Design Status of the Capillary Brine Residual in Containment Water Recovery System

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One of the goals of the AES Life Support System (LSS) Project is to achieve 98% water loop closure for long duration human exploration missions beyond low Earth orbit. To meet this objective, the AES LSS Project is developing technologies to recover water from wastewater brine; highly concentrated waste products generated from a primary water recovery system. The state of the art system used aboard the International Space Station (ISS) has the potential to recover up to 85% water from unine wastewater, leaving a significant amounts of water in the waste brine, the recovery of which is a critical technology gap that must be filled in order to enable long duration human exploration. Recovering water from the urine wastewater brine is complicated by the concentration of solids as water is removed from the brine, and the concentration of the corrosive, toxic chemicals used to stabilize the urine which fouls and degrades water processing hardware, and poses a hazard to operators and crew. Brine Residual in Containment (BRIC) is focused on solids management through a process of "in-place" drying - the drying of brines within the container used for final disposal. Application of in-place drying has the potential to improve the safety and reliability of the system by reducing the exposure to crew and hardware to the problematic brine residual. Through a collaboration between the NASA Johnson Space Center and Portland Status University, a novel water recovery system was developed that utilizes containment geometry to support passive capillary flow and static phase separation allowing free surface evaporation to take place in a microgravity environment. A notional design for an ISS demonstration system was developed. This paper describes the concept for the system level design.

Nomenclature

AES	=	Advanced Exploration Systems
ARFTA	=	Advanced Recycle Filter Tank Assembly
ARS	=	Air Revitalization System
BRIC	=	Brine Residual in Containment
CAD	=	Computer Aided Design
CapiBRIC	=	Capillary Brine Residual in Containment
CMM	=	Cubic Meters per Minute
LSS	=	Life Support Systems
ISS	=	International Space Station
JETS	=	Jacobs Engineering, Technology and Science
PSU	=	Portland State University
PTAU	=	Pretreated Augmented Urine
TCCA	=	Trace Contaminant Control System
UPA	=	Urine Processor Assembly
VDC	=	Volts Direct Current
WPA	=	Water Processor Assembly

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I. Introduction

Technologies that effect primary and/or secondary wastewater treatment invariably generate a residual brine waste stream. The brines generated typically contain significant amounts of water, the recovery of which is critical to closing the spacecraft water loop and enabling long duration exploration. Further complicating the recovery of water from the brine waste stream, the dried residual waste tends to be laden with toxic solids which pose a hazard to crew and are corrosive and highly fouling to the water processing hardware. The goal is to achieve 98% water recovery which requires a brine processor to achieve. Currently, there exists no state of the art in brine dewatering technology and, therefore, no current means of closing this critical spacecraft water technology gap. Brine Residual in Containment (BRIC) is concept for brine water recovery that is focused on solids management through a process of “in-place” drying - the drying of brines within the container used for final disposal. The BRIC concept was developed in 2011 with the initial focus on integration into a terrestrial application such for a Lunar or Mars base[2,3]. As an extension of the BRIC concept for exploration, a novel approach of optimizing the evaporator geometry has been proposed to support passive capillary flow, static phase separation, and evaporation to take place in a microgravity environment. The technology maturation of the concept, referred to as CapiBRIC, is described herein.

II. CapiBRIC Concept Description

The concept for a capillary-based brine drying system was co-developed through NASA and Portland State University, and has been described previously by Callahan et al.,[4]. The conceived system employs capillary forces generated using the combined effects of surface tension, wetting and container geometry to create a “microgravity bucket” from which static phase separation and brine drying can be acoomplished similar to drying on Earth. The initial focus was placed on the development of a capillary device that would be expected to: (1) provide sufficient free surface area for unimpeded brine evaporation in microgravity; i.e. a ‘microgravity bucket’ or drying tray, (2) maintain stability of a brine “pool” when subjected to relevant loads, and (3) be capable of passive capillary pumping to fully saturate the device and maintain infilling rates during the brine drying process. The first incarnation of the device that was conceived to accomplish this consisted of a unique capillary-based geometry. The tray, by capillary action, would contain the brine in a cylindrical “pool” within a drying chamber, Figure 1. Air is sweeped between the annular space created between the brine “pool” and the containment layer. Clean water vapor evaporated from the free surface is conducted out of the chamber as a humidified sweep gas. Waste brine solids are left behind in the structure. At the end of the process, the mostly solid brine residual remains contained in the device which can then be disposed of and replaced with a fresh unit.

