10-14 July 2016, Vienna, Austria

Development of the Continuous-fill Brine Evaporation Bag (BEB) System

Lance Delzeit[1].
NASA Ames Research Center, Moffett Field, CA, 94035

Anna Hayden[2] and Caleb Felker[2]
Space Life Sciences Internship Program, Moffett Field, CA, 94035

Hali Shaw[3]
UCSC, Moffett Field, CA, 94035

David Beeler[4]
Bionetics, Moffett Field, CA, 94035

and

Kevin Howard`[5]
Wyle, Moffett Field, CA, 94035

The existing water recovery system on the International Space Station (ISS) is limited to 70% reclamation; consequently, long duration space missions are currently unfeasible due to the large quantity of water necessary to sustain the crew. The Brine Evaporation Bag (BEB) is a proposed system to supplement the existing water recovery system aboard the ISS and future deep space missions that can increase water recovery to 99%. The BEB project previously focused on the development of only the bag portion of the system. This paper focuses on the development of the BEB Evaporator. It will discuss the work to understand, optimize, and improve the entire BEB system while implementing a continuous-fill process. The results of that development and the advantages and limitations of the continuous-fill process will be presented.

Nomenclature

ΔP	=	Differential Pressure
ARFTA	=	Advanced Recycle Filter Tank Assembly
BEB	=	Brine Evaporation Bag
Cr	=	Chromium
EDV	=	Russian liquid transfer tank on the ISS
ePTFE	=	expanded Polytetrafluoroethylene
ISS	=	International Space Station
mil	=	0.001 inches
mN/m	=	millinewton per meter
PU	=	Polyurethane

---

[1] Physical Scientist, Bioengineering Branch, and Mail Stop 239-15.
[2] Engineer, Bioengineering Branch, and Mail Stop 239-15.
[3] Engineer, Bioengineering Branch, and Mail Stop 239-15.
[4] Engineer, Bioengineering Branch, and Mail Stop 239-15.
[5] Engineer, Bioengineering Branch, and Mail Stop 239-15.

I. Introduction

NASA has reviewed 27 different brine drying technologies with the potential for space applications.1 The Brine Evaporation Bag (BEB)[2-6] is one of those brine drying technologies.[2-10] Past research showed the feasibility of the BEB's basic technology and its potential for space applications;[5] however, that research focused on modifications to the BEB bag and not the entire BEB system. This paper focuses on the development of the BEB evaporator and the complete BEB system. The goal is to develop a continuously-filled BEB System that occupies a smaller volume than a batch system. Three generations of continuous-fill BEB prototypes were built and tested and the results are presented in this paper.

The brine used in this research effort is the ISS (International Space Station) Alternate Pretreat Brine.[11] It is made from urine with phosphoric acid, chromic acid, and other chemicals added and has been dewatered to reduce the volume by 80%.

This paper is the first description of a Continuous-fill BEB System and focuses on the physical development and operation of that system. A sister paper is also being publish which describes the performance characteristics of the Continuous-fill BEB System.[12]

II. Development of the Continuous-fill Subsystem

The BEB System is composed of two major components which work in conjunction with each other: the BEB and the BEB Evaporator (Figure 1). The BEB consists of a sealed bag containing a hydrophobic ePTFE membrane that allows water vapor and gases to pass through. It is operated under vacuum and heated to boil away the water at low temperatures. The water vapor is recovered and the solids are contained inside the bag for disposal. The BEB evaporator is an aluminum vacuum chamber that provides heating, and secondary containment for the BEB. The BEB is formed by heat sealing the top and bottom polyurethane sheets together along the outer lip. This heat seal is then pinched between the lid and the box of the BEB Evaporator which adds one additional mechanism for ensuring that the seam does not leak. The polyurethane sheets used range from 8 to 14 mil thick.

