is then circulated through the liquid cooling garment and also to PLSS components via a heat exchanging cold plate. The SWME takes advantage of recent advances in micropore membrane technology to provide robust heat rejection with a high tolerance to contamination. The SWME design has roughly 14,900 hollow fibers (HoFi) that provide approximately 0.6 m^2 of open pore area. These HoFi contribute to the SWME's resistance to coolant loop contaminants that will accumulate over the planned 800-hr operational life. The HoFi are thin-walled, porous tubes made from polypropylene that are approximately 300 µm in diameter. The HoFi geometry allows a high-membrane surface area to be contained in a compact module resulting in a heat rejection device that is durable and reliable.

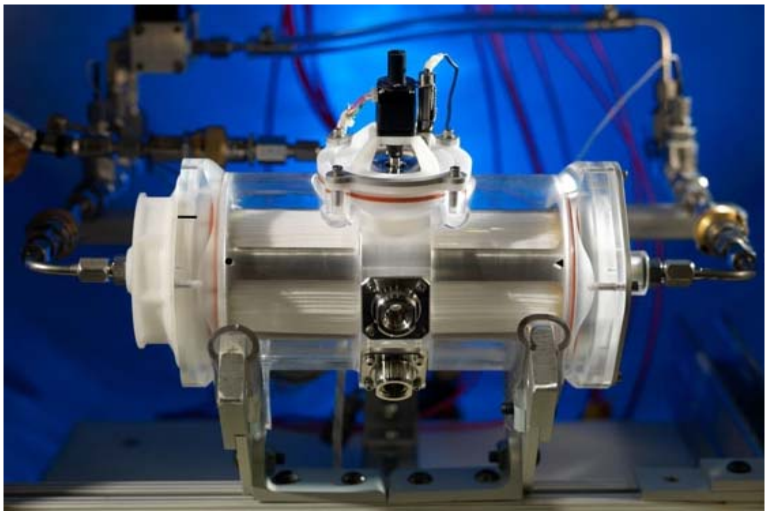


Figure 1. Gen2 SWME

Several sheet and HoFi membrane SWME prototypes, have been designed and tested at NASA Johnson Space Center (JSC).[1-3] In 2010, a new HoFi SWME prototype, called Gen2, based on earlier designs was created. This Gen2 SWME is predominantly plastic and has a flight-like valve built into the housing (see Fig. 1).[4] Long duration testing was also performed, namely 200 hours of stand-alone SWME testing followed by 400 hours with the same test article in the PLSS 1.0 breadboard testing. The long duration tests differed from previous testing in that no attempt was made to conservatively project water constituents over the course of 100 EVAs. The circulating coolant was instead allowed to accumulate contaminants over the duration of testing in a flight-like manner, with evaporated coolant being replaced with baseline water similar to that currently available on ISS. These tests included variable metabolic testing to simulate actual EVA use, more severe bubble tests and freeze tests, and mars atmosphere simulation testing.[4,5]

The baseline SWME feedwater for these tests is shown in Table 1. The constituent concentrations were generated with margins based on the capabilities of the ISS Water Processor Assembly (WPA). The feedwater represents, with some margin, the contaminants reasonably expected to be delivered by the spacecraft WPA to the PLSS.

Table 1. SWME Feedwater

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

The long duration performance testing of the SWME yielded variable performance over 600 hours. [5] In the stand-alone testing, performance was variable but trended upward to > 800 W of cooling at 200 hours of testing. Microbial assay of the circulating water loop showed a decrease in colony forming units consistent with biofilm formation. A month later with the onset of the PLSS 1.0 testing, SWME performance declined approaching 700 W.

Wetted surfaces of fittings in the loop had coatings consistent with biofilm. At the same time an increase in reddish-brown deposits were observed, coincident with pressure drop increases across the SWME and filters. Analyses of these deposits were consistent with corrosion products of non-passivated stainless steel and brazed components, both of which were present in the PLSS 1.0 coolant loop. Although bubble testing midway in the stand-alone SWME tests showed strong bubble clearing capability, subsequent tests later in the long duration testing showed that this capability had been completely lost. At the end of the PLSS 1.0 testing, droplets of coolant were observed on the exterior of the SWME fibers suggesting some loss of the hydrophobicity of the membranes.

These findings have underscored the need for careful control of materials in coolant loop designs for long duration testing and PLSS 2.0. Wetted metallic surfaces of the circulating loop will be made of passivated 316L stainless steel. Plastic tubing will be screened to avoid contamination from leachants. The need for consistent biocide control is also necessary because the baseline water supply from the WPA will contain organic material that will concentrate from evaporation and coolant resupply of the normal SWME operation. Silver and iodine are currently being used for biofilm control in current spacesuit programs but are not recommended for long duration operation because they tend to be eliminated by exposure to metals and organic polymers, both of which are present in the AEMU coolant loop design. The PLSS 2.0 program seeks to investigate the efficacy of ortho-phthalaldehyde (OPA) biocide to provide stable biofilm control and show to be successful for the water loop of the ECLSS system on the ISS. This would be coupled with periodic cleaning of the circulating loop with anion/cation exchange resin and activated carbon beds, followed by recharging the loop with OPA, a system called the Water Recirculating Loop Maintenance Device (WRLMD).

Testing is in progress to evaluate the long duration performance of two SWME systems in parallel coolant loops, one with proper material control only and the other with both material control, biofilm and water quality control as described above. This testing will inform the design and maintenance requirements for the vehicle systems that service the AEMU.

II. Water Recirculating Loop Maintenance Device (WRLMD).

BACKGROUND

The primary purpose of the SWME water loop maintenance activity is to remove dissolved inorganic ions which can cause detrimental impacts to the SWME or associated components in the recirculation loop. These inorganics are introduced by the influent water source, corrosion of metallic components in the water loop and possible other water streams that communicate with the SWME. Mixed ion exchange resins can be used to mitigate the inorganic contamination. These resins have the ability to remove charged species (anion and cation) from solution by exchanging H^+ and OH^- groups, which also allows the pH to remain near neutral. An additional concern is the proliferation of microbiological growth in the recirculation loop. To minimize this issue, a biocide may be added which will inhibit or control the growth of microorganisms. These activities, ion exchange and biocide introduction, are currently used in the ALCLR setup with the EMUs aboard space station to maintain the recirculation water loops.

An ion exchange bed, biocide delivery bed and biocide removal bed were developed for the SWME to aide in maintaining the water quality. The ion exchange bed developed is a patented low pressure drop bed, which uses a segmented geometry to reduce the associated pressure drop. The biocide addition bed uses an organic biocide ortho-phthalaldehyde (OPA), which was developed for the coolant loops aboard ISS. Additionally, an activated carbon bed was also developed to remove residual biocide, associated reaction products of the biocide and other organics present in the water loop. These beds when used at prescribed intervals are intended to maintain the water quality of the SWME loop.