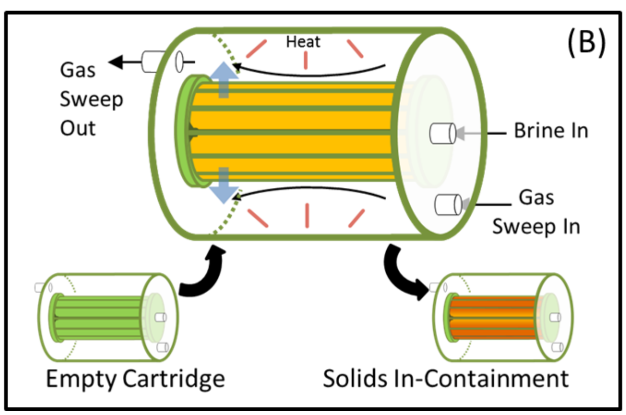

Figure 1. Capillary based static containment BRIC concept. Figure presents the concept discussed in this paper where a capillary device contains the brine pool. The brine pool concentrates as water is evaporated and removed by the sweep gas. The remaining brine residual may be discarded with the capillary device.

A. CapiBRIC System Design

Figure 2 shows the notional system for a CapiBRIC concept. The system would receive brine from the primary water recovery processor, e.g. the ISS Urine Processor Assembly (UPA), with interface defined by the system providing the brine. A sweep gas would then be drawn from the local environment and introduced to the free evaporation surface of the capillary-based brine drying unit. The humidified sweep air is then expelled via a vent to the local environment. The vehicle Air Revitalization System (ARS) and/or Trace Contaminant Control System (TCCS) is relied upon to remove containants, if necessary, and to recover the moisture as condensation provided to the water polishing system, e.g. the ISS Water Processor Assembly (WPA).

