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Status of the Redesign of the Extravehicular Mobility Unit Airlock Cooling Loop Recovery Assembly

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During EVA (Extravehicular Activity) 23 aboard the ISS (International Space Station) on 07/16/2013 an episode of water in the EMU (Extravehicular Mobility Unit) helmet occurred, necessitating a termination of the EVA (Extravehicular Activity) shortly after it began. The root cause of the failure was determined to be ground-processing short-comings of the ALCLR Ion Beds which led to various levels of contaminants being introduced into the Ion Beds before they left the ground. The Ion Beds were thereafter used to perform on-orbit routine scrubbing operations for the EMU cooling water loop which led to the failure. The root cause investigation identified several areas for improvement of the ALCLR Assembly which have since been initiated. Enhanced washing techniques for the ALCLR Ion Bed have been developed and implemented. On-orbit cooling water conductivity and pH analysis capability to allow the astronauts to monitor proper operation of the ALCLR Ion Bed during scrubbing operation have been investigated and are being incorporated. A simplified means to acquire on-orbit EMU cooling water samples has been designed as well. Finally, an inherently cleaner organic adsorbent to replace the current lignite-based activated carbon, and a non-separable replacement for the separable mixed ion exchange resin have been selected. These efforts are being undertaken to enhance the performance and reduce the risk associated with operations to ensure the long-term health of the EMU cooling water circuit. The intent of this paper is to provide an update of the effort to re-design the ALCLR (Airlock Cooling Loop Recovery) hardware. Last year, this effort was in the early stages of concept development and test which was reported in ICES Paper ICES-2016-221. Those phases are now complete and the final outcomes, as well as plans to build and field the hardware, are being reported on.

Nomenclature

ALCLR = Airlock Cooling Loop Recovery
COTS = Commercial off the shelf
EMU = Extravehicular Mobility Unit
ERT = EVA Recovery Team
EVA = extravehicular activity
FPS = fan/pump/separator
IATCS = Internal Active Thermal Control System
ISS = International Space Station
LCVG = Liquid Cooling and Ventilation Garment
MIB = Mishap Investigative Board
SEMU = Short Extravehicular Mobility Unit
TOC = Total Organic Carbon
uS = micro-Siemens

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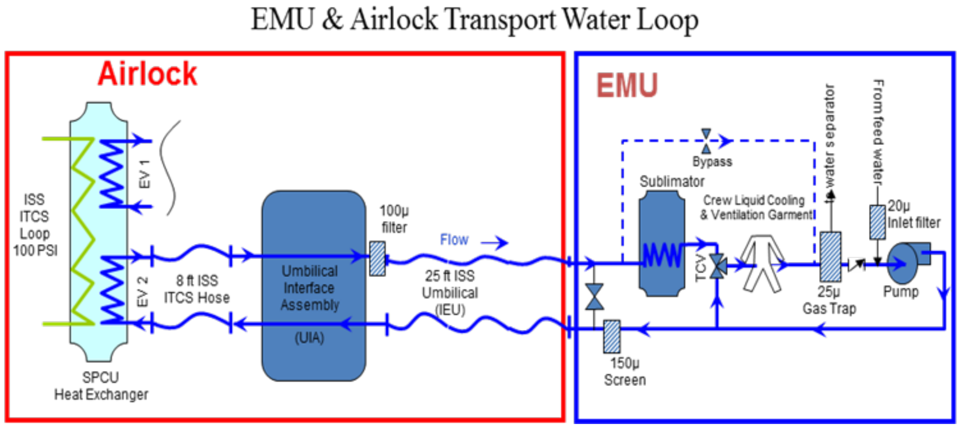
I. Overview of the EMU Transport Loop

The EMU Feed-water loop provides water to a Sublimator porous plate for system cooling. Heat is rejected by the sublimation of the Feed-water to the vacuum of space. The Feed-water tank provides roughly 8.4 lbs of water for cooling along with storing crew respiration and perspiration condensate from the ventilation loop. The EMU cooling water loop transfers a majority of the crew heat load to a Sublimator for cooling. Crew thermal comfort is manually controlled by varying the cooling water flow to the Sublimator and by varying water flow to the crew-member. (Figure 1)



EMU Feed water Loop

Figure 1. EMU Cooling Water Plumbing Schematic

Maintaining the EMU cooling water loop for long-term (6 year or more) operation presents the EMU team with significant challenges. The known risks to the loop, risks inherent in the current ISS mission, can be identified by past failures and by examining the interfaces between the EMU and ISS systems. The Fan/Pump/Separator and key cooling water loop filters have failed due to contaminants and corrosion products that are produced by EMU wetted components and by the ISS Airlock's Low Temperature Loop Heat Exchanger which provides cooling water for suited crew-members prior to activating the EMU's Sublimator. These failures are made more likely by extended stagnation time of the water in the EMU water loops.[1,2]

In the past there have been contamination issues with water originating from ISS spanning from contamination originating in the airlock heat exchanger, to unexplained increases in TOC. Each of these events was unexpected and required post-event remediation, new maintenance procedures, and hardware and (ground) testing to keep the EMU system viable.[1,2]

In 2003 EMU serial numbers 3005, 3011 & 3013 were left on-board the ISS after the Columbia accident and began to experience significant performance degradation and failure within approximately a year after being initially charged with water and launched to the ISS. The EMU hardware fan/pump/separators were not able to function. After extensive testing of the water in the system, and invasive forensic determination of the source of contaminants that had deposited on the pump rotor, it was determined that the ISS Airlock heat exchanger was releasing nickel and silicon into the water and depositing in the EMU fan/pump/separator along with biological material. After this event the development of the ALCLR hardware aided in removing the free ionic material in the water originating from the Airlock and provided a periodic disinfection capability. Through periodic testing via water samples and examination of EMUs returned from orbit, it was determined that the ALCLR hardware was an effective mitigation to the EMU cooling water loop contamination.[1,2]

II. Current ALCLR Hardware Description

The ALCLR water processing kit was developed as a corrective action to EMU cooling water loop flow disruptions experienced on the ISS in May 2004 and thereafter. The components in the kit are designed to remove the contaminants that caused prior flow disruptions. ALCLR water processing kits have been used since 2004 as standard operating procedure. Periodic analysis of EMU cooling loop water and hardware examinations were used as a means to determine adequate functionality and optimized processing cycles as well as ALCLR component shelf life.

The ALCLR water processing kit (Figure 2) was devised to scrub and remediate the various chemical and biological contaminants and by-products that were found to have fouled the magnetically coupled pump in the EMU cooling water loop FPS (Fan/Pump/Separator). The heart of the kit is the EMU Ion Filter, which is a 50:50 by volume packed bed of mixed anion/cation exchange resin and activated carbon. This component is periodically installed in-line to the EMU and Airlock Heat Exchanger cooling water loop and serves the purpose of removing inorganic and organic constituents such as nickel and iron corrosion products and organic acids with the ion exchange resin. Furthermore, uncharged organic contaminants are removed with the activated carbon.[3,4]

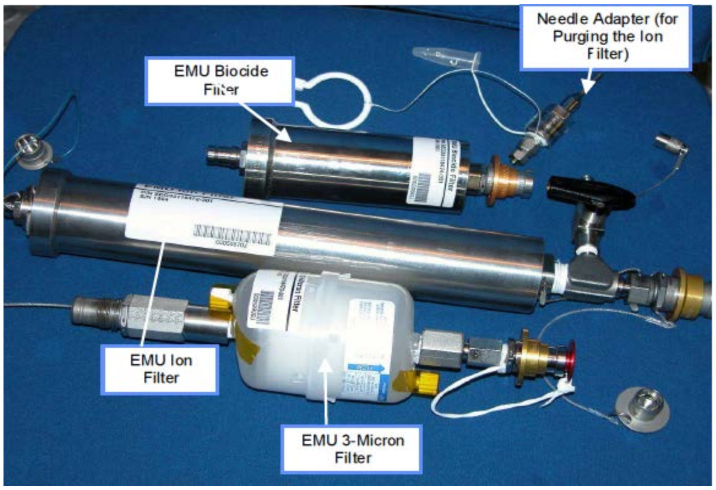


Figure 2. ALCLR processing kit components.