Low DP Ion Exchange bed

A proof of concept low DP ion exchange bed was developed for use in the SWME test system at JSC. The ion exchange bed was constructed primarily out of polycarbonate, with the only exceptions being the stainless steel cassette screens (304SS) and the polymer resin bags (PEEK). The bed has a diameter of 7 cm (2.75 in) and an overall length of 25.4cm (10 in). Inside the bed are four individual cassettes of two different sizes, one pair is 6.4 cm (2.5 in) in height and the other pair is 3.81 cm (1.5 in) in height, with both having sets with overall lengths of 19 cm (7.5 in). A photo of the SWME ion exchange bed and a similar prototype bed is displayed in Figure 2. The cassettes are held in place inside the cylindrical housing using cassette retainers made from perforated polycarbonate sheet. These retainers allow for flow distribution at the inlet of the bed. The ion exchange resin is contained in PEEK mesh bags that have an approximate mesh size of 60**,** corresponding to an open area of 56%. The mesh bags were packed with approximately 100 cm^3 of total ion exchange resin and are stitched closed. The bags were then placed in the polycarbonate cassette frames and secured with the outside 304SS cassette screens. The overall volume of the SWME ion exchange bed was 450 cm^3 (27.5 in^3) and the bed was proofed to a pressure of 275 kPa (40 psig).

Biocide introduction

Due to the proliferation and growth of microorganisms in the Internal Active Thermal Control System (IATCS) aboard the International Space Station (ISS), a biocide delivery resin was developed. The resin was developed using the biocide ortho-phthalaldehyde (OPA), which was immobilized on a methyl-methacrylate based resin material. This immobilized resin was then packed in an existing canister and when placed in the IATCS flow loop would elute into the fluid stream to a desired concentration. Typical elution profiles for the IATCS call for elution of 100 mg-OPA/L into the IATCS, however levels of up to 300 mg-OPA/L are also used in various loops of the IATCS aboard the ISS to keep microbiological populations in check. The concentration of OPA eluted from the resin material is directly related to the volume of the coolant loop being treated and the amount of OPA delivery resin packed into a canister. This elution relationship has been extensively tested and proven consistent for all applications of the OPA biocide. While the OPA biocide was developed for IACTS use, its safe and efficient elution ability makes it a potential candidate for other fluid streams requiring periodic maintenance to control microorganisms.

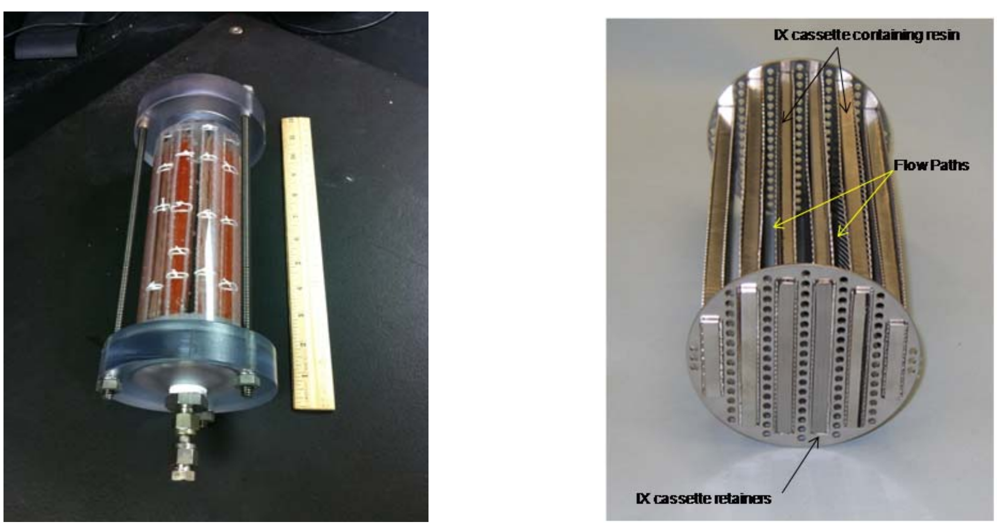


Figure 2. (A) SWME ion exchange bed (B) Initial low DP ion exchange bed prototype.

Targeted duty cycle

The duty cycle selected for the current SWME test thus far has been intermittent and based on a review of the chemical and microbial analyses. The plan is to empirically set a duty cycle based on continuing test results.

III. Test Set-up

The test bed for the WRLMD has been built in the Leak Test Vacuum Chamber (LTVC) at JSC in the Space Suit Systems Laboratory. The LTVC has two identical, parallel, independent, closed coolant loops--each with a pump, a heat exchanger with chiller cart, a water reservoir, main and trim heaters and various instruments. All wetted components in the test loops have been cleaned and passivated. The only mechanical difference between Loop A and B is the addition of quick disconnect ports in Loop B, which facilitate the usage of the WRLMD. The heat exchangers and chiller carts on each loop provide coolant fluid flow and heat load to quickly condition loop at the beginning and end of each test. The main and trim heaters are used to add a heat load to the test loops.