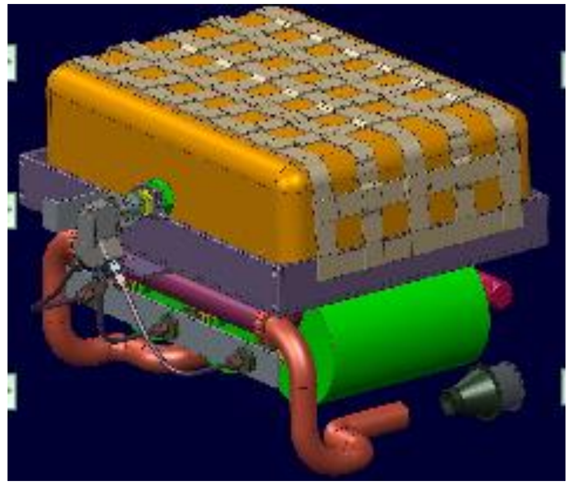

Figure 2. CapiBRIC System Context

The CapiBRIC system is intended to be as simple and passive as possible while maintaining crew safety and reliability. While the system only needs a sweep gas to function, heat and reduced pressure may be used to increase production rate and overall recovery process. Figure 3 shows a notional system layout in which heater is included. A very low flow of sweep gas is provided by a blower. The overall flow air rate is limited to prevent entrainment of gas in the evaporator. Evaporation will be driven by the vapor pressure differential between the free brine surface and the sweep gas. Water vapor diffused into the sweep gas will result in a higher relative humidity with some other volatile gases relative to the inle air stream. Testing has indicated an exhaust relative humidity approximately 10% higher than the inlet. For any gas phase contaminants or odors is expected that in an Exploration mission the CapiBRIC exhaust might be integrated such that the vent gas is sent directly to the ARS or TCCS system. A demonstration on the ISS might require an odor control device at the vent outlet. Options for the absorption filter in the outlet gas stream are being considered. On the liquid side of the system, brine is received from the primary processor, and stored in an intermediate reservoir. The design assumes that brine is provided by the ISS Urine Processor Assembly (UPA) Advanced Recycle Filter Tank Assembly (ARFTA). The brine stored in the reservoir is hydraulically isolated from the primary processor and connected and open to the BRIC evaporator when processing. In the concept as proposed, each BRIC evaporator is sized to hold 1-L of brine. The baseline design assumes capillary forces will draw brine from the reservoir into the evaporator and maintain a constant volume within the evaporator, replacing water evaporated with an equivalent volume of fresh brine at the rate of evaporation. As described previously, residual brine solids accumulate in the evaporator the unit is full or evaporation rate become self limiting. Each unit is expected to be able to process between 3 to 7 L of brine depending on the composition of the pretreated urine and the percent recovery achieved in the UPA. The design also included an inlet and outlet filter, an optional heater with temperature controller, absolute or relative humidity sensors to monitor the drying process, a liquid sensor, a delta pressure sensor In general pressure control will be critical to maintain the capillary flow throughout the process.

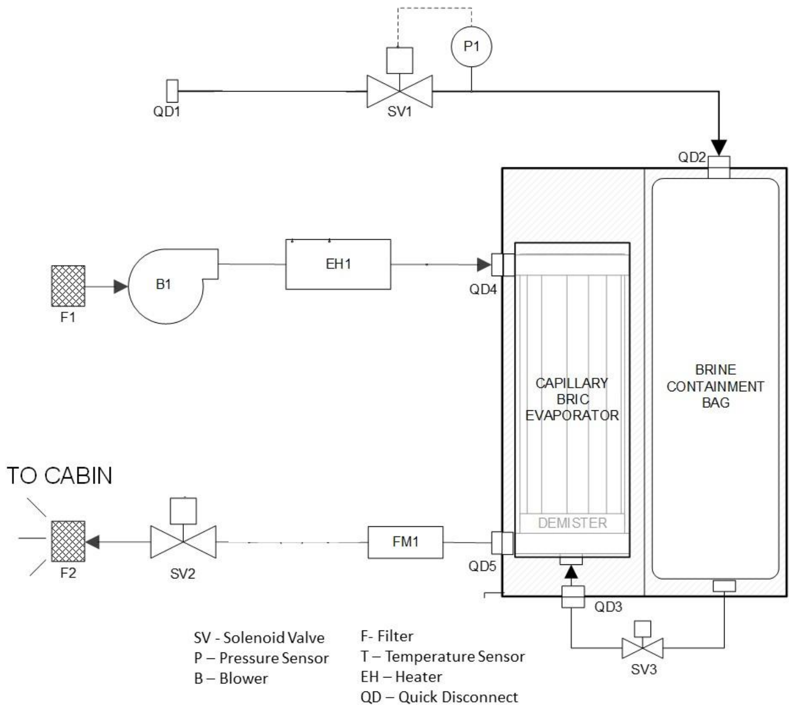

Figure 3. CapiBRIC Notional Flow Schematic

1. *Evaporator Core Design*

The heart of the CapiBRIC system is the capillary evaporator. The capillary containment tray contains the brine and provides a surface area for evaporation. Capillary containment is provided a unique geometery. End caps and containment layers close out the assembly to provide porting for brine and sweep gas interfaces and to allow the units to be hemetically sealed for disposal after use. The containment layers are anticipated to be constructed of light weight materials. A notional cross-section of the evaporator is shown in Figure 4.

