

Preliminary Feasibility Testing of the BRIC Brine Water Recovery Concept

Michael R. Callahan¹
Jacobs Technology, Houston, TX, 77058

and

Stuart J. Pensinger², Karen D. Pickering³
NASA Johnson Space Center, Houston, TX, 77058

The Brine Residual In-Containment (BRIC) concept is being developed as a new technology to recover water from spacecraft wastewater brines. Such capability is considered critical to closing the water loop and achieving a sustained human presence in space. The intention of the BRIC concept is to increase the robustness and efficiency of the dewatering process by performing drying inside the container used for the final disposal of the residual brine solid. Recent efforts in the development of BRIC have focused on preliminary feasibility testing using a laboratory- assembled pre-prototype unit. Observations of the drying behavior of actual brine solutions processed under BRIC-like conditions has been of particular interest. To date, experiments conducted with three types of analogue spacecraft wastewater brines have confirmed the basic premise behind the proposed application of in-place drying. Specifically, the dried residual mass from these solutions have tended to exhibit characteristics of adhesion and flow that are expected to continue to challenge process stream management designs typically used in spacecraft systems. Yet, these same characteristics may favor the development of capillary- and surface-tension-based approaches currently envisioned as part of an ultimate microgravity-compatible BRIC design. In addition, preliminary feasibility testing of the BRIC pre-prototype confirmed that high rates of water recovery, up to 98% of the available brine water, may be possible while still removing the majority of the brine contaminants from the influent brine stream. These and other early observations from testing are reported.

Nomenclature

BRIC	=	brine residual in-containment
COTS	=	commercial off-the-shelf
DI	=	deionized
ELS	=	exploration life support
IR	=	infrared
ISS	=	International Space Station
t	=	change in time
M_c	=	mass of influent condensate
M_e	=	mass in the liquid volume of evaporant
M_r	=	mass of residual brine solids
M_{bw}	=	mass of available brine water

¹ Principal Investigator, Engineering and Science Contract Group, 2224 Bay Area Boulevard, Houston, TX, 77058, Mail Stop JE-77, Member.

² Project Engineer, Crew and Thermal Systems Division, 2101 NASA Parkway, Houston, Texas, 77058, Mail Stop EC3.

³ Lead, Water Hardware and Technology Development Group, Crew and Thermal Systems Division, 2101 NASA Parkway, Houston, TX, 77058, Mail Stop EC3.

I. Introduction

The development of closed-loop life support technologies will be critical to sustaining humans in space and to meeting NASA's goals for human space exploration. A significant gap in closing the spacecraft water loop remains in the development of technologies for extracting water from wastewater brines.¹⁻³ The available water contained in these brine streams can be up to 30% of the total water budget. Loss of this source of recyclable water is unsustainable for missions with limited and/or no options for resupply. A major challenge associated with the development of brine dewatering technologies has been the design of robust systems that can handle a process stream laden with a high solids content. As water is recovered from the brine, the residual brine stream is transformed along a continuum from a liquid, to a slurry, to a wetted semisolid, and finally to a dried solid state. Brine dewatering systems must be able to accommodate these changes of state, as well as, the complex chemical nature of the brine and brine residuals which tend to render these substances toxic to crew, and corrosive and highly fouling to process equipment. A brine dewatering concept has been described which attempts to obviate some of the design complexity associated with the recovery of water from wastewater brines. The concept, referred to as BRIC or brine residual in containment, implements a technique in which brine drying is effected within the container used for final disposal of solid brine residual waste. For BRIC, the in-place drying design is expected to allow for high water recovery without the complexity associated with attempting to mechanically remove, transport, and store the brine solids. The BRIC design also plans to incorporate thin-film-drying processes and vacuum and radiative heat transfer methods to increase the efficiency of the drying process and promote options for fluid/solid management under conditions of microgravity. Development of the BRIC concept has been in work for the past two years. Efforts have included the design, buildup, and preliminary testing of components for a BRIC demonstration unit. The main objective of the current development stage has been to collect information on the basic functionality and performance of a BRIC pre-prototype design. Recent work has focused on the development of the BRIC evaporation chamber, with an emphasis placed on observing the behavior of actual brine waste streams dried under BRIC-like conditions. The evaporation rate, phase separation, and residual solids captured in a 1-g environment were also continued to be considered as part of these early development goals. Results and observations from the current round of brine testing are reported herein.