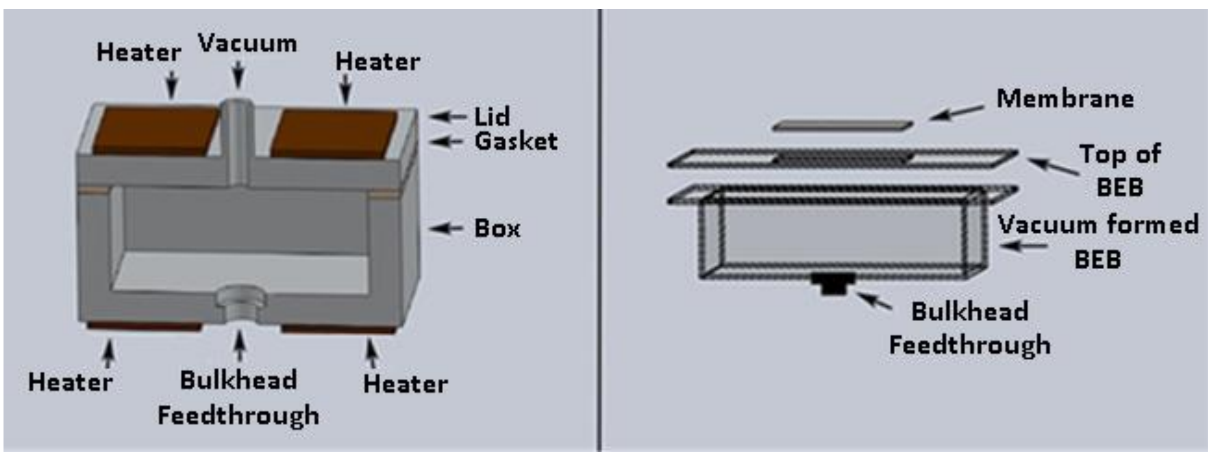

Figure 1. The BEB evaporator (left) and BEB (right).

The entire Continuous-fill BEB System includes several auxiliary components and is shown in Figure 2. The Continuous-fill BEB System is filled from a reservoir of brine which, on the ISS, could be an Advanced Recycle Filter Tank Assembly (ARFTA) or an EDV (Russian liquid transfer tank).

The BEB produces steam at nominally 70°C and 100 torr (the BEB's normal operating condition). The steam, as it is compressed within the vacuum pump up to 760 torr (atmospheric pressure), is condensed to liquid water. Thus, the natural product of the BEB System is liquid water which can be pumped directly into a storage tank (EDV), or alternatively, directly back into the primary water processing system. Therefore, the water and other volatile organics[12] which accompany the water vaper, are never released into the cabin as is required with air evaporation systems (unless they add additional equipment such as condensers, gas-liquid separators, etc.).