In service, a 3-micrometer filter is placed downstream of the EMU Ion Filter to capture fines from the packed bed prior to return of the polished water to the EMU cooling water loop (Figure 3). After scrubbing with the EMU Ion Filter, the EMU Biocide Filter is installed to add residual iodine biocide for microbial control. The EMU Biocide Filter is a packed bed of ion exchange resin impregnated with iodine.[1,2,3,4]

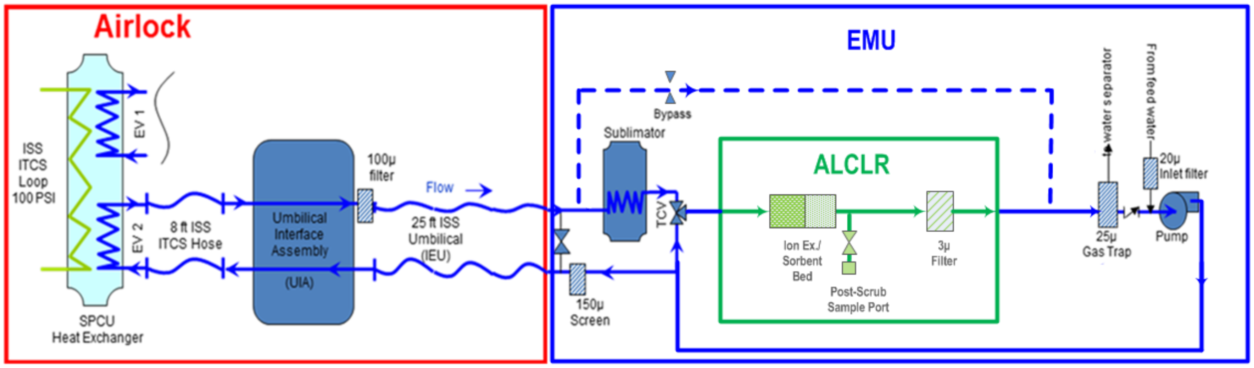


Figure 3. Current ALCLR In-line Configuration

III. Drivers and Overview of the ALCLR Redesign Effort

During EVA 23 from the ISS on 07/16/2013 water entered the EMU 3011helmet resulting in the termination of the EVA shortly after it began. It was estimated that 1.5-L of water had migrated up the ventilation loop and into the helmet, adversely impacting the crew-members hearing, vision and verbal communication. Subsequent on-board testing and ground-based TT&E (Test, Tear-down and Evaluation) of the affected EMU hardware components led to the determination that the proximate cause of the mishap was blockage of all eight water separator drum holes with a mixture of silica and silicates. The blockages caused a failure of the water separator function which resulted in EMU cooling water spilling into the ventilation loop, around the circulating fan, and ultimately pushing into the helmet.

The root cause of the failure was determined to be ground-processing short-comings of the ALCLR Ion Filters which led to various levels of contaminants being introduced into the filters before they left the ground. Those contaminants were thereafter inadvertently introduced into the EMU hardware on-orbit during ALCLR scrubbing operations. Simple means to analyze two parameters of the water in the EMU water cooling loop and the effluent from the ALCLR Ion Filters could have prevented the mishap.

A Mishap Investigation Board was convened to investigate the mishap and an EVA Recovery Team was chartered thereafter to facilitate the return to nominal EVA capability on the ISS. Both teams recognized that the presence of an on-orbit means to evaluate the chemistry (primarily conductivity and pH) of the affected EMU cooling water loop and the contaminated ALCLR Ion Filters could have led to the avoidance of this mishap.

Report recommendations from both teams address the on-orbit water monitoring issue as follows:

1) *Mishap Investigation Board, International Space Station Extravehicular Activity Suit Water Intrusion High Visibility Close Call, IRIS Case Number S-2013-199-00005, Dec. 20, 2013.*[5]

Recommendation #20: The ISS Program should *institute a systematic process of monitoring water quality and chemistry aboard ISS to track changes that can affect critical ISS systems including the EMU*, crew health, and multiple ISS Systems that use water and are sensitive to its chemical makeup. *This process should include consideration of onboard monitoring capability*. It should also include return of any removed hardware to the ground for evaluation.

2) *EVA Recovery Team Summary Report, EVA 23 Mishap Action Response, Root Cause Final Report, Nov.21, 2014.*[6]

Corrective Action #11: Develop a comprehensive suit water quality specification and water management plan to ensure that source water quality parameters that adversely affect suit operation are understood, controlled and verified at all facilities that process EMU hardware. *This should include a strategy for on-orbit water system health insight and monitoring* including on-orbit acceptability limits.

The MIB and ERT recommendations related to the EVA 23 mishap were key drivers to the ALCLR redesign effort. A primary goal of the redesign effort is to select and integrate an in-line conductivity sensor which would dwell in the effluent stream of the ALCLR Ion Filter during scrubbing operations to identify, real-time, if an Ion Filter break-through occurs due to an unanticipated contaminant load or an Ion Filter anomaly. Identification, development and integration of an in-line or off-line pH measurement capability is also included in the redesign effort to allow the measurement of effluent pH, given that large swings in effluent pH can occur if an ion exchange bed were to break-through.

Additional findings from the EVA 23 investigation included shortcomings of the current ALCLR Ion Filter. The activated carbon currently utilized in the design is lignite-based, and an inherent source of low-level contaminants (ionic and particulate) to the downstream Ion Filter ion exchange resin. It was recognized that commercially available synthetic carbon material offered equal or greater organic carbon scrubbing capacity while reducing the risk of ionic and particulate contamination to the downstream Ion Filter ion exchange resin. Identification and testing of such a synthetic carbon is included as a goal in the ALCLR redesign effort.

Furthermore, it was recognized that the ion exchange resin currently used in the ALCLR Ion Filter is “separable” by design, meaning that purposeful differences in resin size and density allow for in-line resin regeneration in ground applications. This offers no advantage to the EMU application and in fact, represents a risk. “Separable” ion exchange resin poses a risk with relatively small ion exchange resin beds due to the potential of a resultant packed bed having an excess of anion or cation exchange resin at the effluent side of the bed. Such an outcome can lead to large shifts in effluent pH near the end-of-life of the Ion Filter, and subsequent adverse impact on downstream wetted materials. That became a driver for the identification of a “non-separable” ion exchange resin as part of the ALCLR redesign effort.

Additionally, it was determined that the 50:50 by volume of activated carbon / ion exchange resin mix currently used (inherited from a prior application) was not optimal for the EMU application based on the organic and inorganic contaminant profiles previously observed. A need to optimize the life of the Ion Filter via an activated carbon/ion exchange resin tailored to the EMU contaminant challenge was therefore included as a goal of the ALCLR redesign as well.

Finally, the in-line monitoring of conductivity and the in-line or off-line measurement of pH required a great deal of design effort to maximize the benefits of the enhanced capabilities, while minimizing weight, power, logistics and crew-member touch-time impacts. The overall design effort is detailed in this paper.

III. Design Changes to the ALCLR

The MIB and ERT recommendations for changes to the ALCLR system that would reduce the greatest amount of risk to the EMU were approved for implementation. These changes included an in-line conductivity sensor, pH measurement in the case of an EMU Ion Filter breakthrough identified by the in-line conductivity sensor, an ALCLR bypass valve, and an upstream sample port for ease of ALCLR processing and sample acquisition. The updated ALCLR in-line configuration is shown in Figure 4.

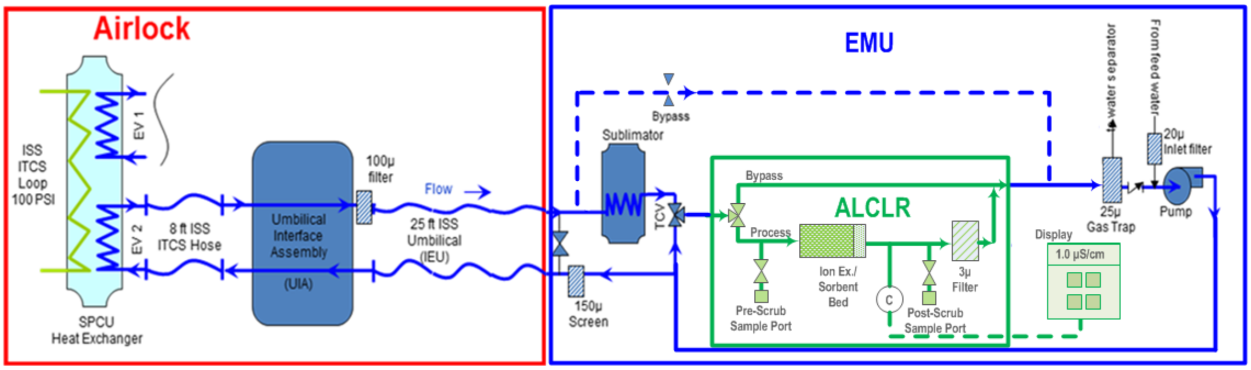


Figure 4. Redesign of the ALCLR In-line Configuration

A hand-held conductivity meter has been implemented on-orbit for analyzing post-scrub samples for conductivity as an interim risk mitigation approach. There is a risk posed by a time lag between sample grab and analysis on-orbit, however, due to cabin CO_2 migration into the sample, altering the conductivity results. higher in conductivity than the sample being analyzed.