II. Description of the Brine Residual In-Containment Concept

A description of the BRIC concept is provided by Callahan et al., 2011⁴. In short, liquid brine is transferred to an evaporator using a metering pump and/or differential pressure between the evaporator and the ambient environment. A thin layer of brine spreads across the surface of a disposable solids collection container. Spreading is accomplished by gravity and/or surface force interactions. Variable heat control and vacuum pressure are supplied to facilitate evaporation and maintain temperatures at the desired set point. Water vapor from the evaporating brine is transferred to a condensing heat exchanger via a vapor duct. The condensing heat exchanger is used to return purified water vapor to a liquid state. The condensate is collected in the condensate tank. An optional recirculation loop that uses the vacuum pump exhaust or an additional blower is incorporated to transfer vapor and aid in the overall evaporation process. A baffle or demister element in the vapor duct is used to prevent brine aerosols from entering the condensing chamber. After each drying cycle, a fresh liquid brine layer is introduced into the evaporation chamber. Once the limit of the evaporation chamber has been reached, the chamber becomes filled with solids or the evaporation rate reaches a minimum limit, the disposable solids collection container is physically removed. A new collection container is introduced into the evaporation chamber and the brine drying process is continued. In the current BRIC designs, direct radiative heat transfer technologies—e.g., infrared (IR) and microwave systems—are currently being targeted as the evaporative heat source. The application of a thin brine layer is being considered to promote rapid heating of the brine and to enhance the potential use of surface force interactions—e.g., capillary and electrostatic forces—to provide static phase separation of liquid, vapor, and solid brine process streams in the absence of gravity. In addition, conventional means of mechanically inducing a gravity vector normal to the evaporation surface may also be investigated. Under this regime, the heating element would likely be located about the circumference of a stationary shaft with drying and solids collection occurring on the inner circumference of a disposable drum and/or drum liner rotating about the axis of the shaft. A simplified diagram of the BRIC concept is shown in Fig. 1.