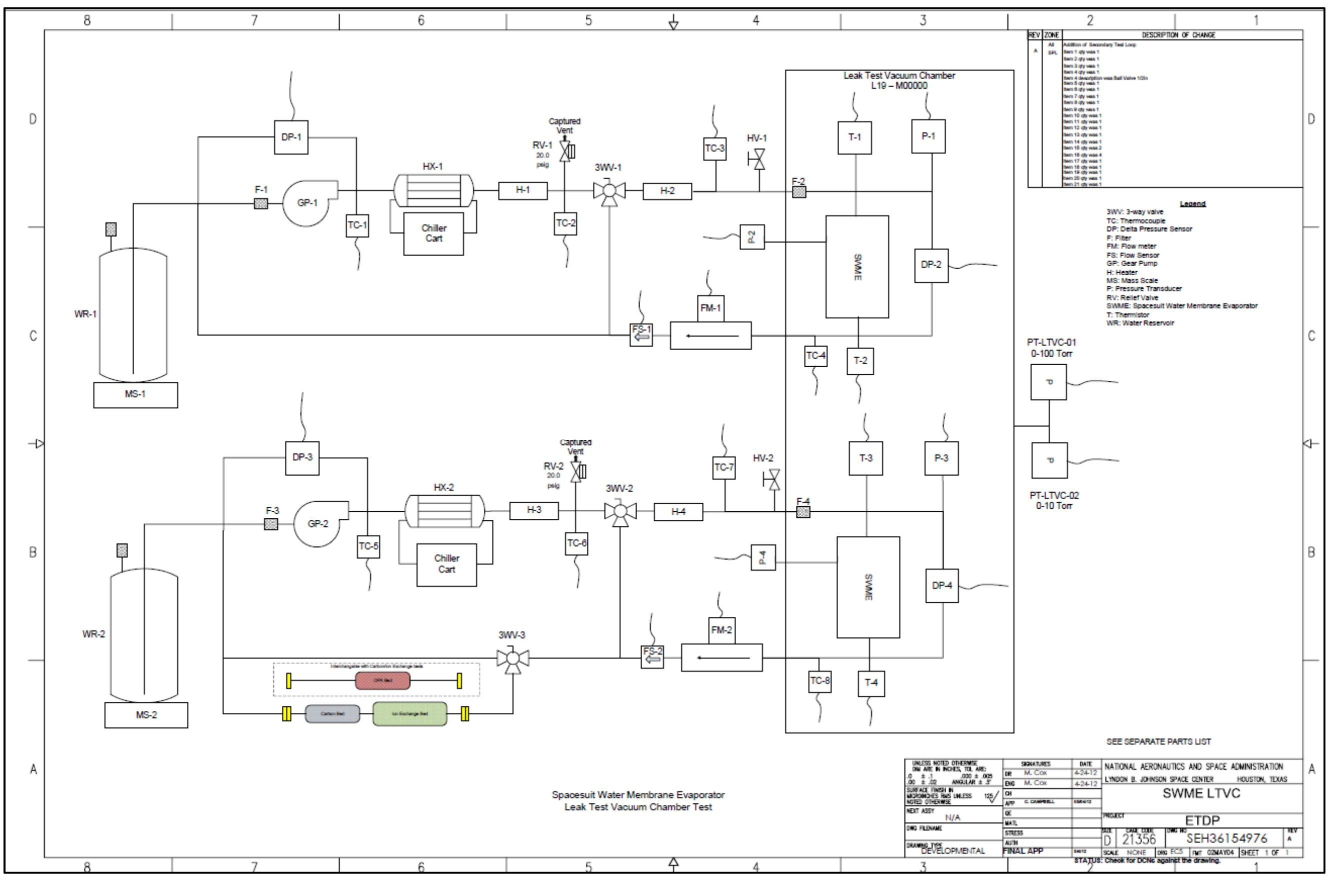


Figure 3. Schematic of Leak Test Vacuum Chamber Circulating Loops: Loop A is above Loop B.

Figure 3 is a schematic of the test loop illustrating the SWME test articles, other major components and instrumentation. The SWME water inlet temperatures on each loop will be maintained by the main 1000W immersion heater and a 50W trim heater. Makeup water is continuously supplied as needed from the reservoir feedwater tanks as feedwater is evaporated.

Each of the water reservoirs is weighed continuously during test to calculate total water evaporation due to heat rejection. The water flow rate is controlled by adjusting the pump motor speed controller and monitored by micro-motion Coriolis flow-meters. SWME heat rejection rates are controlled by the backpressure valve, which, when adjusted, will change the SWME vapor side pressure, also referred to as backpressure. Backpressures can range from water saturation pressure corresponding to inlet temperatures (when the valve is closed), to values less than the water triple point pressure (when the valve is fully opened). SWME A and SWME B are equipped with thermistor temperature sensors to accurately measure the inlet and outlet water temperatures, which are used to calculate real-time heat rejection rates. The SWMEs are also equipped with pressure transducers to accurately measure the delta pressure of the test article inlet and outlet. A rack mounted computer-based data acquisition (DAQ) system is used to monitor and to record both facility and evaporator parameters shown in Table 2.

Table 2. Critical Test Parameters

PARAMETER	RANGE	Accuracy	UNITS
Backpressure	0 – 100	0.05%	Torr
Chamber Temperature	-250 – 350	0.5	°C
Make-up Water Weight	0 – 200	0.01% FS	kg
Chamber Pressure	0-1000	0.19%	Torr
Water Flow Rate	50 – 113	0.5%	kg/hr
Test Article Inlet Temperature	0 – 100	0.01	°C
Test Article Outlet Temperature	0 – 100	0.01	°C
Test Article Inlet Pressure	0 – 25	10%	psia
Test Article Delta Pressure	0 – 5	10%	psid
Pump Delta Pressure	0-15	10%	psid

One of the circulation loops, the test loop (also referred to as Loop B), is serviced by the WRLMD, while the other, the control loop (also referred to as Loop A), is not. Aside from the WRLMD service, the test and control loops are run simultaneously and as close to identical as possible. Both loops are run with 91 kg/hr with a 10 °C outlet temperature, with a heat rejection rate of approximately 293W. Circulating water is tested on a weekly basis to determine OPA concentration and water analysis. The results of the weekly water analysis determine when the servicing by the WRLMD is conducted.

IV. Results

Two parallel SWME test set-ups are under evaluation in this comparative study. Loop A is fed influent water per Table 1 and does not undergo a periodic scrub of the water recirculation loop, nor is biocide added to it.

Loop B is also fed water per Table 1 and periodically undergoes a maintenance cycle which includes ion exchange/organic adsorbent scrubbing followed by the addition of OPA biocide. To-date, three ionic exchange/organic adsorbent cycles have been conducted on Loop B.

The chemical composition of the water was tracked with the following parameters: standard anions (fluoride, chloride, nitrite, sulfate, nitrate & phosphate), standard cations (lithium, sodium, ammonium, potassium, magnesium & calcium), possible metals (aluminum, chromium, copper, iron, manganese, nickel, silicon & zinc), total organic carbon, pH, conductivity and OPA. Figure 4 represents conductivity as a function of time to provide the reader with a general sense for the inorganic contaminant load of the two loops. A full report of all of the parameters is available through the authors.