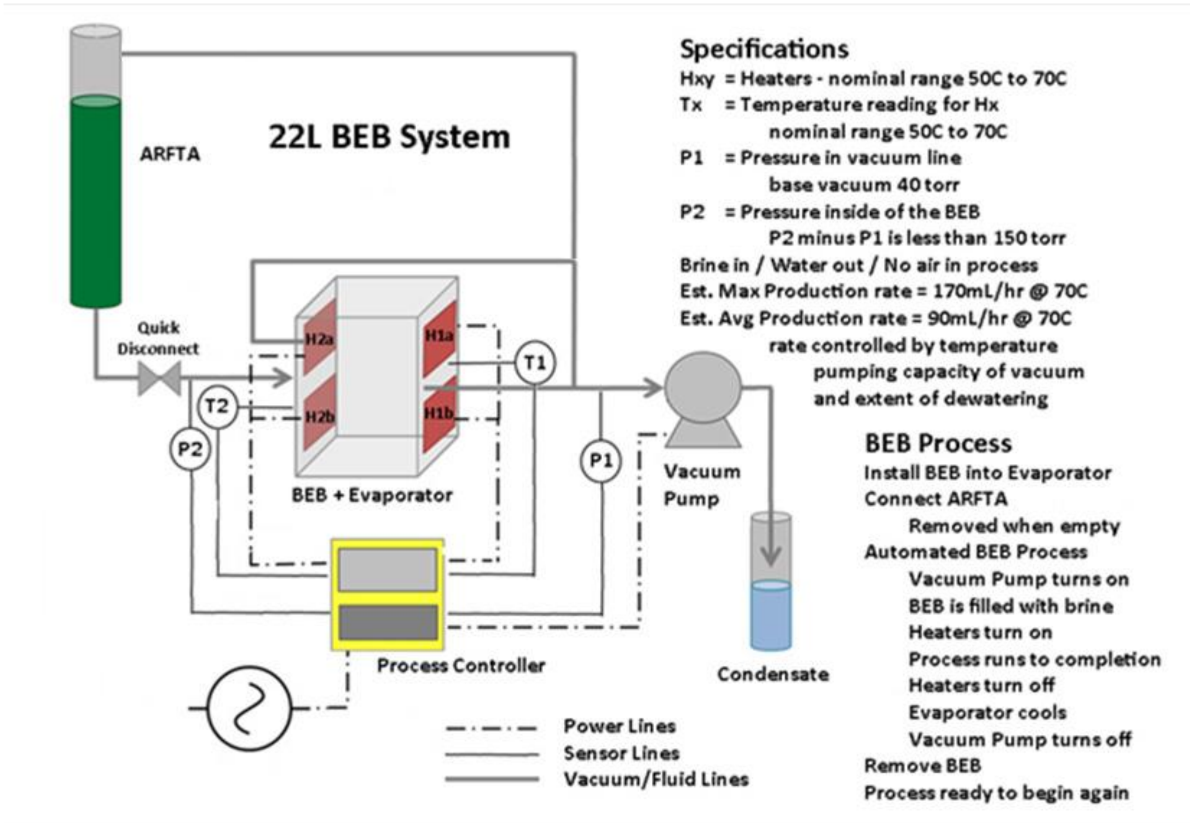

Figure 2. Schematic of the BEB System.

A. 1 ATM ΔP Filling of the BEB

Historically, the BEB Evaporator could only operate in batch mode and was simply filled once in a batch mode and then run.[6] The initial design for the continuous-fill process used a simple connection between the BEB and the reservoir for filling the BEB as the water vapor was removed. The differential pressure between the reservoir and the BEB drives the continuous-fill process, keeping the BEB filled during the dewatering process. This design of the Continuous-fill BEB System is microgravity compatible and would only require the ARFTA or EDV to leave the bellows open to cabin pressure.

The result of this fill method is shown in Figure 3. The 1 atmosphere pressure difference across the membrane (ΔP) forced the brine through the 0.1 micron pores of the membrane. Initially this was surprising since the water breakthrough pressure for the membrane is 4 atmospheres: four times higher than the applied ΔP. After reexamining the situation, however, the cause of the leakage became clear. The water breakthrough pressure is based upon the surface tension of the brine, which is much lower than that of water.

It should be noted that even though the brine had broken through the membrane, the brine did not continue to flow through. This phenomenon, which I will call "scabbing", will be discussed below in detail. It is best seen in Figure 3B where the transparent lid is still in place and there is no sign of liquid between the membrane and the lid. If the membrane had continued to leak after breakthrough, there would be either liquid or dried brine residue visible between the membrane and lid, and there is neither.

Figure 4 shows the surface tension of urine verses its concentration.[13] It shows that the surface tension of the urine decreases as the concentration of the urine increases. Extrapolating the linear part of the graph in Figure 4 to the starting concentration of the brine, it can be seen that the surface tension of the brine is expected to decrease to approximately 43 mN/m. This decreased surface tension results in a lower membrane breakthrough pressure for the brine as compared to water. Thus, the 0.1 micron membrane leaks at a ΔP of 1 atmosphere.

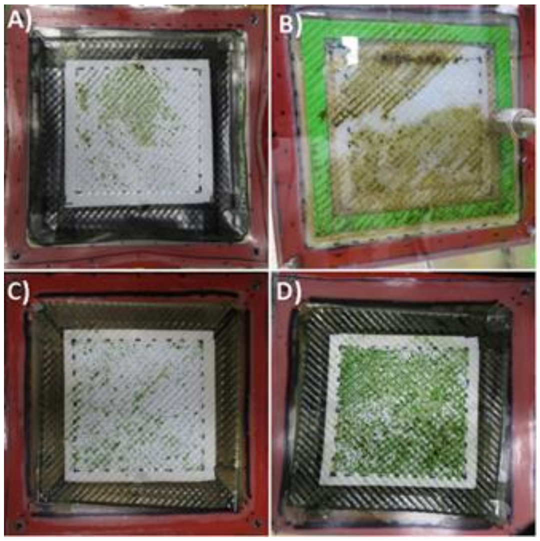

Figure 3. Image of 4 continuous-fill experiments where atmospheric pressure was used to fill the BEB resulting in the brine being forced through the membrane. Note: B) shows the green tape which is part of the screen spacer between the membrane and the Plexiglas BEB Evaporator Lid.

