Continued Development of the Brine Evaporation Bag

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The Brine Evaporation Bag (BEB) is a membrane based bag system for the dewatering of brine. Previous studies showed the ability of the BEB to dewater brine at low temperatures with a 96% mass reduction. Additionally, a microgravity flight showed the BEB is microgravity compatible.

Current work focuses on the effects of temperature, vacuum, purge gas flow rate, membrane area, and membrane permeability on the rate of dewatering within a vacuum oven configured to mimic the Heat Melt Compactor. Within this study, it was found that changing the temperature or level of vacuum would change the rate of dewatering. The purge gas, membrane area, and membrane permeability did not affect the dewater rate. The reason for this behavior may be that the dewatering is heat transfer limited, and out of all the parameters studied, only the temperature and vacuum have an effect on the heat transfer rate.

The ISS produces brine at a rate of 1.2 L/day. This initial study showed that it is possible to remove water from a BEB at a rate of 1.6 L/day in this breadboard configuration; even at moderate temperatures. Development of a dedicated BEB Evaporator will be discussed. In addition, it is further postulated that a specifically designed BEB Evaporator would result in an increased dewatering rate allowing for even lower operating temperatures or faster dewatering rates.

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Nomenclature

BEB	=	Brine Evaporation Bag
BVAD	=	Baseline Values and Assumptions Document
C	=	Celsius
cm^3	=	cubic centimeter
ePTFE	=	expanded polytetrafloroethylene
ESM	=	Equivalent System Mass
g/L	=	gram per liter
HMC	=	Heat Melt Compactor
in^2	=	square inches
ISS	=	International Space Station
kg	=	kilogram
kg/m^3	=	kilogram per cubic meter
L	=	liter
L/day	=	liter per day
L/min	=	liter per minute
min	=	minute
mL/hr	=	milliliter per hour
nm	=	nanometer
PE	=	polyethylene
psi	=	pounds per square inch
s	=	second
μm	=	micrometer

I. Introduction

LONG-duration manned missions beyond low earth orbit into deep space will require closing the water loop. No matter how efficient a primary water processor becomes, it will never obtain the water recovery ratio required for long duration deep space missions. The primary water processor is designed to recover the largest amount of water for the lowest cost. The lowest cost trade-off means that there will always be water being thrown away as waste. Therefore, a brine processor will be necessary to recover the remaining water within the brine waste of the primary water processor; this will close the water loop. By using a brine processor which is not limited by the requirement of "lowest cost", additional water will be recovered from the brine resulting in significant cost savings.

For a brine water recovery system to be considered the logical choice for any mission, the equivalent system mass (ESM) of that system must be much less than the mass of the water being recovered from the brine for that mission. The International Space Station (ISS) is scheduled to operate until 2024 and produces nominally 1.2 L/day of brine for a crew of 6. This is 4380 L of brine that can be processed to recover water. If you were to consider 10% of the mass of the water recovered to be a reasonable maximum mass of the brine recovery system, then the brine system for the ISS may weigh as much as 400 kg. However, for a 1 year mission to Mars and a 4 person crew, there may be only 292 L of brine; this means that a brine water recovery system would need to weigh less than a system for the ISS (no more than 29 kg), which is a much more restrictive requirement. Therefore, a brine water recovery system for most deep space missions must be highly reliable, low ESM, and intrinsically microgravity compatible.

II. Background

The Brine Evaporation Bag (BEB) has had 3 years of development. This development effort covered the thermal decomposition of urea[1], the early development of the BEB itself[2], and lastly a microgravity test of a BEB[3].

The study involving the thermal decomposition of urea determined the time available for the processing of urine (urea) at various temperatures. As the temperature of the dewatering process increased, the rate of thermal decomposition of the urea also increased. Urine contains urea. Urea decomposes to produce ammonia. Ammonia is detrimental to humans and equipment in a space environment. On the ISS, acid is added to urine as a stabilizing agent and to prevent the release of ammonia. However, as the urea decomposes to ammonia, it neutralizes the acid within the brine. This neutralization increases the brine's pH, resulting in the eventual release of ammonia gas since the pH is no longer low enough to keep the ammonia bound in the form of ammonium ions ($H^+ + NH_3 \leftrightarrows$

NH_4^+). For a nominally pH 2 brine, the time constant for the release of ammonia is approximately an hour at 90 °C, a day at 70 °C, and a week at 50 °C.[1] Relatively speaking, an hour, a day, and a week, are the processing times available at their respective temperatures of 90 °C, 70°C, and 50 °C before the brine begins to release ammonia.

