Use of Aquaporins to Achieve Needed Water Purity On ISS for the EMU Space Suit System

Terry R. Hill – Brandon W. Taylor
terry.hill-1@nasa.gov – brandon_taylor@baylor.edu
NASA's Lyndon B. Johnson Space Center
2101 NASA Parkway
Houston, Texas 77058

Abstract

"Use of Aquaporins to Achieve Needed Water Purity On ISS for the EMU Space Suit System." With the U.S. Space Shuttle fleet retired, the supply of extremely high-quality water "super-Q" - required for the EMU Space suit cooling on this ISS - will become a significant operational hardware challenge in the very near future. A proposed potential solution is the use of a filtration system consisting of a semi-permeable membrane embedded with aquaporin proteins. Aquaporins are a special class of trans-membrane proteins that facilitate passive transport of water and other substances across a membrane. The specificity of these proteins is such that only water is allowed through the protein structure, and this novel property invites their adaptation for use in water filtration systems, specifically usage on the ISS for the EMU space suit system. These proteins are found in many living systems and have been developed for commercial use today.

Use of Aquaporins to Achieve Needed Water Purity on the International Space Station for the Extravehicular Mobility Unit Space Suit System

Terry R. Hill [1] and Brandon W. Taylor [2]
NASA Johnson Space Center, Houston, TX, 77058 and Baylor University Waco, Texas, 76798

With the retirement of the U.S. Space Shuttle fleet, the supply of extremely high quality water required for the Extravehicular Mobility Unit (EMU) space suit cooling on the International Space Station (ISS) will become a significant operational hardware challenge in the very near future. One proposed solution is the use of a filtration system consisting of a semipermeable membrane embedded with aquaporin proteins, a special class of trans-membrane proteins that facilitate passive, selective transport of water in vivo. The specificity of aquaporins is such that only water is allowed through the protein structure, and it is this novel property that invites their adaptation for use in water filtration systems, specifically those onboard the ISS for the EMU space suit system. These proteins are also currently being developed for use in terrestrial filtration systems.

Nomenclature

A/L CLR = (or ALCLR) AirLock Coolant Loop Remediation
Ar/R = aromatic/arginine
BTU = British thermal unit
CFU = Colony Forming Unit
DMSD = dimethylsilanediol
EMU = Extravehicular Mobility Unit
EVA = extravehicular activity
FPS = Fan-Pump-Separator
ISS = International Space Station
LCVG = Liquid Cooling and Ventilation Garment
MgO = magnesium oxide
MF =
mL = milliliter
PLSS = Portable Life Support System
PWR = Portable Water Reservoir
S/N = serial number
TOC = Total Organic Compounds
WPA = Water Processing Assembly

I. Introduction

The International Space Station (ISS) Extravehicular Mobility Unit (EMU) space suit system was originally developed for use on the U.S. Space Shuttle as a method to mitigate some failure scenarios where the Shuttle payload bay doors fail to close and lock properly. This system has since evolved from a suit designed to help secure the Shuttle to one capable of capturing and repairing satellites, and enabling astronauts to assemble and repair the ISS. While the EMU as a whole has a proven track record for robust performance, the suit's thermal cooling loop has historically been very sensitive to the purity of water in both the feed supply and thermal loop. With the retirement of the U.S. Space Shuttle fleet retired, the supply of extremely-high-quality water required for the EMU

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[1] EMU Space Suit Subsystem Engineer, Crew and Thermal Systems Division, 2101 NASA Parkway, Houston, TX 77058/Mail Stop EC5, terry.hill-1@nasa.gov.
[2] Student, Baylor University, brandon_taylor@baylor.edu

space suit cooling on the ISS will become a significant operational hardware support challenge in the very near future.