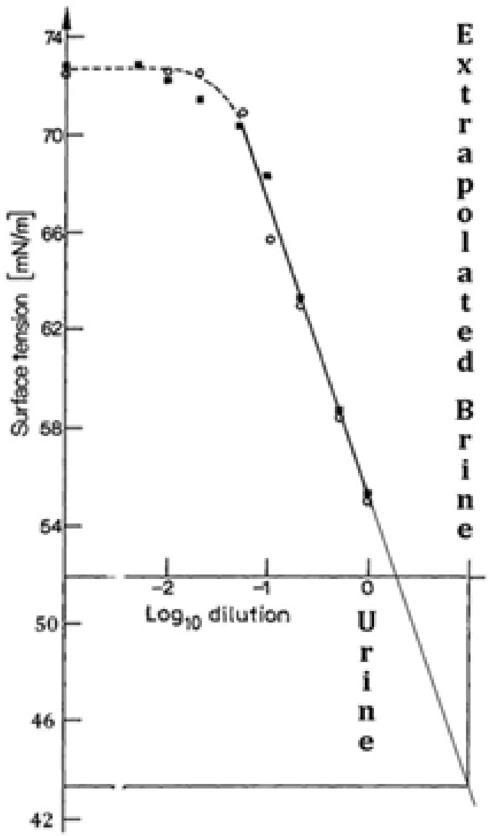

Figure 4. Graph of the surface tension of diluted urine extrapolated to the starting concentration of the brine feed.

B. 1 ATM On/Off Valve-filling of BEB

In order to control the pressure within the BEB, an on/off value was installed into the line between the reservoir and the BEB, as well as a pressure gauge to monitor the pressure within the BEB. The pressure gauge was used to meter brine into the BEB and to keep the pressure within the BEB reduced.

The result of this setup was less than satisfactory (data not shown). With the batch-like injections of brine into the BEB, the temperature, pressure, and production rate were all unstable. With the initial injection of brine, the temperature of the BEB System drops, also causing a drop in the pressure within the BEB. After the BEB is top-off with the additional brine, the temperature increases along with the pressure within the BEB. This behavior is the result of temperature changes of the gas trapped within the BEB, as well as the release of dissolved gas from the freshly added brine adding to the pressure within the BEB.

With these instabilities, the use of an on/off value to fill and control the pressure within the BEB was discarded in favor of a more continuous method of filling the BEB with brine while keeping better control over the pressure within the BEB.

C. Sub-atmosphere Continuous-filling of the BEB

In order to prevent the membrane from leaking and the instabilities of the on/off filling method, a sub-atmosphere continuous-filling method was developed. This continuous-fill method keeps the ΔP across the membrane low by capping the brine reservoir and applying a partial vacuum to the headspace above the brine. In this geometry, the ΔP across the membrane can be controlled.

It was observed that brine leaked through the membrane at a headspace pressure greater than 350 torr. For headspace pressures between 350 and 250 torr, reduced breakthrough was observed. Therefore, the headspace pressure was limited to less than 150 torr in order to control breakthrough. With the base pressure of the vacuum system at nominally 25 torr, the ΔP across the membrane is below 125 torr. Even at this low ΔP across the membrane, occasional pinhole leaks (which "scabbed over") were identified with close scrutiny. These spots are a result of the occasional large pore that is present which lies significantly outside the normal distribution of pore sizes.

Since even small pinhole leaks are undesirable because of the potential for astronaut exposure to Cr(VI), a double membrane construct was developed. The single membrane that made up the top of the BEB (Figure 1) was replaced with the three-layer, double-membrane of Figure 5. In this construct, the inner membrane (membrane against the brine) performs the same function as the original single membrane. However, since this membrane can still have minute pinhole leaks which scab over, a second membrane is included to prevent inadvertent contact when the BEB is handled. The screen spacer between the membranes prevents the pinhole leak from contacting the second membrane.