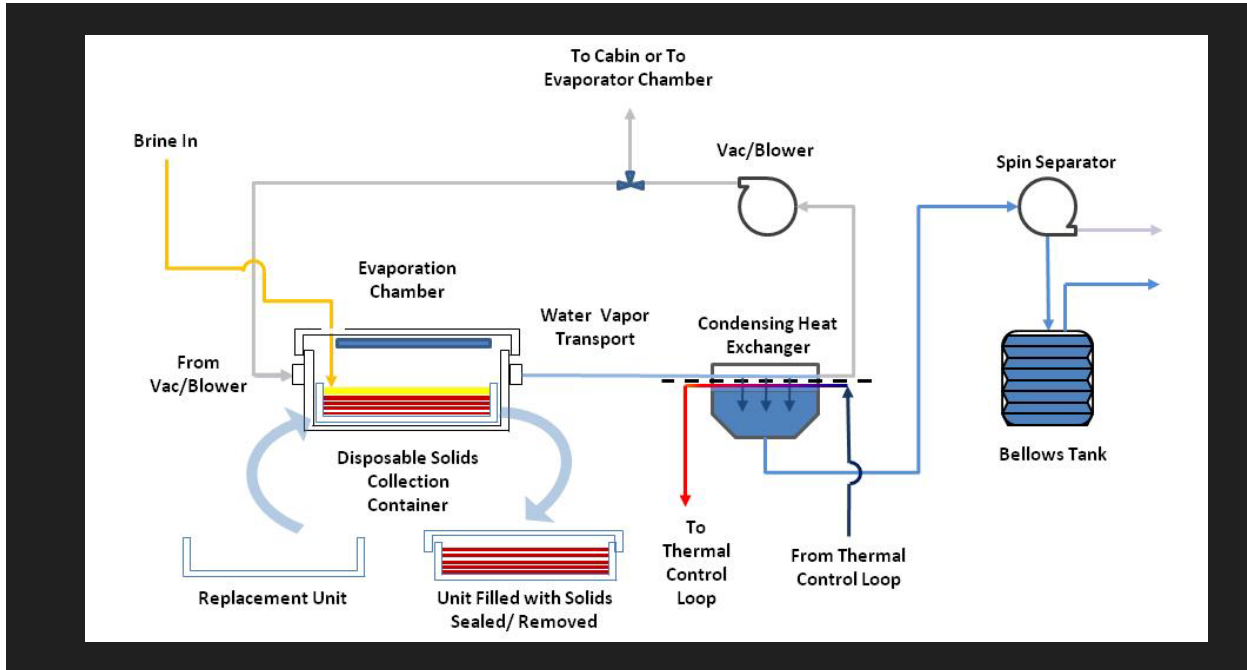


Figure 1. Simplified Schematic of BRIC Concept

III. Materials and Methods

A. Test Hardware

A BRIC pre-prototype unit was assembled using commercial off-the-shelf (COTS) products and/or modified COTS items. The purpose of the pre-prototype was to collect information on the basic functionality and performance of a BRIC design to be used in the development of higher-fidelity test systems. The pre-prototype of a BRIC demonstration unit is shown in Fig. 2. In the pre-prototype, the functional components of the condenser assembly have been replaced by a COTS refrigerant-based vapor trap. Heating is accomplished by way of an IR heating element. The IR heat source for the pre-prototype system included either a 175-W tungsten-halogen heat lamp or a 500-W ceramic IR heating element. The influent process stream was introduced manually on a batch basis, or via use of a peristaltic pump and feed port. Finally, liquid/vapor phase separation and de-misting functions in this phase of development rely on gravity-related buoyancy effects.

B. Test Overview

A preliminary set of performance testing was conducted for the BRIC pre-prototype in late 2011. The major goal of these tests were to develop an understanding of the system performance and operation. Detailed results from these tests have been reported by Callahan et al., 2011⁴. Based on these tests, a number of short-term development goals were identified; preliminary testing with *actual* brine solutions was deemed to be of highest priority. The objective of these tests was to observe the drying behavior of representative spacecraft brine solutions processed under BRIC-like conditions. Of particular interest was whether the general application of in-place brine drying, specifically, phase separation and solids retention, appeared to be amenable when processing *actual* brine test solutions. Brines representing three separate potential spacecraft waste streams were selected. A description of the selected brines is provided below.

BRIC testing of the brines was conducted in two test series. The first test series was conducted in a single-batch mode. Single-batch testing was performed on each brine type. Testing was conducted by processing 300 to 350 g of brine solution to apparent dryness in a single-batch run. The purposes of these tests were to provide a first look at how each brine type behaved within the BRIC drying process and to help develop/refine a BRIC drying test protocol. The second test series included multibatch testing. For this test series, a single brine was selected and 150 g of material were dried in 10 successive batch runs. These tests were intended to provide a first look at one of the

proposed modes of BRIC operation in which the dried brine residual is layered into the solids collection container through a successive multibatch process.