One proposed solution is the use of a filtration system consisting of a semipermeable membrane embedded with aquaporin proteins, a special class of transmembrane proteins that facilitate passive, selective transport of water in vivo. The specificity of aquaporins is such that only water is allowed through the protein structure, and it is this novel property that invites their adaptation for use in water filtration systems, specifically those onboard the ISS for the EMU space suit system. This paper will discuss the current water quality requirements for the ISS EMU space suit, some of the challenges with regard to the future water supply for the EMU, and possible solutions by utilizing the characteristics of aquaporins based upon some of the current implementations of aquaporins that have been developed for terrestrial filtration systems.

II. Overview of the Extravehicular Mobility Unit Water Loop

The ISS EMU space suit has life support systems to regulate the thermal and breathable-gas environment inside of the suit. The suit's thermal loop, which will be the focus of discussion in this paper, is comprised of a two-part water loop: the liquid transport circuit that circulates water through the liquid cooling garment that is worn by the astronaut; and the feed water circuit.

A. Liquid Transport Circuit

The flow path of the EMU liquid transport circuit originates at the EMU Fan-Pump-Separator (FPS) (a combined unit that has the breathable-gas ventilation loop fan that is magnetically coupled to the liquid transport circuit water pump, and provides the capability to separate water condensation from the ventilation loop and dump the condensation into the closed-loop water system), which then delivers water to the thermal control valve that provides the astronaut the ability to control the amount of water that will bypass the sublimator. At the thermal control valve, a portion of the water is allowed to flow through the liquid cooling ventilation garment and back to the FPS. The water that is allowed to bypass the thermal control valve will flow to the sublimator, discharge heat upon sublimation, and provide the heat exchange function between the liquid transport circuit and the feed water circuit.

Once initially charged with water, the liquid transport circuit is subject to the biological challenges of most every water system. Microorganisms are naturally present in the hardware at some level despite the best attempts at sterilization. Additionally, contamination can be accumulated directly from the astronaut via the hardware that removes exhalation condensation from the ventilation loop. Whereas some level of biological growth is tolerated, the liquid transport circuit must be filtered and iodinated every 90 days after the initial charge with water.

B. Feed Water Circuit

The feed water circuit provides the capability to reject the heat from the EMU that has been either generated by the astronaut's metabolic processes, from the EMU's avionic systems, from the life support mechanical systems, or from the external environment. Two reservoir tanks that are initially charged with approximately 10 gallons of ultrapure water supply the feed water circuit. A detailed discussion regarding the necessity of the ultrapure water is addressed in subsequent sections. The feed water circuit provides enough water to support cooling for an 8-hour extravehicular activity (EVA). In the event that the 10 gallons of water from the primary tanks are prematurely depleted, the reserve tanks can provide an additional 30 minutes of cooling capability at a 1000 British thermal unit (BTU) rate **(per what unit of time????),** enough time to allow the astronaut to return to the ISS airlock.

Water flows from the feed water tanks to the sublimator, which acts as a heat exchanger between the feed water circuit and the liquid transport circuit. The sublimator uses the triple point of water, where the three phases of water are present. Upon exposing the EMU to the vacuum of space, water flow to the sublimator from the feed water system is initiated and forms a layer of ice on the surface of the sublimator that is exposed to vacuum. After the ice layer is formed, water from the feed water circuit remains liquid by picking up the heat from the liquid transport loop via the heat exchanger in the sublimator. The heat removed from the liquid transport loop is dissipated into space via the sublimation of the sublimator ice layer. As the ice sublimates, the voids left behind in the ice layer are filled with additional water from the feed water circuit.

A porous plate that contains thousands of near-microscopic holes is required as part of the ability of the sublimator to allow and control the rate at which water sublimates to vacuum. Due to the very small diameter of the holes in the porous plate, fouling by feed water impurities is of utmost concern and has historically been the source of thousands of man-hours to investigate sublimator failure. Therefore, unlike the less-sensitive transport water circuit, the feed water circuit requires a water supply of the utmost purity. It is our belief that the natural water transport function of aquaporins may be applied to achieve the needed purity.