2. *Safety Features*

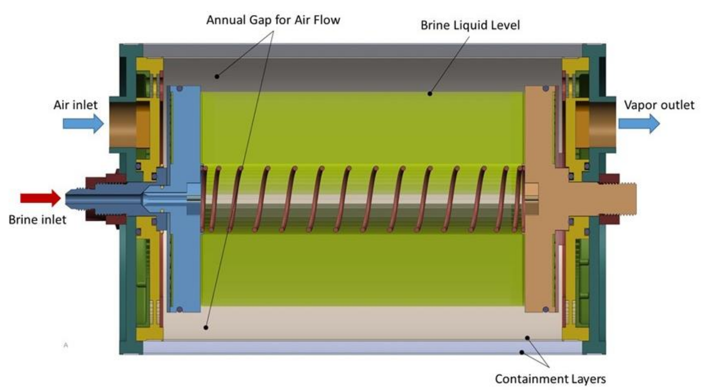

Figure 4. Cross Section of evaporator sub-assembly with highlighted features and fluid flow (left),

The capillary evaporator assembly incorporates a specific geometry to contain brine while maintaining a free surface for evaporation. Figure 5 a CAD model of the capillary drying unit. A light weight inner shell provides a level of containment if liquid were to "spill" from the tray. Another level of containment is provided by the outer shell, expected to be more robust to protect the system from puncture or deformity. A demister is incorporated at the vent ports to contain any liquid that escapes the capillary evaporator tray to prevent release of liquid brine should it become entrained in the sweep gas. This feature could also be incorporated outside the disposable BRIC unit to minimize the complexity of the assembly and save on consumable mass. On the air side, a retaining shutter is incorporated to end cap to seal the flow passage prior to removal of the tray. On the liquid side, a light weight quick disconnect on the brine inlet seals the liquid passage when the unit is removed from the system. A blower and optional controllable heater will be incorpated to the drive evaporation process. The blower speed is intended to be predefined and energized during the entire drying process; therefore, no feedback for real time control of the blower is incorporated at this time. The temperature is controlled by a thermostat circuit on the heater with feedback provided by a sweep gas temperature sensor. A cut-off circuit cuts power to the heater if the maximum temperature (set by the local materials temperature limits) is exceeded. Humidity sensors are placed before and after the evaporators. When the system is processing, the humidity levels are fairly static in reference to each other. A spike or drop in downstream humidity relative to upstream humidity may indicate a drop in sweep gas flow or a dry tray, respectively. A delta pressure sensor is place about the evaporator. An increase in delta pressure may indicate a clogged and/or breached demister. A liquid sensor is incorporated in the exhaust line. Power to the blower is cut if this sensor indicates the presence of liquid brine. Power is also cut to the nominal closed solenoid valve between the brine reservoir and evaporator.

Figure 5. CAD model of capillary drying unit.

B. Suitability for Exploration

The CapiBRIC system is designed specifically to function in microgravity. The geometry may be also modified for functionality in partial gravity environments. The materials of construction for the CapiBRIC system, especially the evaporator unit, must be compatible with the corrosive pretreated urine brines. Although, evaporator containment is driven by its geometry, the surface properties of the materials used in construction will be chosen for to best optimize the enhanced the stability and performance of the tray. The CapiBRIC core technology is inherently flexible to support a variety of mission. Since containment and phase separation are a function of the container geometry, surface tension and wetting characteristics, it is expected that the design as is and/or can be slightly modified to accommodate various wastewater compositions, including wastewater that contains surfactants. The CapiBRIC is highly modular on-demand system that should easily accommodate different crew sizes with fluctuating wastestreams and utilization profiles.