In general, the drying runs were conducted by loading the brine material into a pre-weighed disposable solid waste container assembly. The solids container assembly used for this testing consisted of a Teflon bag adhered with two-sided tape to an aluminum pan (19.5 cm diameter, 7.3 cm high). The bag was cut to a height of approximately 20 cm and adhered to the inside surface of the BRIC vacuum housing using Kapton tape. For single batch testing, the brine was loaded manually. In the multi-batch test the brine was pumped into the evaporator between each batch cycle using the peristaltic feed pump assembly. The heat source for testing was a 500 W infrared ceramic heating element located approximately 10.2 cm (4 in.) from the surface of the evaporating liquid. In general, the power was varied between 60 and 200 W. Heater power adjustments were typically made in order to maintain the temperature of the bulk liquid brine below 60 °C and to prevent/mitigate the onset of vigorous boiling. The vacuum pressure was typically controlled between 4.0 and 5.3 kN/m² (35 and 40 mm Hg). Processing was continued until the residual brine solids in the evaporating fluid were determined to reach apparent dryness. Visual observation of the dried brine mass was used as the primary means of assessing the dryness of the solids. A temperature probe in the working fluid was used as a secondary indication of the end of evaporative cooling and completion of the solids drying cycle. Evaporation rates were measured for each batch run, based on the change in brine mass over the estimated time to dryness. The residual solid mass in the solids collection assembly and the mass of condensate collected in the vapor trap were determined gravimetrically at the end of each test run. Solids analysis was used to estimate the available water in the brine material, the percent of water remaining in the dried brine residual, and the brine water recoveries. Chemical analyses were performed to determine the major constituents of the brine influent and product water condensate.

C. Brine Preparations

Brines representing three separate potential spacecraft waste streams were selected. These included a urine brine analogue from the International Space Station (ISS) Urine Processor Assembly (UPA) and two brines proposed for a Lunar Outpost.⁵ The latter two brines are described as ELS Test Solutions 1 and 2. A general summary of the brine waste streams are provided in Table 1. The ISS UPA waste stream consists of a urine only waste stream, pretreated with approximately 0.1% chromic acid, 0.6% sulfuric acid, and 20% flush water. Brines from this waste stream have generally been concentrated up to 70 to 80%. The ELS brines are mixed waste streams originating from either pretreated urine plus humidity condensate (ELS Test Solution 1) or pretreated urine plus humidity condensate and hygiene wastewaters (ELS Test Solution 2). Each individual wastewater stream, urine, humidity condensate and hygiene, was stabilized using respective concentrations of 0.5%, 0.05%, and 0.1% Oxone and 0.23, 0.11, and 0.22% sulfuric acid. The urine waste stream also contained approximately 20% flush water. In some cases, a humidity condensate ersatz was used in the generation of the ELS test solutions. The brines from the ELS test solutions were generally concentrated up to 90 to 94%.

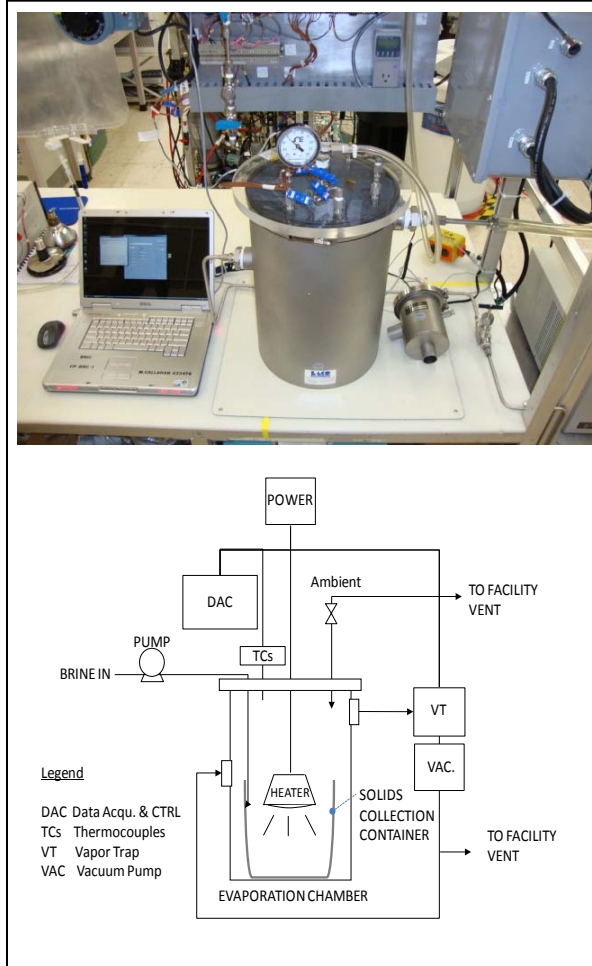


Figure 2. BRIC pre-prototype photograph/schematic.