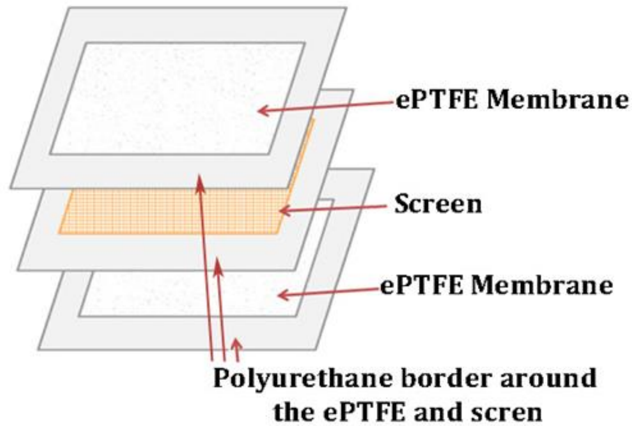

Figure 5. Screen reinforced membrane construct.

Numerous BEBs were built and tested using the double membrane construct. Figure 6 shows the top of six BEBs after the completion of their runs. By visual inspection, none of them showed any sign of leakage through the double-membrane construct. The membranes are pristine white indicating no brine leakage through the double membrane construct. Contrast the pristine white of the membranes in Figure 6 against the green stained membranes of Figure 3 where the brine leaked through the membrane.

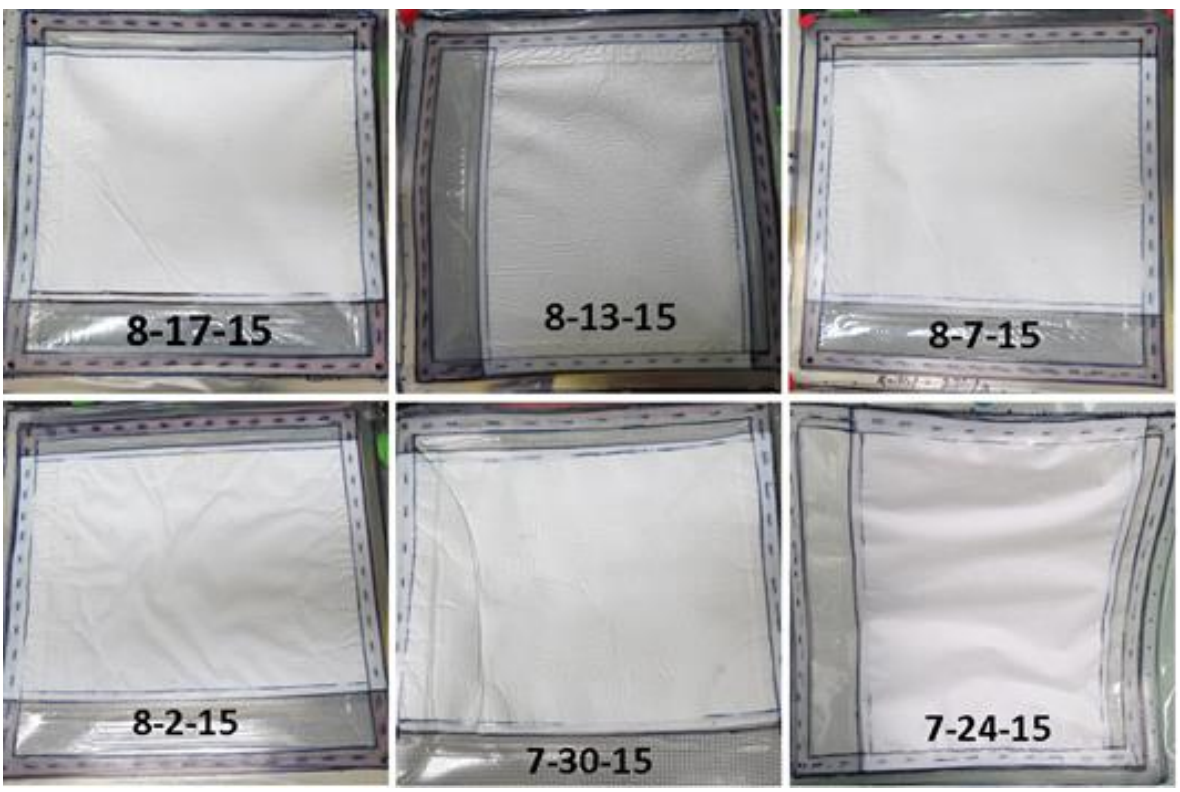

Figure 6. The membrane of the 6 Gen3 BEBs at the end of their runs. No evidence of membrane leakage is identified.