An in-line conductivity sensor will be implemented downstream of the ALCLR Ion Filter to monitor the conductivity of effluent water from the Ion Filter real-time, to determine if the Ion Filter ion exchange resin has reached the exhaustion point, or if the Ion Filter is performing off-nominal for some other reason. A conductivity threshold will be set, and once this conductivity threshold is exceeded, the conductivity sensor shall send a signal to a digital display which will include a light to notify the crew-member to take action. Actions can be taken real time to remediate poor water quality and reduce risk to the hardware and to the crew-members.

The EMU Ion Filter currently has a downstream sample port integrated into the outlet of the housing. However, there is no method of taking a sample of the EMU cooling loop water upstream of the EMU Ion Exchange Filter if needed. A sample port will be added upstream of the EMU Ion Filter identical to the one integrated into the outlet of the housing. This upstream sample port will allow for drawing a sample of the pre-scrub sample water, which will provide insight into the health of the EMU cooling loop water.

A bypass valve will be added to allow the crew-member to replace the Ion Filter, the 3-Micron Filter, or the Biocide Filter while the EMU pump is still running. The bypass valve will be a 3/8” three-way hand valve. Changing filters while the EMU is running will reduce the number of fan cycles on the EMU. Reducing the number of fan cycles is desirable because excessive fan cycles allows for more moisture in the F/P/S, promoting corrosion.

For operational convenience, the EMU Ion Filter, the conductivity sensor, the downstream sample port, and the 3-micron filter will be packaged together in a new EMU Scrub Assembly as shown in Figure 5. This allows the ISS crew to replace the Ion Filter, conductivity sensor and 3-micron filter simultaneously when the Ion Filter has reached the end of its useful life. The EMU Scrub Assembly interface to the rest of the ALCLR system is via the same quick-disconnects that are used to attach the current Ion Filter in the current ALCLR configuration.

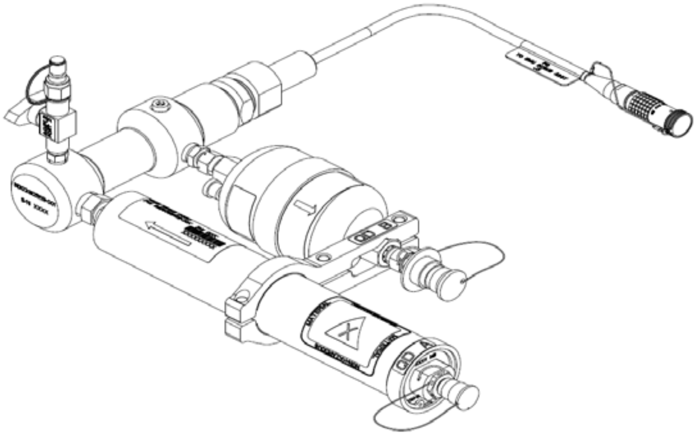


Figure 5. EMU Scrub Assembly Configuration

A. Operational Scenario

The operational scenario of the-designed EMU ALCLR assembly starts with the beginning of an EVA series. An EVA series can be 1 to 6 EVAs with less than or equal to 2 weeks between EVAs and a maximum time between first and last EVA of 8 weeks. To remove any contaminants that may have formed during EMU/Airlock down time, both EMU/Airlock coolant loops, and EMUs planned for use in the upcoming series of EVAs will be scrubbed using the ALCLR Ion Filter and 3-micron filter in series. This scrub will occur within four weeks prior to the suits being used for that series of EVAs.

No more than two weeks after that series of EVAs, the EMU/Airlock coolant loops and EMUs used need to be scrubbed with the ALCLR Ion Filter and 3-micron filter in series (see Figure 6) to remove all contaminants that were formed during the EVA series. This ensures that the gas trap and pump area are not left with contaminants that may form precipitates that could adversely impact functionality.

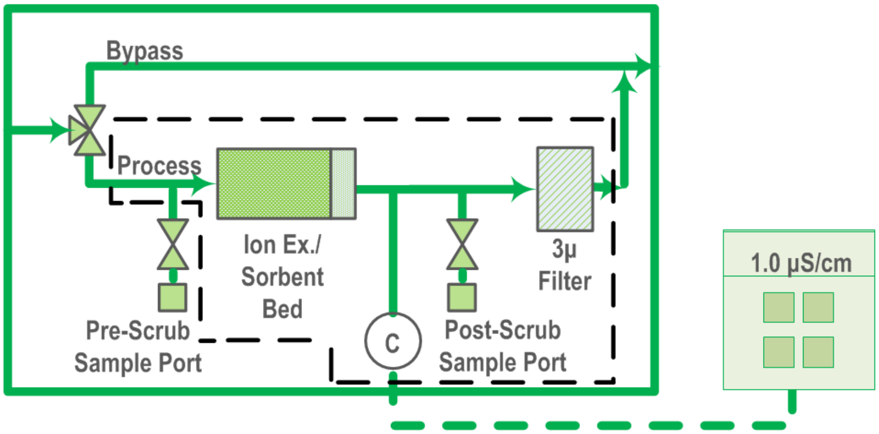


Figure 6. ALCLR in Scrub Configuration

After completion of the cooling loop scrub, the Ion Filter is iodinated for a brief period of time by placing the Biocide Filter upstream of the Ion Filter and flowing for 15 seconds. This serves to reduce the microbial population before storage of the Ion Filter (see Figure 7).[9]

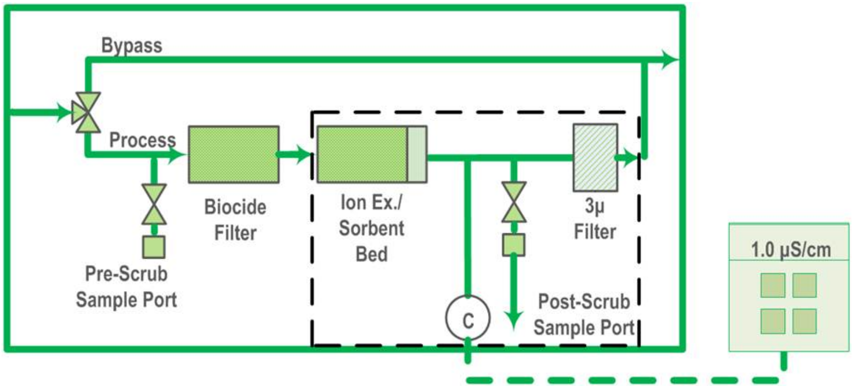


Figure 7. ALCLR in Ion Filter Iodination Configuration

After the suits and loops are scrubbed, they will be iodinated (see Figure 8) using the Biocide Filter to provide a residual biocide for microbial growth control. If the EMUs, wetted LCVGs or heat exchanger and airlock coolant loops are not used for more than 90 days, the EMU, LCVG, heat exchanger and airlock coolant loops shall be scrubbed and iodinated again.[9]

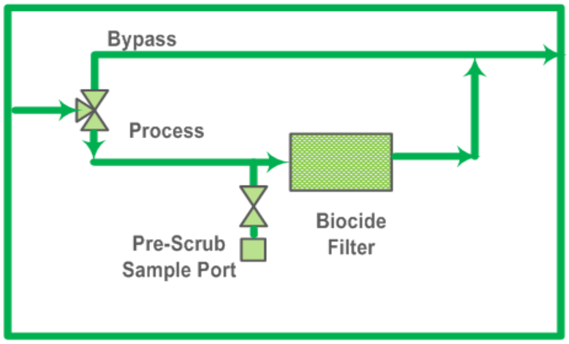


Figure 8. ALCLR in Scrubbing Configuration

A. Design Effort Status

The ALCLR bypass valve and upstream sample port are fabricated from commercial off-the shelf (COTS) parts. The upstream sample port will be identical to the existing downstream sample port. A 3-way ball valve was selected as the ALCLR bypass valve. A trade study was performed to select the best methods of conductivity and pH measurement methods. A commercially available conductivity sensor and display were chosen for conductivity measurement. The conductivity display will be mounted on the ISS Airlock wall with Velcro tape. A custom power cable will be designed to provide 28 VDC to the conductivity sensor and display from the ISS Airlock Power Supply Assembly (PSA). However, the best method of measuring pH was found to be commercial pH test strips. A pH sample bag assembly is being developed for the ALCLR similar to one currently in use on-orbit the ISS for OPA and ammonia analysis in IATCS coolant water.[9]

B. Certification Plans

It was initially assumed that the redesigned ALCLR will have low risk classification, the same as its current classification. However, discussions with the ISS Safety community have led to a determination that the EMU Ion Filter is a Criticality I item, meaning that its failure to function could lead to loss of an ISS crew-member or the vehicle. Therefore, the target for the EMU Ion Filter to be certified for 12 uses after being subjected to qualification-level vibration.