C. System Operation

Based on the vane evaporator design, the CapiBRIC is intended to function on a batch basis. Specifically, a 22-L batch of brine is received from the primary processor to the CapiBRIC brine reservoir. The brine drying units are filled a by capillary driving pressure between the reservoir and each drying unit. The drying sweep gas is passed through the annular gap between the cylindrical brine pool and the inner containment shell. As water vapor is removed a capillary underpressure is generated and more brine moves to the evaporator. The process continues until the evaporator becomes full of solids or evaporation rates become self limiting. The crew is required to change out the evaporator cartridge and initiate the next batch. An 80% duty cycle is targeted which correlates to a 17.6 days / 22 L batch of brine processed. In an exploration mission, the alerts provided in Table 1 would be expected to be transmitted based on hazards, failures and under performance of the system. With the CapiBRIC design, a maximum water recovery ratio of 80 – 90% is expected. With a drastically reduced diffusion length, the alternate BRIC evaporator concepts are expected to facilitate drying at high drying rates which may allow higher water recoveries.

Table 1. Summary of CapiBRIC Hazards, Operational Failures and Performance Issues

System Hazards/Operational Failures	Loss of Performance	Degraded Performance
Power to system over/under - current sensor	Air is not flowing - dP sensor	Vapor content out of range - absolute humidity sensors
Blower is not blowing - RPM feedback, current sensor	Air is not hot - temperature sensor	Brine flow is slow - quantity indicator on reservoir (TBD)
Heater is not heating - temperature, current sensor	Brine is not flowing - quantity indicator on reservoir (potentiometer integrated with net)	-
Heater is too hot (fire hazard) – heater temperature	System not evaporating – Absolute Humidity sensors	-

D. Mass

A packaging exercise was peformed assuming an EXPRESS Rack double locker. Assuming 85% recovery, the system mass is 0.683 kg / kg-water recovered over the mission. The system is estimated to use about 164 W during operation. Assuming an 80% duty cycle (or 17.6 d cycle), the power should be 56.6 kW-hr per cycle. Assuming 85% recovery of water from brine, the power is 3.8 kW-hr/kg-water recovered. Estimates on the consumable mass, i.e., mass of the disposal evaporator to kg of water produced, can be estimated once higher fidelity designs of the evaporator subassembly are known.

E. System Reliability

The system is designed to support three years of operation. The following features of the core technology lead to enhanced reliability:

- One time use limits degraded performance associated with operational wear
- Limited moving parts during operation
- In-place containment eliminates the need to manage brine residuals

Non-routine maintenance for the system has not been defined at this time.

F. Testing

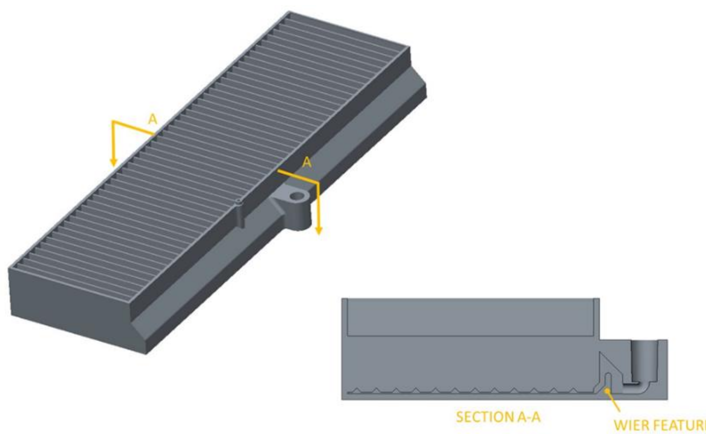

Figure 6. CAD Model of the 1-g Analogue Brine Drying Tray.