III. Overview of the Mechanics of Aquaporins

A. Principles of Reverse/Forward Osmotic Filtration Relevant to use of Aquaporins

Fresh water is an important resource on any space mission. A variety of purification techniques are available to meet demand where continued resupply from terrestrial sources proves problematic or inconvenient. In particular, mechanical filtration systems—in which contaminants are physically separated from influent water—are of interest because of their low energy cost per unit water produced, as compared to other methods such as distillation. Mechanical systems rely on pumps to force wastewater through the filter apparatus, which are typically a fine mesh or polymeric membrane, with apertures small enough to exclude dissolved solute and particulates while allowing the passage of water.[1,2] Filtration methods are often classified based on the size of the apertures they use, which correlates with the size (and importantly, proportion) of contaminants that can be removed. From large to small pore size (low to high filtration capability), the methods currently in use are microfiltration, ultrafiltration, nanofiltration, and reverse osmosis.[1] With larger meshes, as in microfiltration, filtration is achieved primarily through a physical "skimming out" of contaminants. However, as the size of pores and contaminants decreases, the effects of the filter's chemical composition become non-negligible.[3] For example, electrostatic repulsion from a membrane that carries a charge within its operational pH range can contribute to the exclusion of like-charged solutes, as with a positively charged membrane and Mg^{2+} ions dissolved in the influent water.

Of the conventional types of mechanical filtration, reverse osmosis is the most attractive in terms of the size of contaminants removed, and accordingly sees wide use in commercial desalinization plants worldwide.[1,2] Though these plants require pretreatment of source water to mitigate fouling,[4] the membranes they use are capable of rejecting a very high proportion of dissolved salts, up to 99.8 percent under certain conditions.[2]

For certain specialized applications, however, even this high level of purity is insufficient. Aquaporin-based filtration has the potential to achieve essentially complete rejection of solute from influent water and therefore provides a potential solution.

Aquaporins are a special class of transmembrane protein that act as selectively permeable channels for water and, as varies among isoforms, other solutes.[5,6] Aquaporins are widely conserved in nature, being found in almost every organism, and are represented in every major taxonomic division. In humans, one of the numerous isoforms is involved in the concentration of urine in the kidneys,[6] while another isoform is present in bacteria and helps diffuse osmotic gradients that might otherwise rupture the cell. The majority of aquaporins are entirely specific for water and allow its passage at speeds approaching the diffusion-limited rate.[5] However, certain isoforms are known to permit the passage of other solutes (including glycerol, urea, and arsenite),[7] which limits the utility of these isoforms in water filtration schemes.

The water-specificity of most aquaporins is the result of certain shared structural features, illustrating the recurring theme in biology of "form determining function." In keeping with their role as passive transporters of water, aquaporins are constructed much like a pipe, with a central cavity enclosed by a protein "shell."[5-7] The central cavity is shaped like an hourglass, with its widest diameter (~15 Å) reached at either end, with the midpoint of the channel reaching ~3.8 Å × 3.4 Å,[5] approximately the Van Der Waals diameter of water. This constriction results in a physical, size-based exclusion of solutes larger than the channel, and partially accounts for the transport specificity of aquaporin. Structural comparison indicates that the hourglass shape is conserved across all aquaporins. A cluster of four amino acids, known as the aromatic/arginine (Ar/R) selectivity filter, protrudes into the central constriction of the channel and further mediates specificity. This cluster is composed of hydrophobic aromatic amino acids and the amino acid arginine,[8] with the latter carrying a partial positive charge at physiological pH. Additionally, two half-helices in the protein strand create a permanent dipole, contributing further to the positive potential in the center of the channel.[7,9] This charge is thought to provide an electrostatic energy barrier to the translocation of cations through the aquaporin structure,[7] and the dipole is thought to orient water molecules in such a way as to prevent protons from jumping between them and thereby passing through the channel.[9]

Aquaporins associate into tetramers in the membranes of living cells, creating a cluster of four independently functioning channels that are arranged in such a way as to create an additional, central pore.[5] This central pore appears to be largely impermeable, although molecular dynamics simulations predict that molecular oxygen and carbon dioxide may pass through, at least in AQP-1. It has been observed, however, that aquaporin-mediated gas flow is low in comparison to passage through the surrounding cell membrane, with its much larger surface area.[8] Moreover, gaseous impurities, which are readily removed by the Portable Life Support System (PLSS) water/gas separator, are not a likely source of sublimator failure.