The initial development of the BEB showed many limitations of the BEB concept.[2] However, over the years, solutions to these limitations have been found. For example, the current research demonstrated that there are alternatives to only being able to heat seal like materials together, and ways of eliminating the heat damage to the edge of the membrane as it is heat-sealed to the bag.

A microgravity flight experiment of the BEB demonstrated that although the BEB may be constructed from a hydrophobic material, the water will still prefer to adhere to the side wall of the BEB rather than be free-floating. Therefore, the brine will remain in thermal contact with the heat transfer surfaces when in microgravity.[3]

III. Experimental

The experiments were performed in a Yamato ADP21 vacuum oven equipped with a 2.5 L/min Cole Parmer gas flow meter (Figure 1). The flow meter allowed for control of the purge gas flow from 0.5 to 2.5 L/min. The vacuum oven allowed for control of the temperature from 50 °C to 90 °C. The vacuum chamber of the vacuum oven was 20.32cm x 25.40cm x 20.32cm (8 in. wide, 10 in. deep, and 8 in. high).

Figure 1. Vacuum oven set up with purge gas flow control.

The vacuum for the vacuum oven was first provided by house vacuum, and was later switched to a Thomas 45 L/min vacuum pump model# 2688VE44. The house vacuum would cycle causing the base pressure within the vacuum oven to cycle between 85 torr and 235 torr. This equates to a water boiling point that would cycle between 50 °C and 70 °C, respectively. Experiments were performed at both 50 °C and 70 °C. The Thomas vacuum pump produced a base pressure within the vacuum oven of 47.5 torr. The water boiling point that equates to 47.5 torr is 36 °C.

The BEBs were constructed by heat sealing one polyethylene bag inside of another (Figure 2). The offset between the two bags being heat sealed produced the BEB. One of the two bags contains a membrane heat sealed into it prior to the two bags being heat sealed together to form the BEB (Figure 3). The bags used are commercially referred to as "fish bags" because of the high quality heat seal that creates the bottom of the bag that is capable of holding water without leaking. The base of the bag measured 8 in. by 10 in., which is the same size as the vacuum oven.

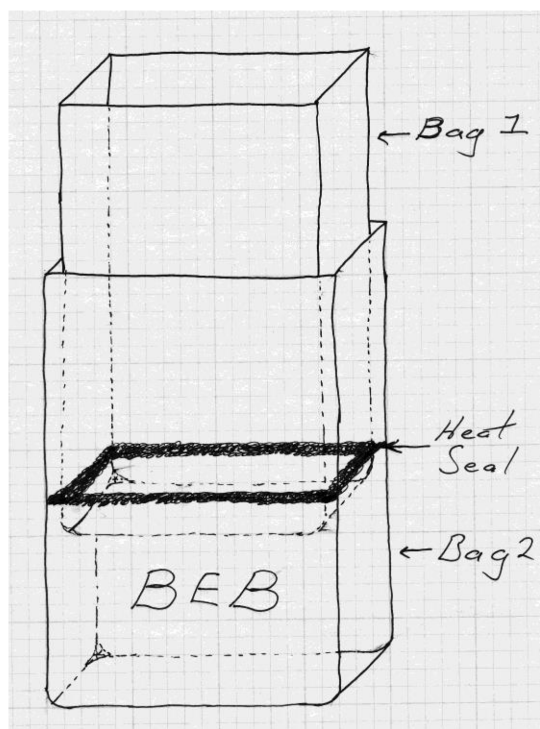

Figure 2. BEB construction using the "fish bags".

The objective of the experiments were to understand the basic behavior of the system, i.e., the effect of membrane size, membrane porosity, membrane location, purge gas flow rate, temperature, and vacuum on the rate of dewatering. These experiments were run using deionized water (DI). DI water was used instead of brine because it was safe to handle and easy to use.

IV. Results

Experiments were performed to investigate the effect of temperature, vacuum, membrane area, membrane permeability, purge gas flow rate, membrane location, and membrane material on the water production rate of the

BEB (Table 1). For initial testing, a standard condition was chosen and investigated. Variations of the standard condition were then made in order to understand the effect of changing the various processing parameters.