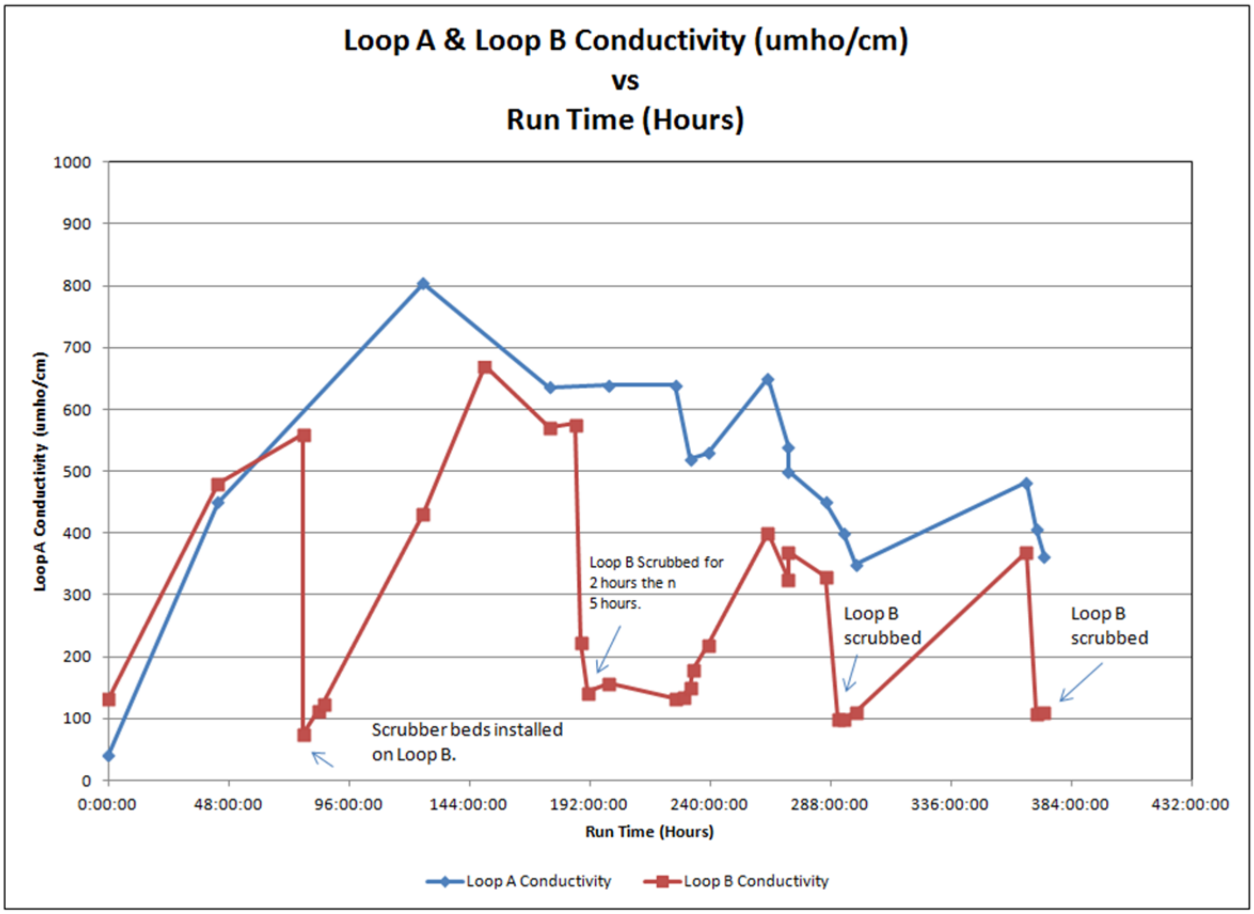


Figure 4: Conductivity vs. Run Time for Loops A & B

OPA Biocide Treatment Data

Several difficulties were experienced with the addition of the OPA biocide to Loop B. First and foremost, the packed bed charged with OPA impregnated sorbent experienced a significantly higher than anticipated pressure drop when an attempt was made to use it as a flow-through OPA addition method (similar to the approach currently used for the ISS IATCS coolant loop). An examination of the bed packing materials is underway to ascertain the cause. Continued additions of OPA in this testing were by manual addition to the SWME feed-water supply.

An additional challenge with respect to the use of OPA as a biocide for the SWME recirculation loop was a repeated reduction in concentration to well below the target 100-ppm concentration used in the ISS IATCS coolant loop. To determine where the loss of OPA was occurring in the loop, two tests were conducted. The first was to expose a 100 ppm OPA solution to a static soak with the hollow fiber membranes from the SWME. During this test, SWME membranes with a surface area of 580 cm^2 were soaked in an OPA solution for approximately one week. Samples were taken at the beginning and end of the week. The results showed that no loss of OPA was observed during the soak test, effectively eliminating the possibility of the SWME fibers up taking the OPA. The second test involved the SWME Test Loop B. During this test, the valve was closed on the SWME, prohibiting any evaporation from the membrane module. Water was circulated for a week through the loop and samples were obtained at the start and end of the test. Results showed minimal loss of OPA over the testing period. This test concluded that the loss of OPA was directly related to the evaporation of water from the SWME membrane.

Figure 5 tracks the OPA concentration as a function of time in Loop B. Table 3 presents the microbiological findings of the two loops.