Most other components of the new ALCLR Redesign build that are the same as the current design will be certified by similarity to the current design. None of the components in the current design or in the redesign are considered fracture critical. COTS components (fittings, valves) are being used wherever possible for new items; these items may not meet ISS requirements and will be certified following the COTS certification approach documented in SSP 50986. COTS components will not be required to meet EEE parts requirements, and EEE parts certification will not be performed. Grade 4 components are likely to be used. Electrical stress analysis, thermal analysis, Non-Standard Parts Approval Request (NSPARs) or a radiation analysis will not be performed for the COTS hardware. The conductivity sensors and the conductivity analyzer may be susceptible to Single Event Upset/Single Event Latch-up/Single Event Burnout (SEU/SEL/SEB). It is expected that the pH test kit will require only materials certification.

IV. Conductivity and pH Measurement Evaluation

Efforts were undertaken to evaluate COTS in-line and off-line means to measure conductivity and pH for the ALCLR redesign effort. The intent of the conductivity sensor is to determine real-time if an ALCLR Ion Filter is not functioning correctly (contaminated or exceeded capacity). Once a conductivity offset indicates that an ALCLR Ion Filter is not functioning correctly, the user will shut off the EMU Pump to halt the water scrubbing step. The conductivity sensor, therefore, will be in-line to be a real-time warning of inadequate scrubbing performance. When an EMU Ion Filter has exceeded scrubbing capacity, the effluent from can undergo significant shifts in pH, depending on whether there is an excess of anion exchange resin capacity (basic effluent) or excess cation exchange resin capacity (acidic pH). That phenomenon has been demonstrated via test and is shown in Figure 9. The intent of the pH measurement, therefore, is to determine if immediate remedial action needs to be taken to flush an EMU Transport Water Loop after an Ion Filter break-through. If the effluent pH were to be determined to be “3” for instance, the corrosion-risk to EMU wetted materials in the Transport Water Loop would be high, and immediate neutral water flushing would be recommended. If, on the other hand, the pH of the effluent was determined to be “6”, for instance, an immediate neutral water flush would not be necessary and the user could likely wait until the next scheduled ALCLR operation.[9]

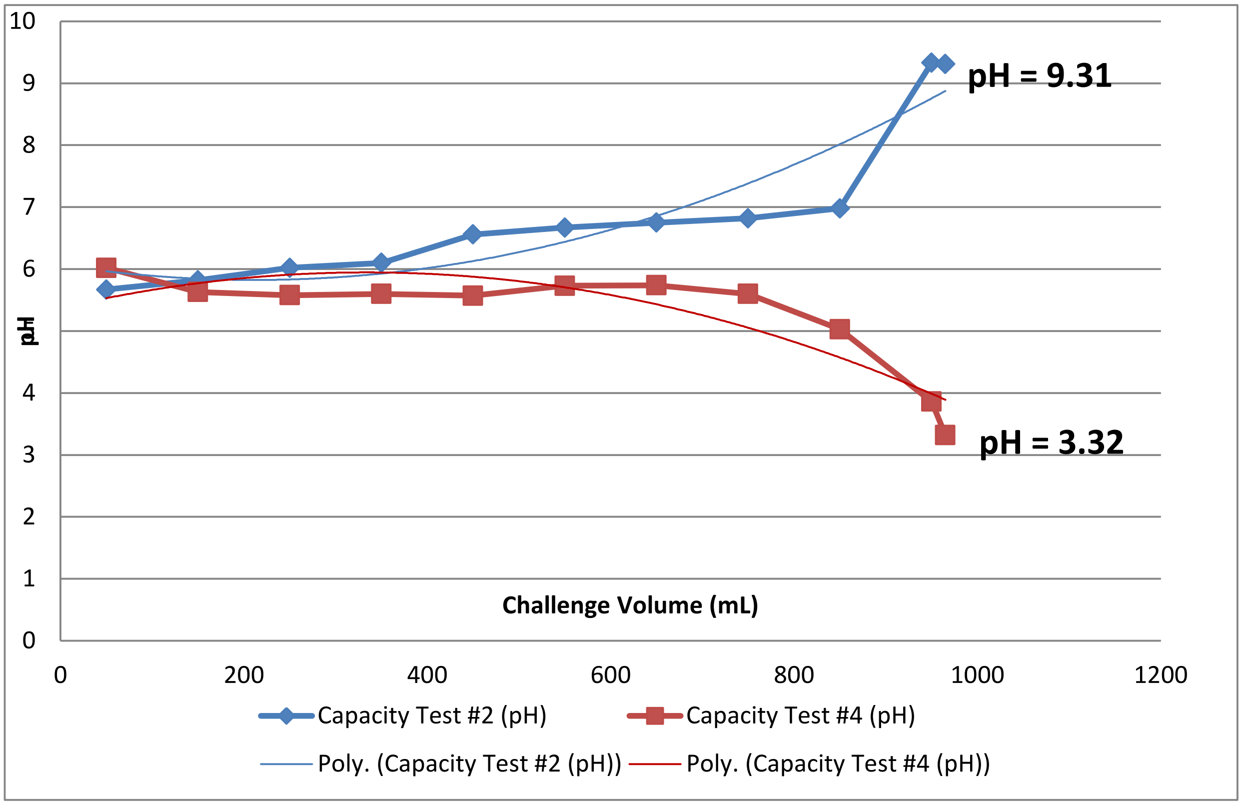


Figure 9. Ion Filter Effluent pH at Break-through Point

An investigation into on-orbit cooling water conductivity and pH analysis capability to allow the crew-members to monitor proper operation of the ALCLR Ion Bed during scrubbing operation has been undertaken. The status of this effort was reported on at the 2016 ICES Conference in Paper ICES-2016-221. The effort culminated in the selection of an in-line conductivity sensor (Foxboro In-line Contacting Sensor 871CR-A2T1B1A-S with Controller 875CR-DF2-A). The measurement of pH via off-line pH test strip integrated into a Teflon bag, in the same fashion as is used for the on-orbit analysis of ISS IATCS coolant for ammonia and OPA concentration was selected as well.[9]

VI. Adsorbent and Ion Exchange Resin Evaluation

A. Background

Significant other findings from the EVA-23 Mishap Investigation and the aftermath were related to the ALCLR Ion Filter ion exchange resin and activated carbon. First off, the current ion exchange resin used in the ALCLR Ion Filter (Purolite UCW-3600) is separable by design. That is, the anion and cation exchange vary by size as intended the manufacturer so that the user can separate them via backflow for in-line re-generation. That feature is a disadvantage for a small packed ion filter such as that used in the ALCLR Ion Filter. Ion exchange resin lot to lot variability has shown that certain material lots contain anion and cation resin that separate rapidly and are at risk of segregating as a small bed is packed. If the effluent side of an ion exchange resin bed is too rich in anion exchange resin or cation exchange resin, the pH of the effluent can shift a great deal toward the basic pH range or acid pH range respectively. One aspect of the ALCLR redesign effort reported on in this paper is the selection and certification of a non-separable mixed bed ion exchange resin to circumvent that risk. [5,6]