Given the presence of gravity, particular aspects of the capillary fluidics approach cannot be tested at full-scale as the force of gravity would dominate over the capillary length scales proposed for an on orbit system. However, testing was performed at Portland State University (PSU) to characterize the infill and stability of fluids within the structure using subscale units in the PSU drop tower used for short duration microgravity simulation. In addition, subscale tests were performed using a spacecraft urine brine analogue to estimate drying rates in wedge and rectilinear structures and in various gravity orientations of the free drying surface, including: drying surface up, perpendicular and down with respect to the gravity field. Included in these assessments were the effects of solids concentration of the brine, air humidity, temperature, and air speed, surface area and contact line length. In general, these tests and analyses have been used to determine the appropriate size of the evaporator to ensure capillary flow rates and the stability of the system against nominal and off-nominal loads, and to suggest that evaporation rates in microgravity can be expected to be relative to ground testing. Finally, in order to augment the subscale testing, a full scale 1-g analogue of the CapiBRIC drying unit was initiated to help validate performance predictions regarding expected water recovery ratio, estimated processing time, and interface definitions for inlets, outlets, and internal processes, including vent gas composition. Testing was conducted using 85% recovered pretreated augmented urine (PTAU) stabilized using the ISS alterntive formuation.[5] The 1-g drying tray simulated the geometry of the capillary evaporator by unfurling the cylindrical design into a flat horizontal arrangement, Figure 6. In addition, the tray test article included aspects of the microgravity evaporator assembly including, the air plenum and demister. The test stand also included a radial blower, ducting, upstream and downstream temperature and relative humidity sensors. Testing involved initial fill of the CapiBRIC drying tray with 1L volume of the PTAU brine solution supplied by gravity feed from a 4-l bag bladder reservoir. The radial blower was then energized with 18 volts direct current (VDC) supplying an estimated 3 meter per second air speed or a volumetric air flow of 0.205 cubic meters per minute (CMM) over surface of the drying tray. Limited vent gas sampling was also performed at the beginning and end of the drying test. Preliminary testing of the air drying system with no heater suggests that exhaust gas contimaminants are well below the levels defined for the ISS[6]. Figure 5 shows an example of a 1-g analogue test run with the blower on, no heater, ambient temperatures, and relative humidities of approximately 43 and 52%, for the inlet and outlet air respectively. Figure 7 shows an example of a drying curve for an 85 to 87% Alternative PTAU brine dried in the 1-g anologue brine drying tray test article. The estimate of the percent water recovery achieved was 73% in approximately 12 days. This recovery level is approximately that needed to achieve 98% total recovery for a combined water recovery from the urine and brine processor. It is predicted from the data that the targeted performance can be met in the 17 day, 80% duty cycle, specified for the system. The addition of heat can be used to accelerate the time to dryness and/or overall water recovery rate. In addition, heat can be used if the relative humidity of the spacecraft environment is higher and more variable than expected for the targeted performance. Finally, alternative tray geometries are being considered that are expected to speed the overall drying rate based on the diffusion lengths within the drying structure.

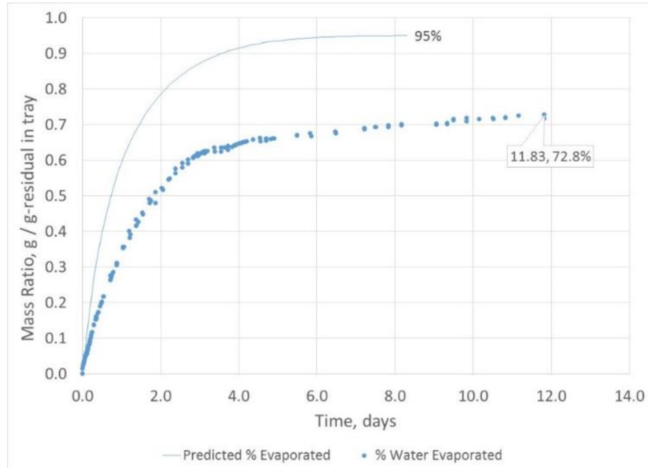

Figure 7. Example of PTAU brine drying curve in 1-g analogue tray test article.