D. Solidification of the Brine Residue

During the development of the BEB, it was discovered that the brine could be dried to a solid block. Prior experience with air evaporation systems was that brine could only be dried to a viscous liquid[7] or with the BEB System a thick paste.[6] It was found that if the drying process was continued for an additional 3 day past the normal finish point of the dewatering process, that the brine residue would be solidified, i.e., converted into a solid.

The normal finish point for an experiment was when the brine feed rate into the BEB and the water production rate both decreased to only a few mL/hr. At this point the brine feed would be closed off, but the rest of the BEB System was allowed to operate normally. Normally, no additional liquid water was produced after closing the brine feed. The water recovery rate was generally around 95% at the normal end point, and nominally 100% after solidification.[12] Drying experiments show that the quantity of water remaining in the solidified brine residue is on the order of a 1/100th hydrate (data not shown).

The solidification process produced little additional water but rather greatly increases the safety of the brine residual by converting it from a liquid which can flow to a solid which won't. Figure 7 shows a BEB which has been dried for the 3 additional days past the normal dewatering end point. This BEB has also been sitting on its fill port at an angle for over six months without deformation or flowing. After solidification, the BEB us generally 60 - 80% filled with brine residue (Figure 7 and Reference 12, additional data not shown). This implies that the ISS Alternate Pretreat Brine is 30 – 40% solids.

Figure 7. A Gen3 BEB processed 3 additional days past its normal end point resulting in a solid residue.

E. Polyurethane BEB Compatibility

Polyurethane is a broad class of copolymer traditionally formed by reacting a diisocyanate with a diol. Block copolymer variants are made by using a mixture of long and short chain diol to create "hard" and "soft" segments within the polyurethane block copolymer which allow for a tailoring of the polyurethane properties. As a class, polyurethanes can have widely varying properties and are generally rated poorly for their chemical compatibility with acids. As such, a long term investigation of the chemical compatibility of the polyurethane used in the construction of the BEB was undertaken.

Figure 8 shows a BEB which contains a 50% dewatered brine. The polyurethane bag shows no sign of leakage or degradation even after 12 months of storage at room temperature. Thus, the polyurethane film used appears to have an acceptable chemical compatibility with the ISS Alternate Pretreat brine. The polyurethane film tested was 12 mil.

Figure 8. Image of a BEB which has been filled with brine for over 12 months with no sign of polyurethane film degradation.

F. BEB Balloon

Figure 9 shows a "BEB balloon". The top of the BEB was sealed and then inflated. The "BEB Balloon" inflated to nominally 20 times its original volume without rupturing. This indicates that a BEB inside of the BEB Evaporator can easily expand the fractional increase in its volume if a pressurization anomaly occurs.

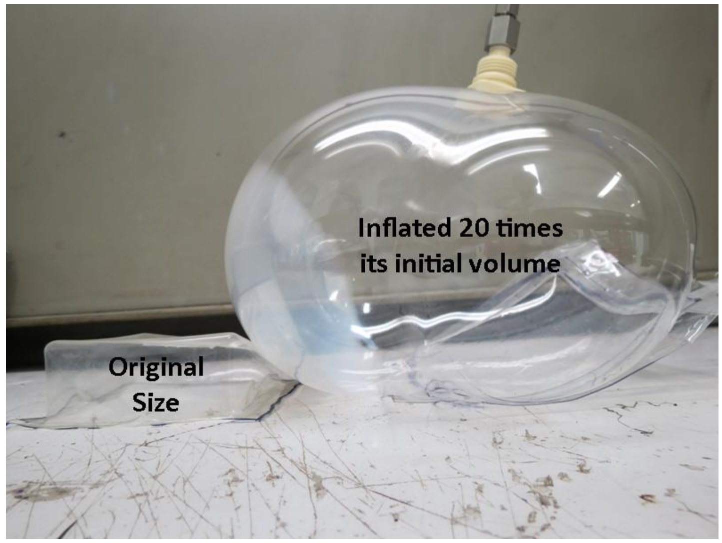

Figure 9. A BEB balloon inflated to 20 times its original volume without rupturing.