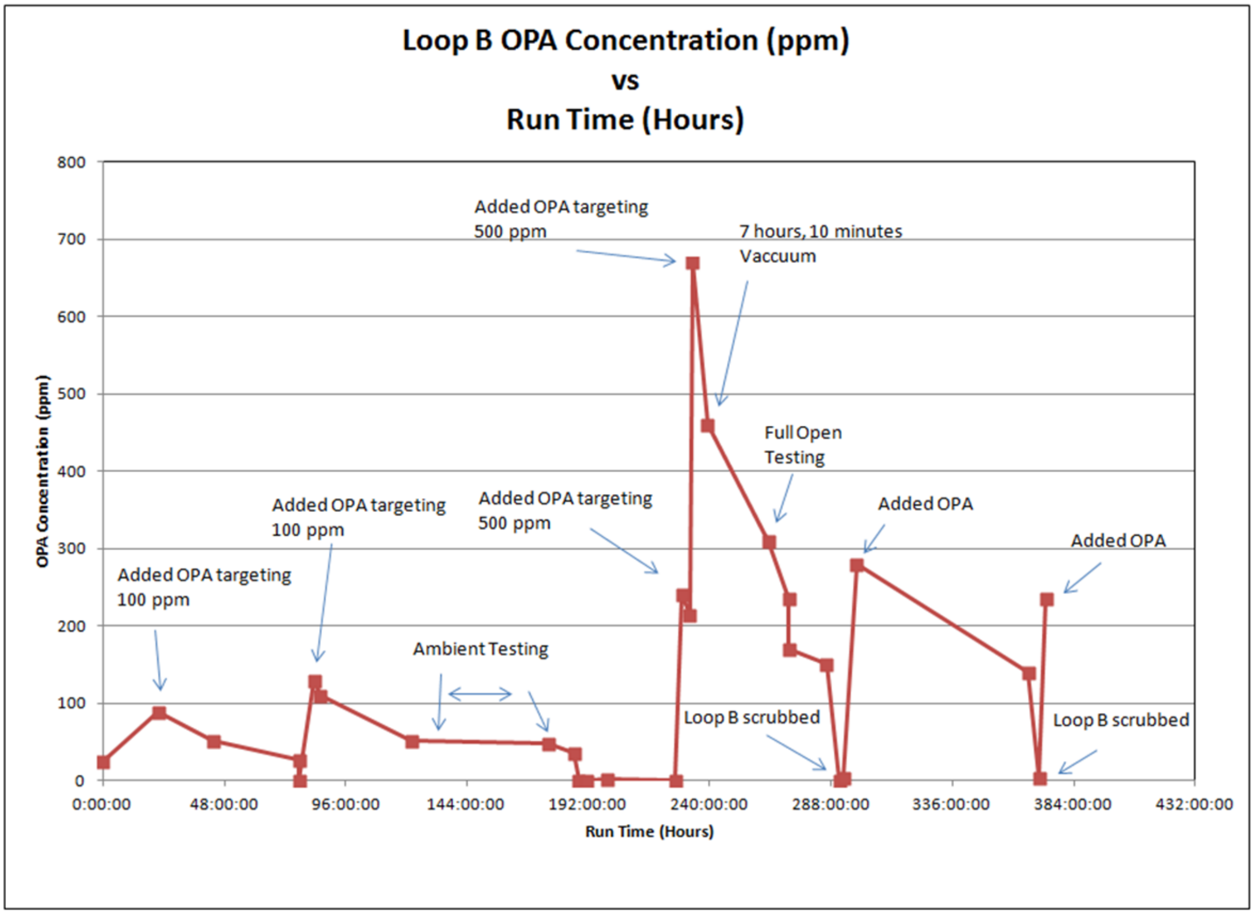


Figure 5: OPA Concentration vs. Run Time for Loop B

Table 3. Microbiological Data for Loop A and Loop B

		Test Stand B (7/24/13)	Test Stand A (7/24/13)	Test Stand B (6/17/13)	Test Stand A (6/17/13)	Loop B (5/14/13)	Loop A (5/14/13)	Loop A 4/22/2013	Loop B 4/22/2013	Loop B Post OPA Delivery (3/6/13)	Loop A (3/6/13)	SWME Water #1 Before Filling Test Rig (1/15/2013)	Loop A Pre-OPA SWME Water (1/25/2013)	Loop B Pre-OPA SWME Water (1/25/2013)
Bacteria (CFU/mL)		<1	3.00E+02	100E+03	1	100E+05	2.20E+03	2.80E+02	1.00E+01	2.80E+05	2.10E+04	4.0E+02	18E+04	2.7E+04
Species Identified			R. pickettii	B. multivorans	N. capsulatum	B. multivorans	R. pickettii	B. multivorans, R. pickettii & Sphingomonas species	B. multivorans	B. multivorans	R. pickettii	R. pickettii, B. multivorans	N. capsulatum, R. pickettii	N. capsulatum, R. pickettii
Fungi (CFU/100 mL)		<1	<1	<1	<1	<1	<1			<1	<1	<1	3	1
Species Identified													Candida Species	Candida Species

Filter Analysis Data

Four filters were received from the two SWME loops after roughly 300-hours of testing as follows:

- Two filters from Loop A (no water maintenance). One 40-micron filter that was located before the pump and one 140-micron filter that was located before the SWME

- Two filters from Loop B (periodic water maintenance). One 40-micron filter that was located before the pump and one 140-micron filter that was located before the SWME

The filters represent the contaminants that have deposited on all wetted surfaces within the non-volatile concentrating section of the test apparatus, including the SWME membrane material itself. It should be noted that deposited residue such as this is generally the direct cause of performance related issues in water systems.

The testing that was conducted on the filters was as follows:

- Weight of deposits on each filter (weight change pre and post filter cleaning)

- Pictures of the filters prior to cleaning

- Elemental analysis of filter deposits via SEM/EDS

Weight of Deposits on Filters

The four filters were dried at 140 F^{o} in a vacuum overnight and were weighed. The four filters were then chemically cleaned with a caustic cleaner, dried, then reweighed. The results are shown in Table 4.

Table 4: Weight of Deposits on Filters

Loop	Filter Rating (microns)	Water Loop Treatment	Deposit Weight (mg)
A	40 (pre-pump)	None	20.52
A	140 (pre-SWME)	None	404.64
B	40 (pre-pump)	Period IX Bed Scrub and OPA Biocide	10.77
B	140 (pre-SWME)	Period IX Bed Scrub and OPA Biocide	1.69