A. Standard Condition

The starting standard condition was chosen such that the dewatering process would occur under boiling conditions and with a reasonable urea thermal decomposition rate. It was assumed that the brine dewatering would take a minimum of one day. Prior urea thermal decomposition work showed that the temperature of the brine must be kept at or below 70 °C in order to limit the extent of urea decomposition and the amount of ammonia that is released. Since the house vacuum was initially observed to be approximately 150 torr (equating to a 60 °C boiling point for water), an initial temperature of 70 °C was chosen so that the process would occur under boiling conditions and still provide a reasonably long process time to effect the dewatering. After starting the experiments, it was observed that the house vacuum actually cycled between 85 torr and 235 torr (boiling points of 50 °C and 70 °C, respectively). Although the cycling in the vacuum was observed, it was decided to keep this as the standard condition.

Figure 3. "Fish bag" BEB with a membrane installed within the sidewall.

For the initial membrane installation, the membrane was located near the top of the BEB, above the water level, in order to prevent issues with leakage. A 32.25 cm^2 (5 in^2) membrane area was selected to so that the membrane area could be easily increased and decreased on the top of the BEB. A polyethylene membrane was chosen to match the polyethylene "fish bag" material so that they could be heat sealed together. A commonly-used, generic, hydrophobic membrane was chosen that had a thickness of 25 μm, 50 nm pores, and a Gurley of 230 s.

The initial concept was to use the BEB in conjunction with the Heat Melt Compactor (HMC). Therefore, a purge gas flow rate of 1 L/min was used since this was the prevailing purge gas flow rate of the HMC at the time of the experiments.

The standard condition (Table 1) produced an average water production rate for 3 runs of 29 mL/hr (0.7L/day) with a standard deviation of 2.6 mL/hr.

B. Vacuum

Due to the cycling of the house vacuum, the vacuum oven was attached to a vacuum pump; this was to provide both a constant vacuum and a higher vacuum than was available from the house vacuum. A Thomas 45 L/min pump was used with a base pressure of 47.5 torr using a gas purge flow rate of 1 L/min. This increased vacuum level decreased the boiling point of the water from cycling between 50 °C and 70 °C to a stable boiling point of 36 °C. Under these conditions the water production rate (Table 1) increased from the 29 mL/hr of the standard condition to 55 mL/hr (1.3L/day).

At a production rate of 1.3 L/day, the ability to recover water at a rate high enough to satisfy the ISS brine water recovery was demonstrated.

C. Temperature

The effect of temperature was not initially investigated due to the low production rate using the standard conditions. However, temperature effects (Table 1) were investigated when it was observed that the production rate increases with an increase in vacuum. At 70 °C and higher vacuum, the production rate was 55 mL/hr. At 50 °C, the production rate decreases to 22 mL/hr (0.5 L/day).

Additionally, the percentage decrease in the production rate is identical to the percentage decrease in the vapor pressure of the water between these two temperatures. Thus, if the production rate may be determined by the vapor pressure of the water, then the production rate may be set by setting the temperature of the process.

D. Membrane Area

In order to determine the effect of membrane area on the production rate (Table 1), a BEB was built with a membrane area of 64.50cm^2 (10 in^2) (double the standard membrane area). This membrane area resulted in a production rate of 31 mL/hr compared to the 29 mL/hr +/- 2.6 mL/hr using the standard condition. Therefore, doubling the membrane area had no effect on the water production rate when the expected result was that the production rate should have been doubled. Therefore, there is no effect on the water production rate due to doubling the membrane area.

In another experiment, using the higher vacuum condition, the production rate of a1.61 cm^2 (0.25 in^2) membrane area was compared to the standard condition using the 32.25 cm^2 (5 in^2) membrane area. The result of this experiment showed that the 1.61 cm^2 (0.25 in^2) membrane area had the same production rate as the 32.25 cm^2 (5 in^2) membrane area, 54 mL/hr compared to 55ml/hr, respectively. This result further emphasized that the membrane area is not the limiting factor in the water production rate.

E. Membrane Permeability

For completeness, membranes of differing permeability were also investigated. A membrane with only half the thickness of the membrane of the standard condition was investigated (Table 1). The parameter that describes the passage of a gas through a membrane is called the Gurley rating. Gurley is defined as the time required to pass 100 cm^2 of air through 1 in^2 (6.45 cm^2) of the membrane with 0.18 psi (1.24kPa).