G. Discussion of Membrane Breakthrough and "Scabbing"

The breakthrough pressure of a pore of a hydrophobic membrane is described by the Young-Laplace Equation (Equation 1) where ΔP is the breakthrough pressure, r is the radius of the pore (assuming a cylindrical pore for simplicity), and γ is the surface tension of the fluid.

$$\Delta P = 2\gamma/r \quad \text{(Young-Laplace Equation)} \qquad \text{Equation 1}$$

Equation 1 shows quite simply how reducing a fluid's surface tension translates directly to a reduction of its breakthrough pressure. It would be expected that once a fluid breaks through a membrane, it will simply continue to flow through.

In contrast, for the BEB System, as soon as the brine breaks through the membrane, the leak appears to stop. This can be explained by considering the implications of Kelvin's Equation (Equation 2) as it applies to the BEB System.

$$P=P_o e^{2\gamma V_m/rRT} \quad \text{(Kelvin's Equation)} \qquad \text{Equation 2}$$

Equation 2 describes how the vapor pressure of a small droplet increases as the diameter of that droplet decreases. P is the actual vapor pressure of the fluid, P_o is the saturated vapor pressure, γ is surface tension, V_m is the molar volume, R is the ideal gas constant, T is the temperature, and r is the radius of the droplet.

This explanation is further illustrated in Figure 10. The water within the membrane has a reduced vapor pressure because of the concave curvature of the meniscus over each pore. If the brine breaks through the membrane, the curvature changes from concave to convex and the vapor pressure of the convex bubble of brine is increased (Equation 2). Because the water in the convex bubble has a higher vapor pressure (P) then the saturated vapor pressure (P_o) of the system, there is preferential vaporization of water from the convex bubble which has broken through the membrane. Additionally, as the water is removed from the convex bubble, its viscosity increases. The increased viscosity results in the leak "scabbing" over and stopping.

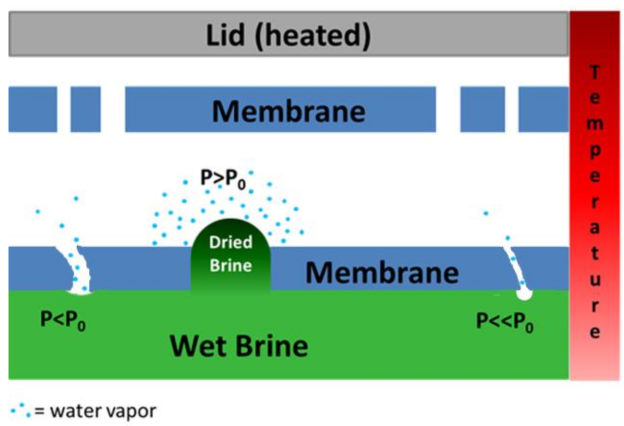

Figure 10. An illustration of how a pinhole leak preferentially dries and "scabs over" preventing any further leakage. P_o is the bulk vapor pressure based upon the temperature, and P is the actual vapor pressure.

Finally, as the convex bubble breaks through the membrane, it moves closer to the heated lid of the BEB. This further increases the brine's vapor pressure, adding to the "scabbing" effect.

III. Conclusion

A continuous-fill mechanism for the BEB System has been developed. The process works well as long as the ΔP across the membrane is kept below the breakthrough pressure of the membrane for the brine used. The breakthrough pressure for the ISS Alternate Pretreat brine tested was found to be between 250 and 350 torr. In order to prevent exposure to the Cr brine, the ΔP across the membrane was limited to less than 125 torr, and a double membrane construct was built. The double membrane construct prevents exposure to Cr brine even if the first membrane has seepage.

Polyurethane also underwent a long term exposure test. After 12 months of exposure, the polyurethane was still in a good, functional condition with no signs of degradation due to exposure to the brine.

Fortuitously, it was also discovered that by processing the BEB for an additional three days past the normal brine dewatering endpoint, the brine residue could be converted from a paste into a solid. The solidified brine residue recovers 100% of the water, makes the BEB easier to handle after processing, and prevents the possibility of liquid leaking out in the event of a bag puncture.