Photos of Deposits on Filters

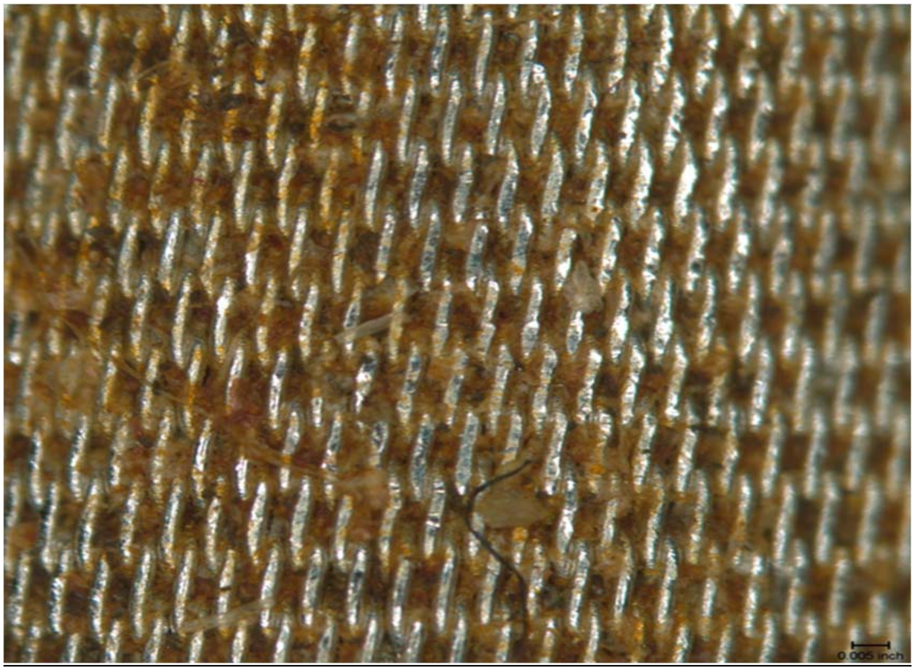


Figure 6: Loop A (No Water Treatment) 40-micron Filter

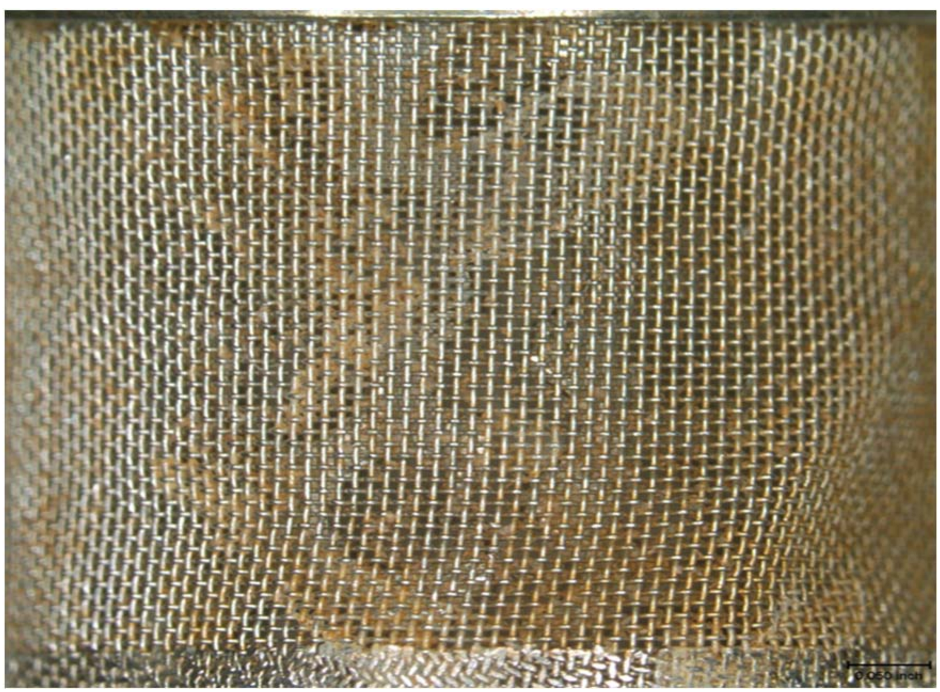


Figure 7: Loop A (No Water Treatment) 140-micron Filter

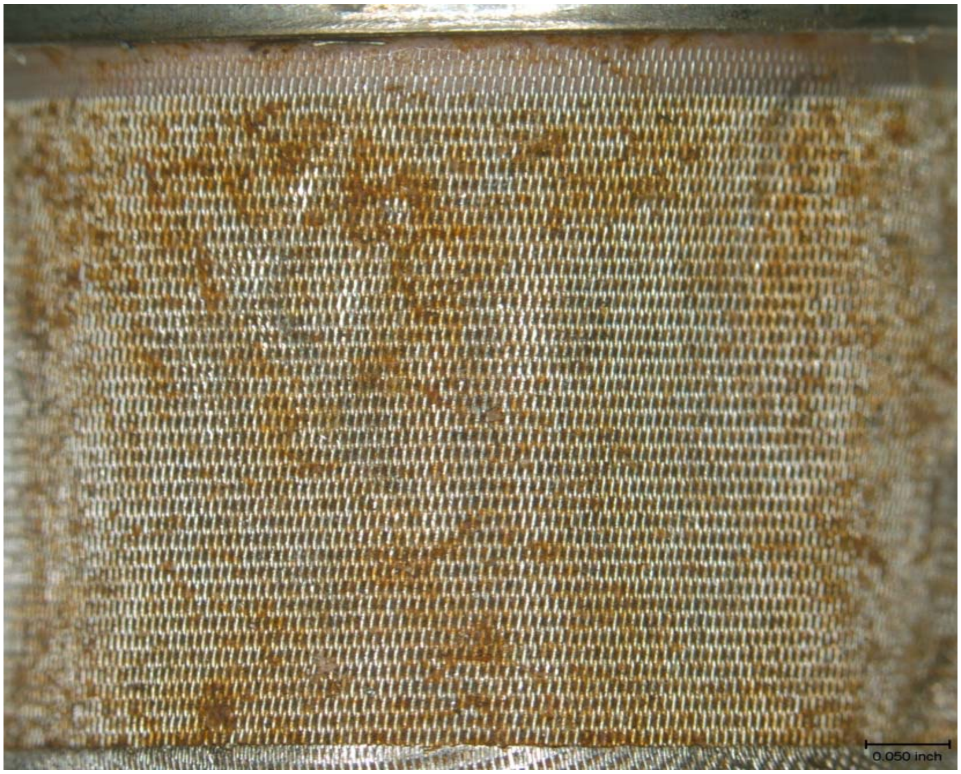


Figure 8: Loop B (Periodic Water Treatment) 40-micron Filter

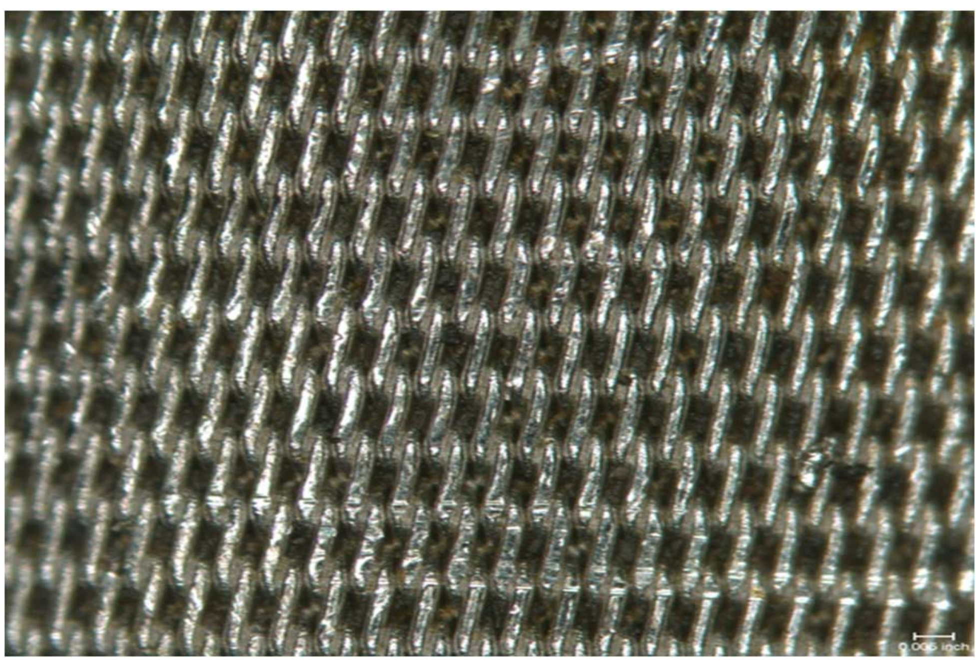
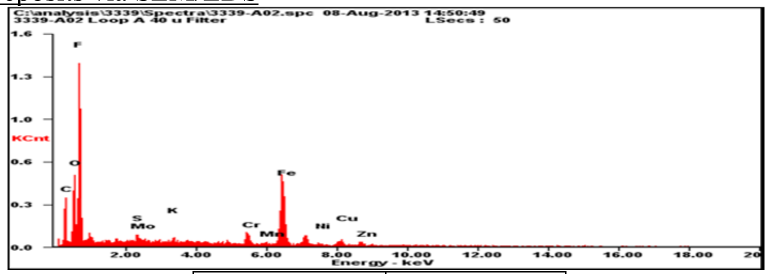


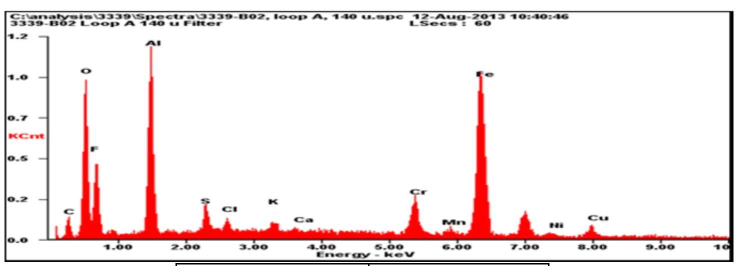
Figure 9: Loop B (Periodic Water Treatment) 140-micron Filter