Secondly, the activated carbon used in the ALCLR Ion Filter is lignite-based (Darco 20x40), is inherently high in contaminants. A great deal of washing of this material must occur before it is used, and there appears to always be a low-level residual of contaminants. Since the activated carbon resides upstream from the ion exchange resin in the ALCLR Ion Filter, this low level contaminant load represents a low level challenge to the ion exchange resin which can deplete it more rapidly that necessary. As part of this redesign effort, a synthetic carbon (Ambersorb 4652) sample was acquired for evaluation as a potential replacement for the Darco 20x40. An added advantage is that Ambersorb 4652 has gone through extensive testing by the NASA/Boeing community and has been certified for an ISS WPA MF bed application; specifically to replace the current activated carbon which has become obsolete. Furthermore, water extract from the Ambersorb 4652 sorbent material has undergone successful EMU Sublimator compatibility testing as part of the UTAS support of the NASA/Boeing sorbent selection process.[5,6]

Finally, the ratio of ion exchange resin to activated carbon in the ALCLR Ion Filter began as 50:50, which was inherited from a previous application of this Ion Filter and not optimized for the EMU contaminant load. This was never tailored to the EMU application. Testing is underway to certify an ion exchange resin to activated carbon ratio of 70:30 respectively which is expected to be more appropriate for the EMU application as has been suggested by prior evaluation of historical contaminant load. [5,6]

B. Ion Exchange Resin Replacement

Two candidate, non-separable mixed ion exchange resins were selected for evaluation (Purolite UCA-9966 and Dowex Monosphere MR-450). The initial step was to evaluate the non-separable claim made by the manufacturer. Each resin was separately added to a 1-liter graduated cylinder with deionized water (~ 500-mL volume of ion exchange resin and ~ 500-mL of deionized water). Each was stirred aggressively with a glass stirring rod, and then allowed to settle. The Purolite UCA-9966 demonstrated a significant improvement over the currently used Purolite UCW-3600 with respect to non-separation, but there was still a degree of stratification of the ion exchange resins observed. On the other hand, the Dowex Monosphere MR-450 demonstrated a superior lack of separation, with essentially no visible stratification observed.

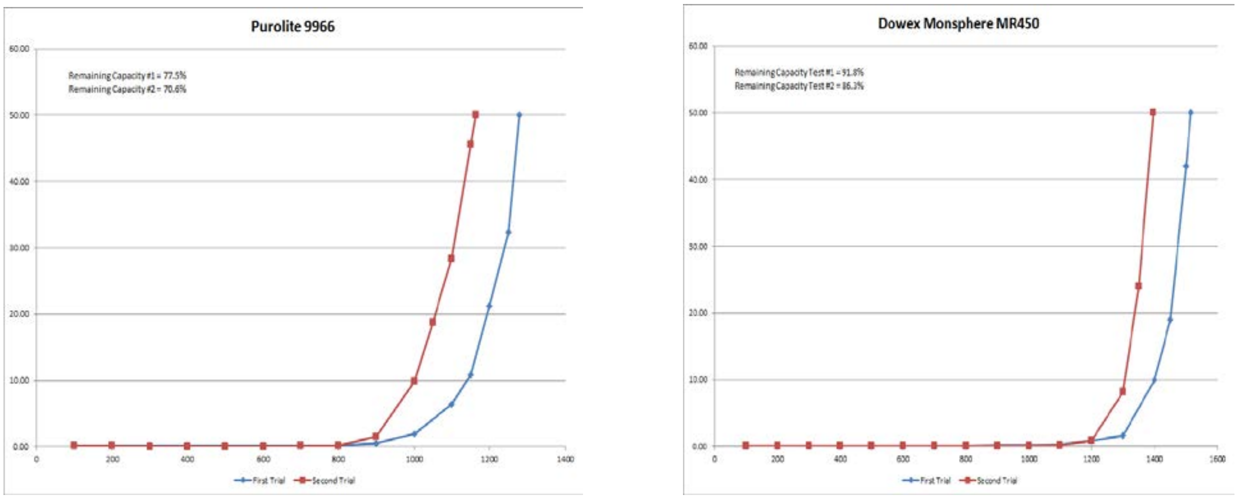
The total ion exchange capacity was evaluated for the two candidate non-separable mixed ion exchange resins (Purolite UCA-9966 and Dowex Monosphere MR-450) and the baseline separable mixed ion exchange resin (Purolite UCW-3600) (see Table 1). All three mixed ion exchange resins demonstrated similar anion and cation exchange capacities, with no obvious advantage to either of the candidate replacements.[7,8]

The operational ion exchange capacity was evaluated for the two candidate non-separable ion exchange resins (Purolite UCA-9966 and Dowex Monosphere MR-450). The average operational capacity of Dowex Monosphere MR-450 was found to be 89.1% whereas the operational capacity of Purolite UCA-9966 was found to be 74.1%, similar to what has been previously observed with the baseline Purolite UCA-3600 (see Figure 10). The Dowex Monosphere MR-450 therefore, demonstrated a 15% operational capacity advantage over the Purolite UCA-9966.[7,8]

Extract from Dowex Monosphere MR-450 non-separable mixed ion exchange resin underwent a 50-EVA EMU Sublimator compatibility test and the results indicated full compatibility as part of this study.

RESIN ID	Supplier Quoted Anion Capacity Meg/ml	Actual Percent Anion Capacity (triplicate test)	Supplier Quoted Cation Capacity Meg/ml	Actual Percent Cation Capacity (triplicate test)
Purolite UCW 3600 (current resin) (separable)	1.9	96.6	1.1	97.2
Purolite 9966 (non-separable)	1.9	99.8	1.0	98.2
Dowex Monosphere MR-450 (non-separable)	1.9	100	1.0	100

Table1. Total Capacities of Candidate and Baseline Mixed Ion Exchange Resins



Purolite 9966
Average Operational Capacity = 74.1%

Dowex Monosphere MR450
Average Operational Capacity = 89.1%

Figure10. Operational Capacities of Two Candidate Non-separable Mixed Ion Exchange Resin

Dowex Monosphere MR450 non-separable mixed ion exchange resin was selected as the optimal choice for the replacement mixed ion exchange resin for the ALCLR Ion Filter redesign. It was observed to be completely non-separable when evaluated via agitated graduated cylinder test, demonstrated an increase of an average of 15% greater operational capacity that either the baseline Purolite UCA-3600 or the candidate Purolite UCA 9966, and has demonstrated compatibility with the EMU Sublimator.

C. Activated Carbon Replacement

Efforts to replace the Darco 20x40 activated carbon gravitated to an evaluation of a synthetic carbon called Ambersorb 4652. This synthetic carbon material was previously selected as a replacement to activated carbon used in the ISS WPA MF Beds. Prior testing by Boeing, NASA and UTAS has demonstrated that Ambersorb 4652 has superior capacity to remove a wide range of organic contaminants including organic compounds that are similar to ones experienced in the EMU cooling water loop. Furthermore, testing has shown that aqueous extract from Ambersorb 4652 is compatible with the EMU Sublimator.

Ambersorb 4652 underwent total capacity testing in parallel with Darco 20x40 using the organic compound glutaraldehyde as the organic compound challenge. Ambersorb 4652 was found to have a significantly greater total capacity (capacity at equilibrium) when compared to Darco 20x40 (see Figure 11). In this experiment, the Figure 11 blue line (Darco 20 x 40) shows more unbound glutaraldehyde remaining in solution after equilibrium adsorption is reached that the red line (Ambersorb 4652), indicative of greater total capacity.[7,8]