III. Forward Work

Under the AES LSS development plan, concepts for incorporating brine dewatering systems within a Water Recovery System (WRS) have been developed and evaluated. In a push to advance these technologies, a down-selection was held under the LSS project. Although not selected as the primary technology for immediate development toward a technology demonstration on the International Space Station (ISS), the down-select panel determined the CapBRIC concept showed sufficient promise as a alternative spacecraft brine processor. The recommendation of the board was to focus future technology development on reducing the consumable mass associated with the disposable evaporator and on resolving the technical issue associated with balancing the pressure differential between the feed reservoir and the evaporator, preferably by eliminating the feed reservoir. Under the current CapiBRIC work plan, the following tasks have been identified for forward on work: (1) Redefinition of CapiBRIC concept for a “single-fill” operation. An alternative concept has been developed based on a new tray geometry developed in colloabration with IRPI, LLC through a Small Buisness Research Initiative (SBIR) Phase I effort, (2) Develop, through prototype and test, a new CapiBRIC evaporator tray assembly with focus on weight reduction of the consuummable elements of the design, improved evaporation performance, and updated mass, power and volume estimates for the revised system-level design, (3) Development of a revised system definition document based on the updated design. In addition, the project intends to participate in a ISS flight opportunity to demonstrate the fundamental asspects of the capillary approach proposed for the CapiBRIC concept. Assuming the system is able to satisfactorly meet the figures of merit deemed relevant for a future brine processing system, the opportunity for continued development of the CapiBRIC system toward a full technology demonstration on the ISS is intended to be pursued.

IV. Conclusion

It highly likely that brine dewatering can be conducted in low-g in nearly the same manner as on Earth with capillary forces replacing the role of gravitational forces. Through this work, a concept for a capillary-based brine drying system has been proposed. At the core of the design is a capillary drying tray or ‘bucket’ which will produce and contain a cylindrical pool of liquid in microgravity. A design for the evaporator assembly provides the necessary features for port interfaces and containment of the brine, including sealable end caps and lightweight flexible side walls. A concept for operation of a CapiBRIC system has been established and preliminary analysis of the system mass, power and volume has been performed. The data package was developed based on the design and has been reviewed by by a panel of experts who determined that system has promise as a future brine dewatering system for exploration. Recommended areas of maturation include the reductions in consumable mass of the evaporator and addressing the technical risk associated managing pressures for a continuous fill system. Future work is focused on the maturation of an alternative concept for a single fill one time use system, improving evaporation and recovery rates, and on completing a limited technology experiment on ISS to demonstrate the fundental asspects of the capillary approach proposed for the CapiBRIC system. The eventual goal of the project will be to develop the concept toward a full technology demonstration on the ISS.

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References

[1]Human Health, Life Support and Habitation Systems Technology Area 06, National Aeronautical Space Administration: April 2012.

[2]Callahan, M.R.; Casteel, M.R.; Glock, D.; and Pickering, K.D. Development of the BRIC Concept for Recovering Water from Wastewater Brines. 41st International Conference on Environmental Systems, AIAA, 2011

[3]Callahan, M.R., Pensinger, S.J., and Pickering, K.D., "Preliminary Feasibility Testing of the BRIC Brine Water Recovery Concept," AIAA 2012-3526, In *AIAA 42nd International Conference on Environmental Systems*, San Diego, CA, July 2012.

[4]Callahan, M.R., Sargusingh, M.J., Pickering, K.D., Weislogel, M.M.. "Advances in Spacecraft Brine Water Recovery: Development of a Radial Vaned Capillary Drying Tray" 44th International Conference on Environmental Systems, Tucson, AZ, 2014.

[5]Mitchell, J.L.; Broyan, J.L.; Pickering, K.D.; Adam, N.; Casteel, M., Callahan, M., and Carrier, C. Ion Exchange Technology Development in Support of the Urine Processor Assembly Precipitation Prevention Project for the International Space Station. 42nd International Conference on Environmental Systems, AIAA, 2012

[6]*Spacecraft Maximum Allowable Concentrations for Airborne Contaminants*, JSC-20584.