Elemental Analysis of Deposits via SEM/EDS



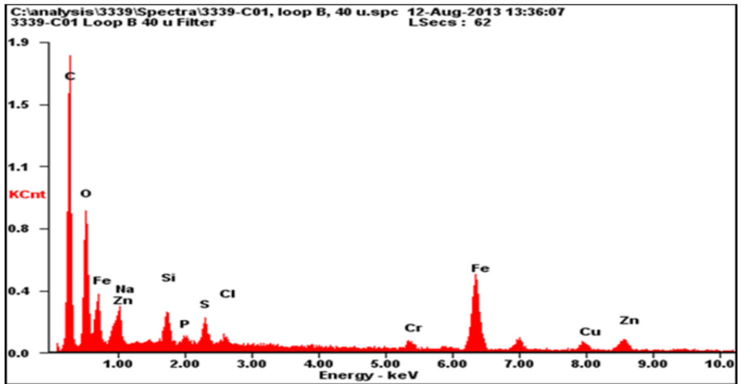
Element	Weight Percent
C K	23.57
O K	13.88
F K	31.54
MoL	00.83
S K	00.26
K K	00.53
CrK	02.31
MnK	00.31
FeK	20.90
NiK	00.81
CuK	03.30
ZnK	01.77

Figure 10: Loop A (No Water Treatment) 40-micron Filter



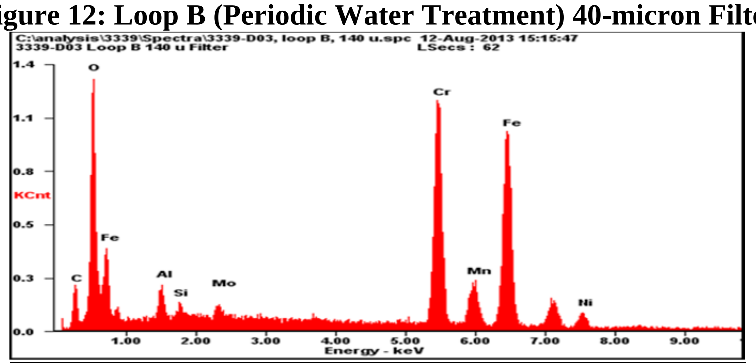
Element	**Weight Percent**
C K	08.99
O K	18.95
F K	10.61
AlK	13.86
S K	01.56
ClK	00.92
K K	00.94
CaK	00.39
CrK	04.76
MnK	00.54
FeK	33.75
NiK	00.95
CuK	03.77

Figure 11: Loop A (No Water Treatment) 140-micron Filter



Element	Weight Percent
C K	56.33
O K	22.62
NaK	00.00
SiK	01.13
P K	00.27
S K	00.87
ClK	00.39
CrK	00.89
FeK	11.29
CuK	02.35
ZnK	03.87

Figure 12: Loop B (Periodic Water Treatment) 40-micron Filter



Element	**Weight Percent**
C K	12.94
O K	22.26
AlK	02.18
SiK	00.66
MoL	01.22
CrK	22.87
MnK	02.83
FeK	31.67

NiK	03.37

Figure 13: Loop B (Periodic Water Treatment) 140-micron Filter

Figure 14 illustrates the pressure drop for Loop A and Loop B as a function of time.

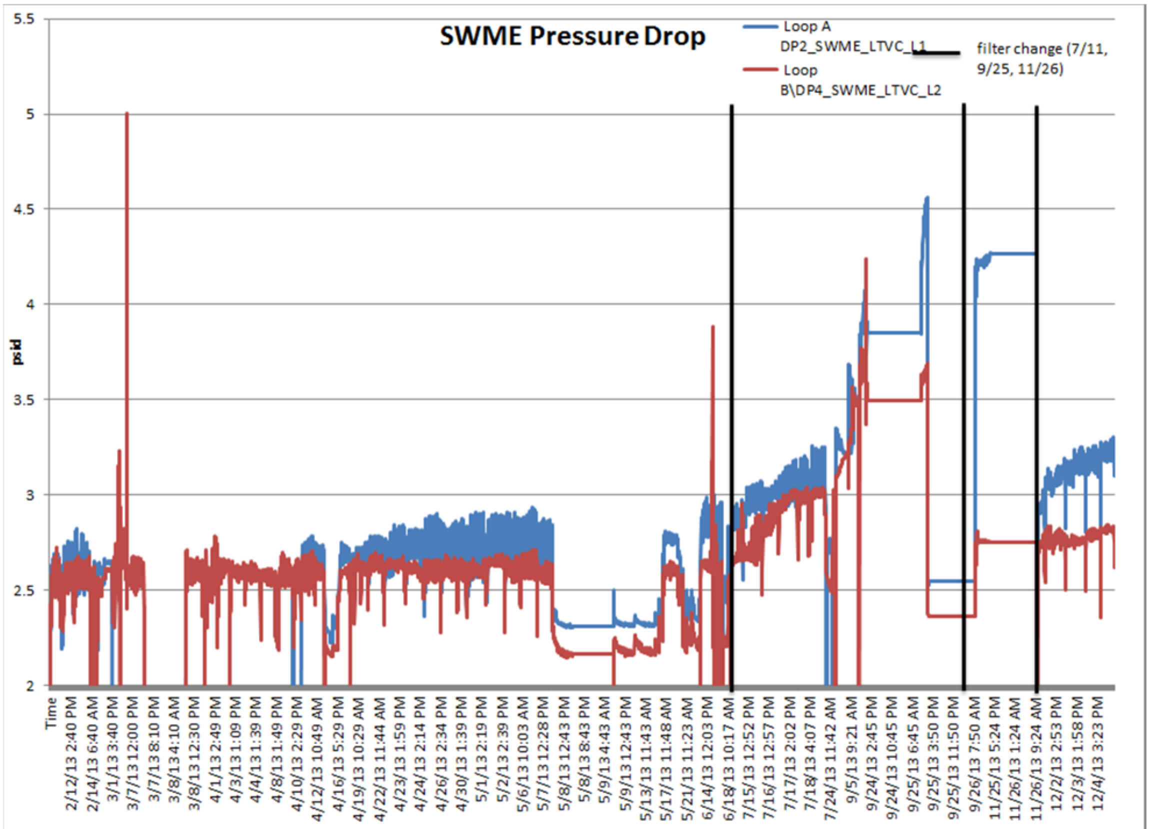


Figure 14
Loop A & Loop B Pressure Drops

V. Discussion

Two parallel SWME test set-ups are under evaluation in this comparative study. Loop A is fed influent water per Table 1 and does not undergo a periodic scrub of the fluid loop, nor is a biocide added to it. The only change in this set-up compared to previous SWME testing is an upgrade of materials of construction to minimize corrosion products and non-metallic extractable contaminants.

Loop B is also fed influent water per Table 1 and undergoes periodic scrubbing and biocide addition. As of this writing Loop B has undergone three scrubs with the segmented ion exchange resin bed and has also undergone several OPA biocide additions.