Acknowledgments

The authors would like to acknowledge the AES Life Support System Project for financial support.

References

[1] Jones, H.W., Wisniewski, R., Flynn, M., Shaw, H., "Space and Industrial Brine Drying Technologies", 44th Int. Conf. on Environmental Systems, ICES-2014-072, 13-17 July, Tucson.

[2] Lance Delzeit, John Fisher, and Alex Polansky, "Brine pH Change Resulting from Urea Hydrolysis and Implication to Brine Dewatering", 41st International Conference on Environmental Systems, ICES-2011-5143, 17-21 July 2011, Portland, Oregon.

[3] Lance Delzeit, John W. Fisher, Greg Pace, and Hali Shaw, "Brine Evaporation Bag Design Concept and Initial Test Results", 42nd International Conference on Environmental Systems, AIAA-2012-3525, 15-19 July 2012, San Diego, California.

[4] Lance Delzeit, John Fisher, Greg Pace, Eric Golliher, "Microgravity Behavior of Water within the Brine Evaporation Bag", 43rd International Conference on Environmental Systems, AIAA-2013-3373, 14-18 July 2013, Vail, Colorado.

[5] Lance Delzeit, John Fisher, Michael Flynn, Kevin Howard, Hali Shaw, and Deirdre Hyde, "Continued Development of the Brine Evaporation Bag", 44th International Conference on Environmental Systems, ICES-2014-017, 13-17 July 2014, Tucson, Arizona.

[6] Lance Delzeit, et.al., "Results for the Brine Evaporation Bag (BEB) Brine Processing Test", 45th International Conference on Environmental Systems, ICES-2015-67, 12-16 July 2015, Bellevue, Washington.

[7] Laura Kelsey, Patrick Pasadilla, John Fisher, and Jeff Lee, "Ionomer-membrane Water Processor (IWP) Engineering Development Unit (EDU)", Proceedings of the 45th International Conference on Environmental Systems, ICES-2015-124, 12-16 July 2015, Bellevue, Washington.

[8] James R. Akse, John Holtsnider, Richard Wheeler, John Fisher, "Brine Dewatering Using Ultrasonic Nebulization" SAE Paper No. 2004-01-2448, *Proceedings of the 34th International Conference on Environmental Systems*, 2004.

[9] Mona Hammoudeh, Michaela Brant, Ariella Yendler, Hali Shaw, Justine Try-My Richardson, Michael S. Roberts, Monica P. Soler, Todd E. Mortenson, Howard G Levine, Michele N. Birmele, LaShelle E. McCoy, Spencer WoodWard, Michael T. Flynn, Lance Delzeit, and Sherwin Gormly, "Microgravity Testing of the Forward Osmosis Bag (FOB), A Personal Water Purification Device", AIAA 2013-3472, 43rd International Conference on Environmental Systems, 2013.

[10] Michael R. Callahan, Miriam J. Sargusingh, and Karen D. Pickering, and Mark M. Weislogel, "Advances in Spacecraft Brine Water Recovery: Development of a Radial Vaned Capillary Drying Tray", 44th International Conference on Environmental Systems, ICES-2014-206, 2014, Tucson, Arizona.

[11] Shaw, H., Flynn, M., Wisniewski, R. Delzeit, L., Lee, J., Jones, H., Shull, S., Sargusingh, M., Beeler, D., Howard, J., Howard, K., Kawashima, B., Parodi, J., "Evaluation of Selected Brine Processing Technologies for

Spacecraft Wastewater", Paper No. ICES-2015-202, Proceedings of the 45th International Conference on Environmental Systems, July 2015.

[12] Lance Delzeit, Anna Hayden, Caleb Felker, Hali Shaw, David Beeler, and Kevin Howard, "Results of the Brine Evaporation Bag (BEB) Technology Down-Select Testing", 46th International Conference on Environmental Systems, ICES-2016-143, 10-14 July, Vienna, Austria.

[13] C.O. Mills, E. Elias, G.H.B. Martin, M.T.C. Woo, and A.F. Winder, "Surface Tension Properties of Human Urine: Relationship with Bile Salt Concentration", J. Clin. Chem. Clin. Biochem. Vol. 26, 1988, pp. 187-194.