The Gurley rating of the membrane used in the standard condition was 230s. A thinner membrane (1/2 as thick) with a Gurley rating of 120s was also investigated. The water production rate of the thinner membrane was 30 mL/hr compared to the 29 mL/hr of the standard condition membrane. Thus, the membrane permeability is not the limiting factor affecting the water production rate.

Just for completeness, an experiment was performed at standard conditions with the exception that no membrane was installed into the BEB. There was just a 32.25 cm^2 (5in^2) hole in the top of the BEB. The water production rate for this open hole was 33ml/hr compared to the 29ml/hr of the standard condition, thus confirming that the membrane is not the limiting factor in the water production rate.

Table 1. Water Production Rates, mL/hr

Standard Condition

using 70 °C, 85-235 torr, 5 in^2 membrane, and 1 L/min purge gas

Run 1	Run 2	Run 3
31	30	26

Vacuum

47.5 torr	85-235 torr
55	29

Temperature

used the 47.5 torr vacuum

70C	50C
55	22

Membrane Area

using the standard vacuum, 85-235 torr

5 in^2	10 in^2
29	31

using the higher vacuum, 47.5 torr

5 in^2	0.25 in^2
55	54

5 in^2 open hole without membrane

33

Membrane Permeability

230 Gurley	120 Gurley
29	30

Purge Gas Flow Rate

using standard vacuum, 85-235 torr

1 L/min	2 L/min	0.5 L/min
29	37	41

using increased vacuum, 47.5 torr

1 L/min	2 L/min
55	49

Membrane Location

top	bottom
59	57

F. Purge Gas Flow Rate

With the earlier observation that the production rate is proportional to the water's vapor pressure, the effect of purge gas flow rate was investigated (Table 1). This investigation included two components. First, the effect of doubling and halving the purge gas flow rate, and second, a calculation to determine whether the purge gas was saturated with water vapor.

Using the standard conditions, the purge gas flow rate was both doubled and halved and the results compared to the water production rate of the standard conditions. The water production rates were 37ml/hr, 41ml/hr, and 29ml/hr, respectively. An explanation as to why the doubled and halved production rates were greater than the standard condition cannot be provided: however, since they are both greater than that of the standard condition when it might be expected that they should be different by a factor of 4, this is good evidence that the purge gas flow rate is not affecting the water production rate.

The experiment was repeated using the higher vacuum condition, and the production rate for the 1L/min purge gas flow rate and the doubled purge gas flow rate were nearly identical at 55ml/hr and 49ml/hr, respectively.

Thus, under the conditions of these experiments, the purge gas flow rate varying between 0.5L/min and 2L/min does not affect the water production rate.

At 70C and atmospheric pressure, air has a density of 1.2g/L (1.2kg/m^3). In 1 hour, a 1L/min purge gas flow rate flows 60L (72 g, or 0.072 kg) of air. At 70C, air can hold about 210g of water per kg of air. Therefore, 1 hour of purge gas flow at 100% relative humidity would hold 15g of water. Thus, even the lowest water production rate (29g/hr for the standard condition) is producing water at 200% relative humidity, or more accurately, as steam. Thus, the purge gas flow should not affect the water production. The only caveat to this is that the airflow through the system may help keep the pump operating better as it pumps the water, and it will help move any condensed water through the tubing after the pump.

G. Membrane Material

Three different membranes were used during these experiments. The first two were both polyethylene with a spunbond type structure. The first membrane was a Celgard K2045 which has a 47% porosity, 50nm pores, and 20μm thickness. The second membrane was a Celgard EK1245 which has a 45% porosity, 50nm pores, and a 12μm thickness. The thinner membrane produced less resistance to the flow a gas through the membrane and thus has a Gurley rating of 120s compared to the 230s of the thicker membrane. However, in testing these membranes, they both performed equivalently (See the previous section on membrane permeability).

The third membrane tested was an expanded polytetrafloroethylene (ePTFE) membrane. This membrane was used for the tests where the membrane was below the water line of the bag since it was possible to heat seal these membranes without leakage. The heat sealing was done by sandwiching the ePTFE membrane between two layers polyethylene (PE) and melting the PE into the pores of the ePTFE membrane. This process securely attached the membrane into the BEB. The high melting point of the ePTFE means that the ePTFE membrane will not be damaged by the heat sealing process as the PE membranes were.