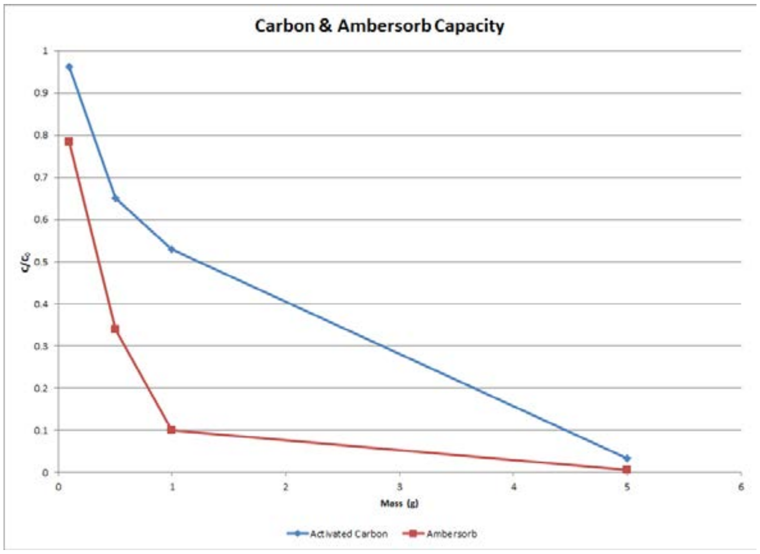
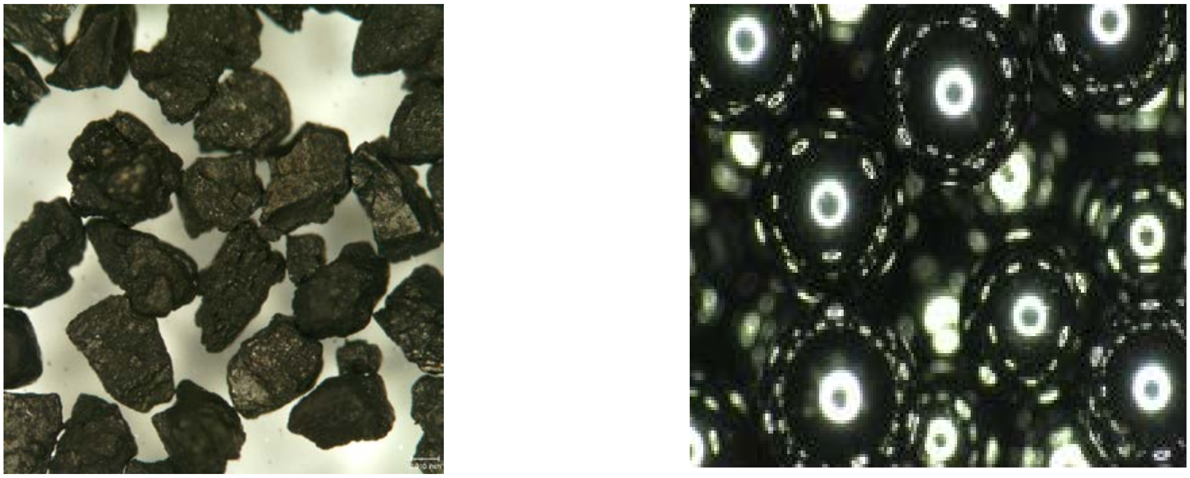


Figure 11. Total Capacity for Glutaraldehyde – Ambersorb 4652 vs. Darco 40x40

Water rinsing operations to reduce the amount of particulates generated from Ambersorb 4652 vs. Darco 20x40 indicated that Ambersorb 4652 is much easier to process and generates far fewer particulates, thought to be due to the material type and uniform, circular shape (see Figure 12)

Furthermore, water extract testing previously reported on by UTAS, Boeing and NASA demonstrates that water extract from Ambersorb 4625 is far cleaner that water extract from Darco 24 x 40.



Darco 20x40 Activated Carbon

Ambersorb 4652 Synthetic Carbon

Figure 12. Magnified View of Darco 20x40 vs. Ambersorb 4652

Ambersorb 4652 synthetic carbon was selected as a replacement for the lignite-based activated carbon (Darco 20x40) currently used in the ALCLR Ion Filter. Ambersorb 4652 demonstrated superior total capacity for organic compounds, is inherently cleaner with respect to water extractables and is easier to process to far less particle generation that Darco 20x40. Finally, Ambersorb 4652 aqueous extract was demonstrated to be compatible with the EMU Sublimator.

VII Re-designed Ion Filter Certification

A. Ersatz Development

Development of an ersatz to be used as a worse-case challenge to an ALCLR Redesign Ion Filter during certification testing was a priority. A review of all EMU cooling water loop chemical analysis data from when the ALCLR was first implemented (2006) until present, excluding the EMU 3011 incident (off-nominal ground contamination), was undertaken. The highest concentration of each commonly observed constituent was determined thereafter. A recipe that included the highest of all commonly observed constituents was developed with margin built in due to counter-ions that are not commonly observed, but were necessary in order to introduce the target constituents (see Table 2)[10.] Ersatz solution was mixed and stability & shelf life were evaluated and confirmed thereafter

Constituent (ppm)	Target (ppm)	Source of Data	Ersatz Actual Obtained per Prior Testing[1]	Source of Constituent
Nickel	1.84	SEMU 3011 STS-129 Return	1.36 (actual max)	$NiSO_4 \cdot 6H_2O$
Aluminum	0.57	SEMU 3009 Ground Testing	0.34 (actual max)	$Al(NO_3)_3 \cdot 9H_2O$
Sulfate	1.91	SEMU 3008 STS-123 Return	2.90 (actual max)	$NiSO_4 \cdot 6H_2O$
Iodide	0.82	SEMU 3009 Ground Testing	0.86 (actual max)	KI
Ammonium	2.47	SEMU 3018 STS-126 Return	3.20 (actual max)	NH_4Cl
Silicon	1.70	SEMU 3003 SpX 4 Return	1.50 (actual max)	$Na_2SiO_3 \cdot 9H_2O$
TOC	7.00	SEMU 3009 STS-135 Return	7.10 (actual max)	Sodium Acetate & Caprolactam
Chloride	N/A	N/A Counter Ion	4.80	NH_4Cl
Potassium	N/A	N/A Counter Ion	0.25	KI
Nitrate	N/A	N/A Counter Ion	3.90	$Al(NO_3)_3 \cdot 9H_2O$
Sodium	N/A	N/A Counter Ion	3.30	Sodium acetate & $Na_2SiO_3 \cdot 9H_2O$
Conductivity (umho/cm)	58.6	SEMU 3011 STS-129 Return	51.7 (actual max)	N/A

Table 2. Ersatz Formulation

B. Ersatz Challenge Test Set-up

A closed loop test set-up was built to simulate an ALCLR Ion Bed cycle in an EMU cooling water loop (see Figure13). Each ALCLR challenge cycle to a full-size Ion Filter is 8.55-lbs (3.99-L) of ersatz per single ALCLR Ion Bed cycle. The flow-rate of ersatz through each Ion Filter is 70-lbs/hr. (31.8-L/hr. or 0.53-L/min), which is the nominal flowrate through an EMU cooling water loop during nominal ALCLR operations. The time on test was the nominal ALCLR scrub cycle length of 1-hr. Three separate Ion Filters of the new design will undergo this testing as will an initial practice Ion Filter.[10]

The parameters to be measured to judge performance of the Ion Filters will be in-line conductivity (using the conductivity sensor and display selected for the ALCLR Redesign) downstream of the Ion Filter on test and sample grabs at TBD time intervals for subsequent chemical analysis. Furthermore, as an Ion Filter begins to break through, as evidenced by conductivity increases or down-stream sampling, the pH test strip selected for the ALCLR Redesign and a laboratory pH meter will be used for pH mapping. Finally, post-test disassembly of each Ion Filter will occur and capacity testing on the Ion Exchange Resin and the Organic Adsorbent will occur in triplicate.[10]