The transport specificity of aquaporin can thus be applied in filtration systems to provide water of exceptional purity. Currently, at least one lab has managed to incorporate aquaporins (bacterial AqpZ) into a synthetic polymer membrane while retaining their transport functionality.[4] One commercial entity, Aquaporin A/S, is also known to be pursuing aquaporin-based filtration, and has several prototypes in testing at the NASA Ames Research Center facility.

B. Proposed Filtration Scheme

<Talk about how the aquaporin channels would be produced such that it would be a potential use to the EMU project: pressure drop, flow rates, filtering efficiency, life cycle duration and cost, etc.>

IV. Changes to the Extravehicular Mobility Unit Water Supply Quality

A. Past Issues

As has been documented in prior papers from the EMU community, the EMU sublimator is highly prone to the clogging of the porous plate by various contaminants. These contaminants historically have fallen within two distinct categories: (1) particulates (organic and inorganic) and film-forming amphipathic molecules,[14] and (2) organic acids/surfactants (abietic acids),[15] with the latter believed to have a tendency to link together and "knot," thus blocking the sublimator pores, which typically are between 3-6 micrometers.

Examples of the earliest sublimator contamination issues occurred early in the program, when the Liquid Cooling and Ventilation Garment (LCVG) employed the Tygon water tubing used during the Apollo Program. Contamination released by this material plugged not only system filters but also the sublimator porous plates. A change was required to a nuclear cross-linked ethylene vinyl acetate tubing, which solved this problem. Additionally aluminum corrosion products became the next cause of performance loss. This was eliminated with the change from aluminum (valve module, valves, etc.) to stainless steel.[17]

1. Extravehicular Mobility Unit Contamination Due to International Space Station Airlock Cooling Loop

Following the Space Shuttle *Columbia* accident February 1, 2003, three EMUs (serial number (S/N) 3005, 3011, and 3013) were left onboard the ISS and began to experience significant performance degradation and failure[*] within approximately a year[†] after being initially charged with water and launched to the ISS.[11] Prior to the accident, the EMUs had been returned to the ground via the Shuttle within 3 to 4 of years after arrival on the ISS. The maintenance practices in place at the time, the unknown issues with the ISS Airlock Heat Exchanger hardware, and the long duration on the ISS facilitated the failure of the units via the clogging of filters and seizing of the FPS assembly by organic and inorganic residues.

One analysis on components of the EMU hardware water loop has identified microbial counts up to 10^6-10^8 Colony Forming Unit (CFU)/milliliter (mL), well beyond the maximum of 50 CFU/mL allowed for potable water on the ISS.[10] The identified microorganisms were of the commonly encountered species Ralstonia, which is known to form biofilms in water systems and in the quantities observed in the testing. These microorganisms can lead to the fouling of filters, gas traps, and other fine orifices.[10]

The inorganic contaminant contributors were identified to be the ISS Airlock Heat Exchanger with BNi_3 braze alloy and/or the EMU valve module and various plumbing that had corrosion-resistant steel surfaces.[10] This resulted in the item 141 Gas Trap accumulations of inorganic particulates consisting of nickel, silicon, and aluminum and the gas trap cover plugged with iron oxide.