H. Membrane Location

With the development of the heat sealing process for attaching the ePTFE membranes into the BEB, it was possible to build BEBs with the membrane below the water level. This allowed for a comparison of the water production rate with the membrane both above and below the water level of the BEB, i.e., with the membrane both covered and not covered with water. The results showed that the location of the membrane had no effect on the water production rate, 59 mL/hr and 57 mL/hr, respectively (Table 1). In microgravity, the brine will be able to move around within the BEB, so that the membrane may, or may not be covered with brine. Thus, this experiment showed that the water production rate is not affected by the membrane being covered with liquid or not.

The only caveat to this result is that the top of the bag, and hence the membrane, was not against a heat transfer surface. Thus, the water could have been condensing onto the membrane and thus mimicking the case where the membrane was below the water level.

V. Discussion

For the configuration of the vacuum oven used to simulate the HMC, the only parameters that affected the water production rate were the temperature and pressure. However, although these parameters may appear to be two independent variables, both affect the same parameter, namely, the delta T of the heat transfer. Whether the temperature is increased or the pressure is decreased, the net effect is to increase the delta T for the transfer of energy into the water by increasing the temperature of the sidewall or by decreasing the temperature of the water by lowering the water's boiling point, respectively.

This result implies that the design of the evaporator used with the BEB is a critical consideration. Therefore, a dedicated evaporator designed and optimized specifically for the BEB is as critical as designing the BEB itself. To this end, it is proposed that a BEB Evaporator is required in order to fully develop and optimize the BEB System.

VI. Future Work – BEB Evaporator

The research completed using the vacuum oven showed that an evaporator specifically built for the dewatering of brine in the BEB needed to be designed. The BEB Evaporator will be this specifically designed evaporator.

A. Concepts

Several considerations need to be addressed in the designing of the BEB Evaporator. First, the volume of the brine residue for a given batch run needs to be determined in order to size the BEB. It is proposed that the BEB should be 1.25 to 2.00 times the volume of the brine residue to be produced per batch. This will allow for the entire volume of the brine residue to be contained within the BEB.

Second, since the BEB will be only slightly larger than the volume of the brine residue, a continuous fill mechanism needs to be design. This will ensure that the BEB remains filled with brine during the entire dewatering process while minimizing the actual size of the BEB Evaporator.

Third, in microgravity, buoyant mixing does not occur. Therefore, the liquid needs to be kept as close to the heat transfer surfaces as possible. Thus, the BEB needs to have a "pancake" shape to minimize the need to transfer heat through the bulk of the brine. As a result, it is proposed that the BEB should be approximately 2" thick and the length and the width of the BEB Evaporator will provide the remaining volume. This design will have the added advantage of increasing both the heat transfer area for putting heat into the brine and the size of the membrane area for removing the water vapor from the brine.

Finally, the ability to heat the BEB Evaporator at the membrane, not at the membrane, or all sides of the BEB Evaporator needs to be investigated. Since there is no buoyant mixing due to microgravity, heating directly at the membrane will put the heat directly at the point of vaporization. However, this is also the point with the greatest resistance to heat flow since the heat will need to move through several layers of porous material, i.e., the membrane and the spunbond covering used to add structural support and protect the membrane.

If heating is applied away from the membrane area, then the heat transfer coefficient will be higher due to the solid film. However, the heat will now have to travel through the bulk solution to the membrane to effect vaporization of the water. Additionally, since the heat is being put into the system away from the membrane, there is the chance that boiling will occur there, and the lack of buoyant effects will leave the gas bubbles along the heat transfer surface thus greatly reducing the heat transfer.

B. Design

The initial design of the BEB Evaporator and the redesign of the BEB for the BEB Evaporator can be seen in Figure 4. The BEB will be redesigned so that the top of the BEB is a flat sheet with a membrane installed into it. The bottom of the BEB will be vacuum formed into an "upside-down top hat" shape such that the rim will be heat sealed to the flat sheet of the top of the BEB. The bottom of the BEB will have a no-drip quick-disconnect installed into it which will connect to its mating piece in the bottom of the BEB Evaporator to allow for continuous filling of the BEB during the dewatering process. The BEB Evaporator will be a box with heaters and thermocouples installed on both the top and the bottom. Vacuum and purge gas flow across the membrane will also be designed into the top of the BEB Evaporator.