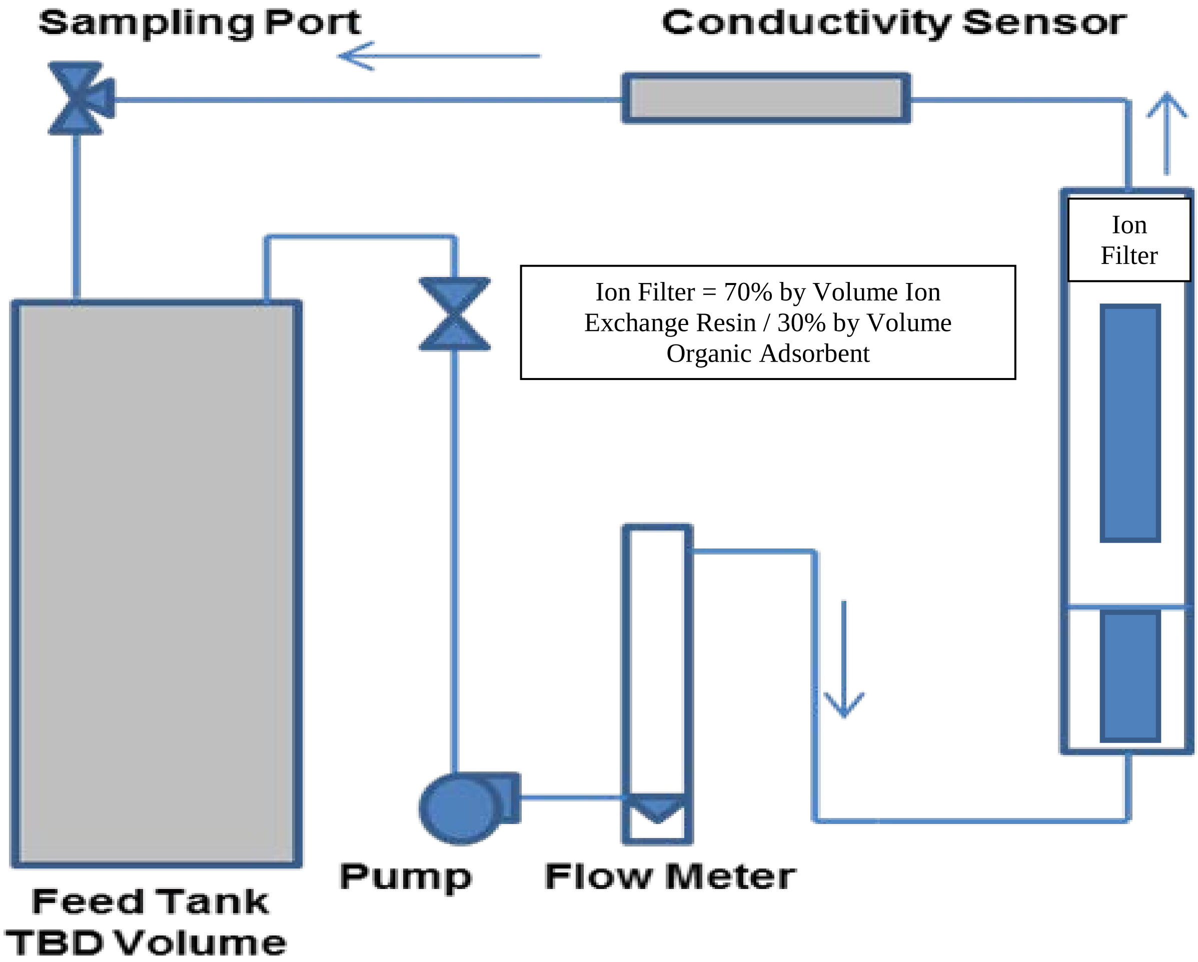


Figure 13. Test Set-up Schematic for Ersatz Challenge

C. Ion Filter Operational Capacity Test Set-up

The operational capacity test to be used for Ion Filter ion exchange resin evaluations after a conductivity break-through and after the ion exchange resin is removed and mixed from the Ion Filter is loosely based on ASTM D3375-95a – "*Standard Test Method for Column Capacity of Particulate Mixed Bed Ion Exchange Materials*". The test set-up is shown schematically in Figure 14 and a test set-up picture is shown in Figure 15.

The testing involves the metering of a sodium chloride feed solution (~ 600-parts-per-million) onto the top of a 25-mL ion exchange resin sample column which contains a fraction of the mixed ion exchange resin sampled from each Ion Filter tested. The effluent from the 25-mL ion exchange resin column is monitored for conductivity. When the ion exchange resin becomes operationally exhausted, break-through of the ion exchange resin is identified by a conductivity rise in the effluent. Per the ASTM procedure, a 50-mho/cm conductivity endpoint indicates the break-through point. The concentration of the sodium chloride challenge, the volume of feed solution to the break-through point and the wet volume of ion exchange resin used are utilized in a calculation that yields an operational capacity value for the ion exchange resin. Figure 15 is an actual picture of the operational capacity test set-up.[10]

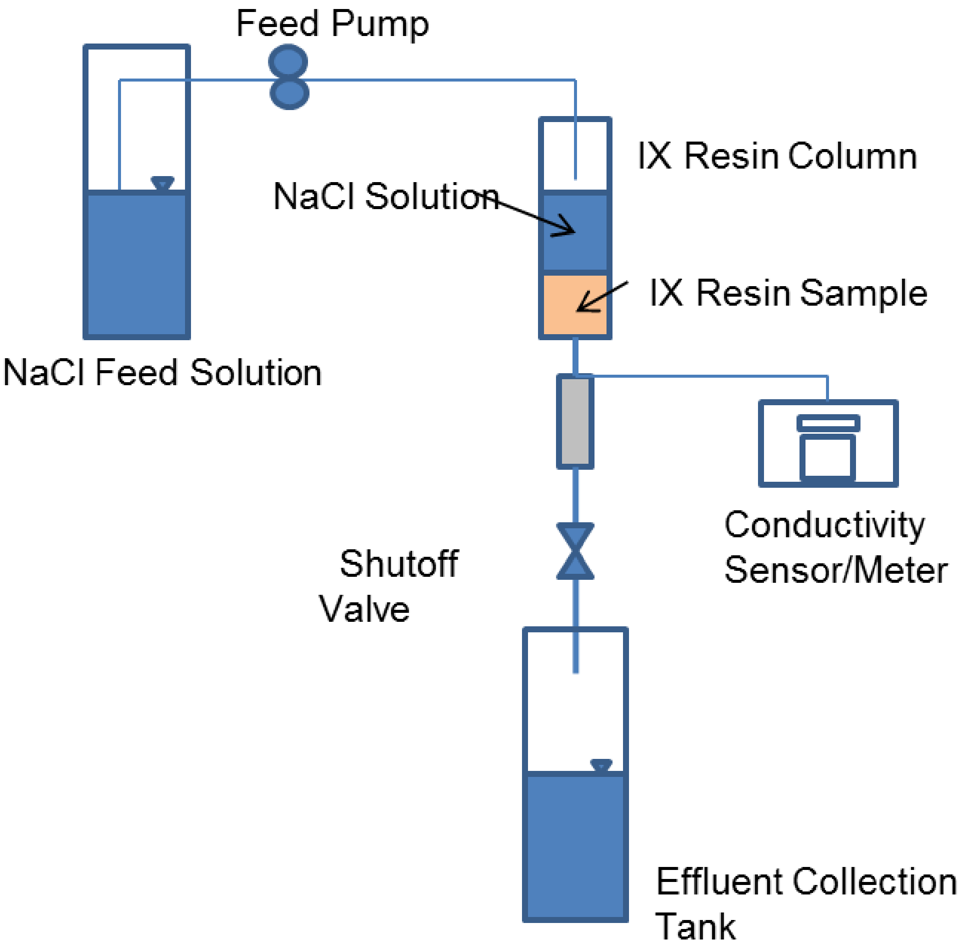


Figure14. Ion Exchange Resin Operational Capacity Test Setup Schematic

The test set-up, depicted in Figures 14 & 15, is an enhancement over the initial test set-up used for past analyses. The metering and shut-off valves allow the setting of the initial flow-rate with DI water vs. previously using the sodium chloride test solution itself. Additionally, the ability to back-flow with DI water was added which facilitates the removal of air bubbles from wetted surfaces and the resin column and allows further mixing of the ion exchange resin in place.