As a result of this series of failures associated with the prolonged time between the cleaning of the water loop, the time between activation of the systems and the contaminants introduced to the EMU from the ISS, the EMU Airlock Coolant Loop Remediation (A/L CLR) hardware was developed and placed into service. The A/L CLR (ALCLR) hardware is a kit of filters and connectors that allow the EMU water loop to be purged of particulates and biological contaminates. The kit consists of an ion exchange filter, a 3 micron filter and an iodine biocide filter that is used to reduce the biological organic count after the cleaning (scrubbing) has occurred.[11] As intended,

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[*] S/N 3005 had cooling problems prior to EVA on 19 May 2003 and again on 19 May 2004, S/N 3011 temporarily lost cooling during suit donning on 19 May 2004, and S/N 3013 had cooling problems starting on 28 May 2003.[10,11]

[†] S/N 3005 was charged with water on 8 October 2002, S/N 3011 charged on 26 April 2002, and S/N 3013 was charged on 26 April 2002.

incorporation of the ALCLR hardware into the maintenance plan resulted in a significant reduction in the total organic and inorganic matter found in the EMU system.[12]

2. *International Space StationWater: Contamination with IRA-67 and Variation in Total Organic Compounds*

Starting in June 2010, the ISS water system began to experience a significant increase in Total Organic Compounds (TOC). In August of that year, it was decided to obtain a water sample for groundside testing with the mini-sublimator test hardware to determine whether the rising TOC would have an adverse affect on the EMU. The increased TOC trending continued until late in October, at which point the levels quickly began to fall and return to normal.[19]

During the testing to determine the nature of the TOC contaminants, it was noticed that dimethylsilanediol (DMSD)-type compound was the primary constituent, and was later identified as IRA-67. An extensive testing program was enacted to determine the source of the IRA-67 and the level of the compound the sublimator would tolerate without failing or adversely affecting sublimator performance. The source of the contaminant was determined to be the ISS water MF filter beds. With the analysis and testing of two subsequent water sample returns from the ISS, it was determined that the IRA-67 leachant drops to tolerable levels by the time roughly 6000 lbs of water have passed through the MF beds (see **Fig. X)**. This indicates that if the available Portable Water Reservoirs (PWRs) are filled with Water Processing Assembly (WPA) water after approximately 6000 lbs of water has passed through the MF beds, this will provide sufficient reserves—given the number of currently planned EVAs—for roughly 2 years of operation.

Insert mini-sublimator plot with water samples from STS-133 & 135

The source of the TOC rise that initiated this activity was found to be due to **YYYY**.

B. Near-Term and Future Changes in Water Supply and Potential Impacts

1. *Obsolescence and Future Supplier Supportability Issues*

Looking forward into the life of the EMU operating in and around the ISS through 2020 and likely 2028, the risk of supplier supportability for hardware components and designs, which will be greater than 20 years old by that time, will be ever increasing. When the vendor for the EMU hardware is no longer in existence or is no longer interested in providing the hardware, and refurbishment and life-extension activities are no longer an option, a new vendor and possibly a new design will be required. Coupled with an aging system is the risk and eventuality of hardware material or component obsolescence. This obsolescence can come in the form of material being deleted from the vendor's catalogue unexpectedly, change in formulation, discovery of toxicity issues and source of raw material, to name only a few. The EMU program has been witness to all of these issues in the past, and these issues will likely continue into the future. Two system components are already in the initial analysis performed by the EMU life support hardware provider, Hamilton Sundstrand (Windsor Locks, CT), and for which there is a new or yet to be defined vendor.

2. *Water Tank Bladder Material*

The water tank structure for the EMU consists of multiple cavities in the PLSS that are lined with a bladder, originally Neoprene. Not long after going into service, the sublimator's performance began to degrade and it eventually failed altogether. It was discovered that the sublimator pores were being clogged with the abietic acid constituents of the Neoprene latex.[14]

A new bladder material was formulated, a change to a Rucothane–based material, which appeared to meet the requirements; however, later testing revealed leachants were comparable to the Neoprene with regard to the sublimator performance.[17] Finally, a material that contained Fluorel[‡] and met the EMU performance requirements was procured in **XX**, and was considered a lifetime buy. That in itself is not of significant interest other than the fact that the source of a magnesium oxide constituent (Maglite D) of the Fluorel was comprised of 95% concentrations per unit volume. In 2010, it was determined that the life-time buy would not meet the new planned usage of the EMU and a new order was placed with a new vendor that attempted to create the bladders using the processes of the original vendor. However, upon receipt of the new bladders the sublimators began to fail once again. Through

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[‡] The use of Fluorel is familiar to NASA as it was used late in the Apollo Program to replace the polyurethane boot sole on the space suit.[16]

extensive testing it was discovered that the original feed stock of Maglite D was no longer available (the last batch was produced in 2004) so a new source of ore (Maglite Y) was found with a 99%.