The estimated mass of the BEB Evaporator will be approximately 7 kg. The system will use less than 275 W (200 W for the heaters and 75 W for the vacuum pump, all at full power). A BEB will weigh approximately 60 g and will be used for 1 week. This results in a BEB resupply of approximately 3.1kg/year. Using the ESM estimates for a Mars mission from the BVAD[4], this gives an ESM estimate of 22 kg or a system mass payout of 3 weeks (Table 2) for the BEB System.

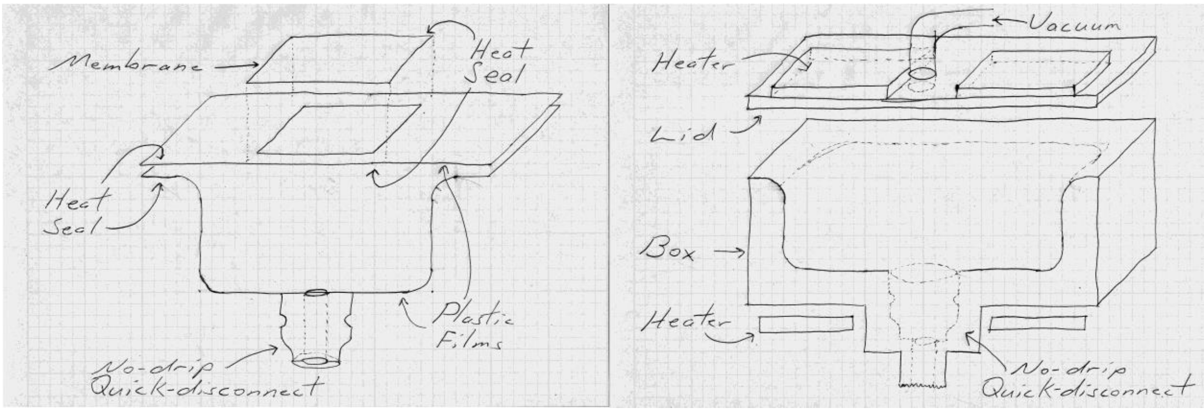

Figure 4. The design for the BEB System with the BEB (left) and the BEB Evaporator (right).

Table 2. BEB ESM Estimate

- Power 23Kg/KW from BVAD
  - 4.4Kg Mass of solar panel to run pump
    0.19KW x 23Kg/KW
  - 0.7Kg Mass of solar panel to boil 1.2L water / 24 hour period
    0.66 KWhr/L x 1.2L/24hr x 23Kg/KW
- Cooling
  - 5.1Kg Equal to Power (4.4Kg + 0.7Kg)
- Mass
  - 6.3Kg Mass of 6"x6"x3" Proof-of-Concept BEB Evaporator
    includes heaters, RTDs, and controllers
  - 1.7Kg Mass of vacuum pump
- Volume 215Kg/m3
  - 0.003Kg BEB Evaporator is 6"x6"x3", assume save volume for ancillary
- Consumables
  - 3.1Kg 60g/bag x 1bag/week x 52weeks

- Total ESM Estimate **21.3Kg**
- System Mass Payout **3 weeks**

Conclusion

The vacuum oven tests showed the BEB concept's ability to produce water at a rate of 55 mL/hr (1.3L/day) at 70 °C. This is a rate high enough to make this process viable for ISS and deep space missions.

The rate of water production was found to be largely independent of all variables tested except for temperature and pressure. This implied that the vacuum oven was heat transfer limited and that a dedicated BEB Evaporator needed to be developed. The ESM estimates of a BEB System composed of the BEB and the BEB Evaporator was less than 22 kg and has a system mass breakeven time of three weeks.

New concepts for the building of the BEB have been developed. These concepts include the vacuum forming of the BEB components and new ways of installing membranes into the films so that the membranes do not leak.

Acknowledgments

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References

[1]Lance Delzeit, John Fisher, and Alex Polonsky, "Brine pH Change Resulting from Urea Hydrolysis and Implication to Brine Dewatering", 41st International Conference on Environmental Systems, 2011.

[2]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, 2012.

[3]Lance Delzeit, John Fisher, Greg Pace, Eric Golliher, "Microgravity Behavior of Water within the Brine Evaporation Bag", 43rd International Conference on Environmental Systems, 2013.

[4]Anthony J. Hanford, "Advanced Life Support Baseline Values and Assumptions Document", NASA/CR—2004–208941, August 2004.