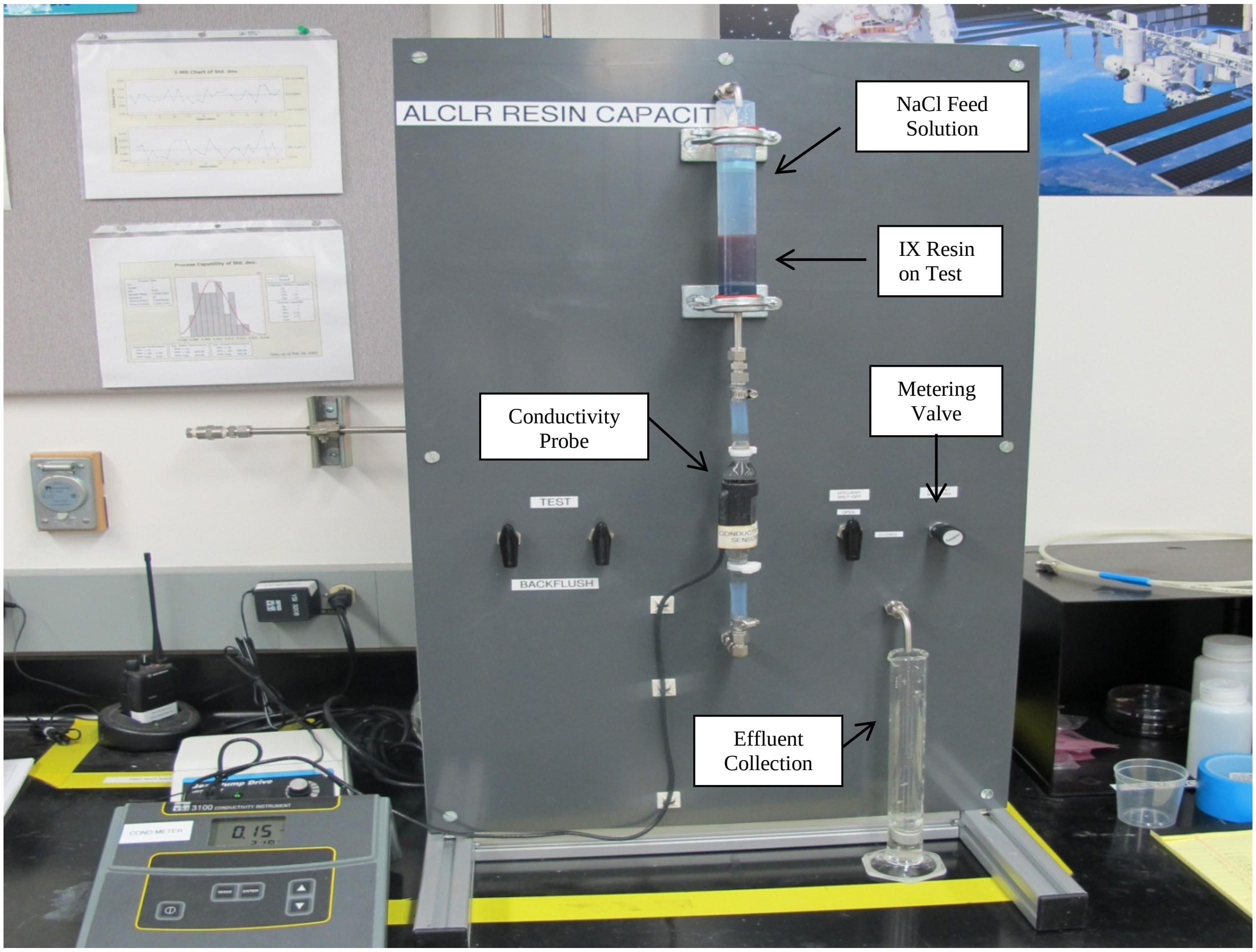


Figure15. Ion Exchange Resin Operational Capacity Test Setup Picture

D. Organic Sorbent Total Capacity Test Set-up

Equilibrium isotherm testing will be done on Ambersorb 4652 that is removed from the Ion Filter, using 1,500 – 2,000- ppm glutaraldehyde aqueous solution as the challenge organic compound. This will be done to determine the remaining capacity on ALCLR Ion Bed organic sorbent after conductivity breakthrough is determined to have occurred on the Ion Filter.[10]

Varying amounts (0.5 – 5.0-grams) of the test organic adsorbent will be placed in plastic test tubes with the challenge glutaraldehyde solution (see Figure 16). The test tubes will then be agitated overnight in a Jar Mill (see Figure 17). At the end of the agitation period, the free water will be analyzed for glutaraldehyde content. The concentration of remaining glutaraldehyde will be directly related to the loss in capacity in the activated carbon due to the ersatz challenges.[10]

Figure 16. Plastic Test Tubes with Varying Amounts of Organic Adsorbent and Glutaraldehyde Test Solution

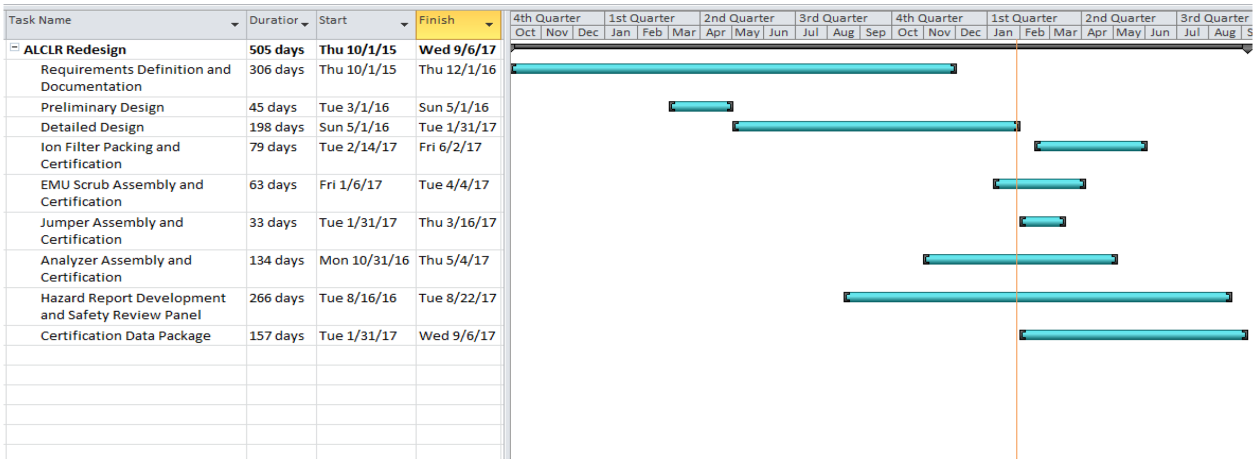
Figure 17. Jar Mill for Mixing

E. Vibration Testing

A packed, redesigned Ion Filter assembly was certified to a qualification vibration level tailored to the HTV and to the two American commercial launch vehicles. The post-vibration pressure drop had increased by 0.4-psi which was deemed insignificant for the application. The free water was drained from the Ion Filter and underwent 2-micron filtration. The fines in the filtered effluent were found to be very sparse and were deemed to be insignificant for the application.

F. Hardware Development and Delivery

Figure 18 depicts the project development schedule. Work began on October 1, 2015 with Authorization to Proceed from NASA. Requirements development and concept development began immediately and led to Systems Requirements Review in February 2016. Preliminary and detailed design began immediately thereafter and culminated in a combined Preliminary Design Review/Critical Design Review in July 2016. Design refinement necessitated by PDR/CDR comments continued throughout the rest of 2016 and concluded in January 2017. Assembly and certification testing of the various system components is underway and will conclude with hardware delivery by the end of May, 2017. Safety review and certification work will extend for the rest of FY17.



Task Name	Duratior	Start	Finish
ALCLR Redesign	**505 days**	**Thu 10/1/15**	**Wed 9/6/17**
Requirements Definition and Documentation	306 days	Thu 10/1/15	Thu 12/1/16
Preliminary Design	45 days	Tue 3/1/16	Sun 5/1/16
Detailed Design	198 days	Sun 5/1/16	Tue 1/31/17
Ion Filter Packing and Certification	79 days	Tue 2/14/17	Fri 6/2/17
EMU Scrub Assembly and Certification	63 days	Fri 1/6/17	Tue 4/4/17
Jumper Assembly and Certification	33 days	Tue 1/31/17	Thu 3/16/17
Analyzer Assembly and Certification	134 days	Mon 10/31/16	Thu 5/4/17
Hazard Report Development and Safety Review Panel	266 days	Tue 8/16/16	Tue 8/22/17
Certification Data Package	157 days	Tue 1/31/17	Wed 9/6/17

Figure18. Project Development Schedule

VII Summary

The root cause investigation for the EVA-23 mishap identified several areas for improvement of the ALCLR Assembly and procedure which have since been initiated or are underway. Enhanced washing techniques for the ALCLR Ion Bed have been developed and implemented. Ground processing controls as well as controls for the quality of water used in hardware processing have been implemented.

An investigation into on-orbit cooling water conductivity and pH analysis capability has been undertaken. Conductivity via in-line contacting conductivity sensor was chosen as the design solution. The measurement of pH via off-line pH test strip integrated into a Teflon bag was chosen as the design solution as well.

A design approach to integrate an in-line conductivity sensor has been undertaken and is presented. The implementation of a simple off-line means to determine EMU coolant water pH, has been addressed. A simplified means to acquire on-orbit EMU cooling water samples is part of the design effort as well. Finally, an inherently cleaner organic adsorbent to replace the current lignite-based activated carbon, and a non-separable replacement for the separable mixed ion exchange resin have been selected and are undergoing testing. These efforts are being undertaken to enhance the performance and reduce the risk associated with ALCLR operations to ensure the long-term health of the EMU cooling water circuit.

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