The chemical analysis results of the starting WPA solution charged into Loops A and B and compares well to the target “SWME Feed-water” shown in Table 1. Minor discrepancies of note include the presence of low-level ammonium (0.24 ppm) which was not a targeted addition to the SWME feed-water and the ammonium accumulated in the SWME recirculation loop water throughout the testing. It is possible that the ammonium is a microbial byproduct of metabolism. Additionally, chromium (0.05 ppm) was a targeted compound of addition to the SWME feedwater per Table 1, but has been infrequently observed in the SWME recirculation loop water

The data from the Loop A SWME recirculation loop water analyses show an expected increase in the SWME feedwater ersatz additives as a function of time. The inorganic accumulation, represented in bulk by the solution conductivity, appeared to be linear in nature early on, with an estimated increase in conductivity of ~6 umho/cm per hour of operation. After roughly 140-hours of testing, the conductivity appeared to plateau in the 600 umho/cm range, suggesting that precipitate of the non-volatile constituents was occurring. The periodic Loop B scrubs were thereafter targeted for the time when the conductivity in Loop B progressed to the 400 - 500 umho/cm range to minimize the opportunity for precipitation.

Loop B underwent three scrubs with the segmented ion exchange bed at the 77-hour, 192-hour and 300-hour points of operation in the experiment (This scrub cycle resulted in a reduction of ~ 80% (from 560 umho/cm to 125 umho/cm) in bulk inorganic ionic species in the first scrub, with like reductions in the other two scrubs. Furthermore, the pH was adjusted from a pre-scrub 4.73 to a post scrub 5.25 in the first scrub, with similar adjustments in pH with the other two scrubs.

A small net increase of sodium after the first scrub (0.12 ppm prior to the scrub, 0.71 ppm post-scrub) may be due to human handling during the installation and removal of the scrubber bed. An additional net increase of silicon after the first scrub (0.37 ppm prior to the scrub, 1.9 ppm post-scrub) may be due to the more strongly bound anionic species such as chloride displacing the more weakly bound silicon (as silicic acid) possibly due to bed pre-conditioning with deionized water.

The use of the segmented ion exchange bed for three scrubs proved to be successful in that a significant reduction in ionic species was observed with essentially a negligible rise in pressure drop across the SWME recirculation loop. Additional scrub cycles will be conducted based on empirical findings from upcoming chemical analyses. It is hoped that the testing will gravitate to a routine scrub cycle that will minimize the accumulation of precipitates within the SWME recirculation loop.

Several difficulties have been experienced with the addition of the OPA biocide to Loop B. First and foremost, the packed bed charged with OPA impregnated sorbent experienced a significantly higher than anticipated pressure drop when an attempt was made to use it as a flow-through OPA additional method (similar to the approach currently used for the ISS IATCS coolant loop). At the time of this writing, it was unknown why this was experienced. An examination of the bed packing materials is planned to ascertain the cause. Continued additions of OPA in this experimentation have been by manual addition to the SWME Feed-water

An additional challenge with respect to the use of OPA as a biocide for the SWME recirculation loop is a repeated reduction in concentration, to well below the target 100-ppm concentration used in the ISS IATCS coolant loop. The rate of decline has slowed somewhat; from ~ 1.2 ppm OPA reduction per hour of operation early in the testing, to ~ 0.9 ppm OPA reduction per hour of operation more recently.

Two tests were conducted to determine where the loss of OPA might be occurring in the loop. These tests concluded that the loss of OPA directly relates to the evaporation of water from the SWME membrane. The OPA is essentially being pulled through the membrane by vacuum.

Once the additional OPA manual additions were increased to the 300 – 500 ppm range, microbial counts in Loop B were non-detectable. Loop A microbial counts gravitated to the 2-log – 3-log per milliliter of water range for the course of the test to-date, with the microorganisms identified as common water-born biofilm forming bacteria.

The use of OPA as a biocide in the SWME recirculation loop has thus far been met with logistic and evaporative loss challenges. The testing has allowed for a more routine OPA biocide manual addition that has minimize the microbial activity within the SWME recirculation loop.

The examination of the filters that were removed from the two SWME loops on test has provided the most direct evidence of the benefit of a periodic maintenance cycle. The Loop A (no maintenance cycle) filter deposits (precipitates) were quantitatively much greater than the Loop B (periodic maintenance cycle) deposits (precipitates).

The deposits were made up of a mixture of intentionally added contaminants (the ersatz non-volatile contaminants), rig material extracts/corrosion products and possibly biofilm.

Deposits on filters represent evidence of deposits expected throughout the concentrate wetted surfaces of the test hardware including the SWME membrane. Deposits (precipitates) are directly detrimental to the operation of water systems in general and should be avoided as part of a maintenance cycle to ensure optimal operation.

References

[1]Ungar, E. K., and Thomas, G. A., "Design and Testing of a Spacesuit Water Membrane Evaporator," *Proceedings of the 2001 Nation Heat Transfer Conference*, ASME, 2001

[2]Vogel M., Vonau W., Trevino L., and Bue G., "Sheet Membrane Spacesuit Water Membrane Evaporator Design and Thermal Tests," AIAA-2010-6039, 40th International Conference on Environmental Systems, Barcelona, Spain, July 2010.

[3]Bue G.; Trevino L., Tsioulos G., Settles J., Colunga A., Vogel M., and Vonau W., "Hollow Fiber Spacesuit Water Membrane Evaporator Development and Testing for Advanced Spacesuits," AIAA-2010-6040, 40th International Conference on Environmental Systems, Barcelona, Spain, July, 2010.

[4]Bue G.; Makinen J., Vogel M., Honas M., Dillon P., Colunga A., Truong L., Porwitz D., and Tsioulos G., "Hollow Fiber Flight Prototype Spacesuit Water Membrane Evaporator Design and Testing" AIAA-2011-5259, 41st International Conference on Environmental Systems, Portland, Oregon, July, 2011.

[5]Bue G.; Makinen J., Cox M., Watts C., Campbell C., Vogel M., and Colunga A., "Long Duration Testing of a Spacesuit Water Membrane Evaporator Prototype" submitted for publication, 42st International Conference on Environmental Systems, San Diego, California, July, 2012.

[6] Lewis, J. F., Cole, H., Cronin, G., Gazda, D. B., Steele, J. W., "Extravehicular Mobility Unit (EMU)/ International Space Station (ISS) Coolant Loop Failure and Recovery", ICES Paper, 2006-01-2040

[7] Steele, J.W., Rector, T., "Airlock Cooling Loop Recovery (A/L CLR) Sampling and Analysis Results – Phase II", Hamilton Sundstrand Internal Document SVME: 6057H

[8] J. Carpenter, G. Gentry, R. Roy, G. Diderich, J. Golden, S. VanKeuren, T. Rector, J. Steele, J. Varsik, M. Wilson, E. Worthy, and H. Cole. Investigation into the High Voltage Shutdown of the Oxygen Generator System Aboard the International Space Station (ISS). AIAA-2012-3613. ICES 2012 San Diego, CA.

[9] Rector, T., Steele, J., and Wilson, M., "ISS IATCS Coolant Loop Biocide Implementation," SAE Technical Paper 2008-01-2159, 2008

[10] Rector, T., Beringer, D., Steele, J., "Ion Exchanger Reactor", U. S. Patent 7,857,979, 2010, (European Patent 08250615.5 – 1213, 2008)