The bladders with the new formulation and higher purity Maglight Y resulted in increased deposition of magnesium oxide (MgO) on the sublimator porous plate. Further investigation of Maglite Y indicated that even though the particle size was smaller, less porosity may actually reduce MgO binding during the curing process. Increase in purity may have resulted in loss of a "natural" cross-link activation with naturally occurring calcium,[18] which lead to much more free MgO to leach into the water and deposit on the sublimator porous plate. An extensive search for stores of Maglite D at other vendors of the original material supplier did not result in any remaining material.

New formulations appear promising, but at this time, no certified replacement has been found for the bladder material.

3. *Water Supply from the International Space Station*

While the ISS water system is currently working as expected, the fact remains that water is one of the most corrosive natural substances, and the ISS will be more than 30 years old by the year 2028. It can be expected that the water system will experience corrosion, changes in leachants as the aging material properties change, and changing organic compositions as 3 decades of organic growth and evolution takes place in the ISS water loop.

Additionally, the composition of the ISS water will continually change due to reclamation of human waste and humidity recovery, and the ever-changing chemicals due to different metabolisms, diets, personal hygiene and makeup products, cleaners and onboard experiments, and material off-gassing.

With the ever-changing water composition that we can expect in the future and the highly sensitive sublimator porous plate, a host of potential contaminates ("unknown unknowns") may not be realized until new sublimator performance degradation or failures occur.

V. Application of Aquaporins to Provide Required Extravehicular Mobility Unit Water Quality

A. Pre-processing of International Space Station Water Prior to Suit Usage

The proposed utilization of the aquaporin technology would be as a pre-processor of the ISS water prior to being loaded into the EMU system. Testing still remains to be completed; however, if the performance of the filters is as expected, the aquaporin technology will provide the single most important and cost-effective hardware implementation to ensure a dependable quality water supply for the EMU.

Initial thoughts would be to design a filter cartridge that would interface between the hardware that currently connects the PWR[§] and the **XX**. This implementation would not require a redesign of any of the existing EMU or ISS hardware.

A second potential implementation would be as a new filter in the current ALCRL hardware as a replacement for or augmentation of the current 3 micrometer filter to ensure highest water quality possible for the EMU liquid transport circuit. However, before this can be determined possible, a feasibility assessment will have to be performed to determine if the pressure drop of the filter will make this a viable option.

B. Potential In-Suit Filtering Applications

Finally, another possible implementation would be to incorporate an aquaporin-based filter into either the liquid transport or the feed water loop of the EMU. Similar to the ALCLR option, pressure drop and life-cycle analysis of the filter technology must be assessed before any feasibility determination can be made. If the technology proves viable, this too has the potential to provide unprecedented water quality in the EMU and would have dramatic positive implication for the longevity of the EMU water loops and sublimator.

VI. Conclusion

With the retirement of the Space Shuttle fleet, the near cost-prohibitive nature of launching water to the ISS for the use by only the EMU, the aging of the ISS water system, the time-varying composition of the ISS water, and the

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[§] The PWR is the term for water bags developed for on-orbit ISS usage to temporarily store water either for transport to the ISS or for storage on the ISS. PWRs have been tested and proven to allow any idolization to last up to 3 years before appreciable organic growth is observed.

highly sensitive heat rejection system of the EMU, a method of affordably providing pure water to the EMU is imperative. The promising benefits of the aquaporin technology, if realized, will provide a cost-effective source of ultrapure water required for the EMU and thus ensure U.S. EVA capability through the remaining life of the ISS.

Appendix

<We will reserve this space for the test results when they come in.>

Acknowledgments

<We will reserve this for the people running our tests, and any peer reviewer we get>.

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