Table 1: Description of Brine Used in BRIC Testing

Brine Type*	Wastewater Constituents**	Pretreat/Flush Chemicals ⁺	% Concentration	Appearance
ELS TS1	45% Urine, 56% Humidity Condensate	Oxone, Sulfuric Acid, DI Water	90 – 93.5	Golden Brown
ELS TS2	13% Urine, 18% Humidity Condensate, 69% Hygiene	Oxone, Sulfuric Acid, DI Water	90	Pale Yellow
UPA	100% Pretreated Urine	Chromic Acid, Sulfuric Acid, DI Water	70	Red Brown to Dark Green

* Some ELS test solutions were prepared with humidity condensate ersatz.

** Wastewater streams were ground-collected from human donors, unless otherwise noted.

+ Chemicals are added to individual wastewater constituents as a common stabilization technique used on spacecraft.

D. Analytical Instrumentation

Standard chemical analyses were obtained according to methods described in Ref. 5. These analyses included pH (4500-H +B), conductivity (2510B), turbidity (2130B), and solids (2540 C&D). pH measurements were made using an Orion 3-Star plus pH benchtop meter (ThermoFisher Scientific, Inc., Waltham, MA) equipped with an Orion glass body combination 8102BN ROSS pH electrode (ThermoFisher Scientific, Inc., Waltham, MA). Conductivity measurements were made using an Orion 3-Star conductivity meter (ThermoFisher Scientific, Inc., Waltham, MA) equipped with a 013005MD conductivity probe (ThermoFisher Scientific, Inc., Waltham, MA). Turbidity measurements were made with a Hach 2100AN turbidimeter. Ion chromatography (IC) analyses were made using a Metrohm dual-piston pump (model 709) with a Metrohm conductivity detector (model 732). A Cetac IC sep AN1-SC and Metrosep Cation 1-2 IC columns were used for anion and cation analyses, respectively. Metals were measured using an Agilent 7500 Series inductively coupled plasma mass spectrometer (ICP-MS). TOC, TIC, and TN measurements were made using a Shimadzu TOC-V analyzer with ASI-V automatic sampler.

E. Calculations

1. Evaporation Rate

Evaporation rates were typically calculated as the mass change in the evaporating fluid from the BRIC solids collection container over a predetermined time. The evaporation rate in milligrams per minute is given by

$$E = \frac{\Delta M_b}{\Delta t} \quad (1)$$

where M_b is the change in the liquid mass of brine over the change in time t . Typically, for this testing time t was determined for the period between the start of a test drying cycle to the point of “apparent” dryness of the brine material.

2. System Mass Balance

System mass balances were typically calculated as the mass condensate collected at the condenser plus the mass of the residual brine solids divided by the total mass of brine evaporated. The system mass balance for any given batch run was given by

$$\%M_t = \frac{M_c + M_r}{M_b} \times 100 \quad (2)$$

where M_c and M_r are the mass of condensate and residual brine solids collected, respectively, and M_b is the mass of the brine processed.

3. Percent Recovery Rate

Water recovery rates were typically calculated as the total mass of water collected at the condenser divided by the total mass of water available in the brine. The measurements were used to estimate the mass balance for the system pre-prototype. The percent recovery is given by

$$\%R = \frac{M_c}{M_{bw}} \times 100 \quad (3)$$

where M_{bw} is the brine mass less total solids determined by gravimetric analysis, and M_c is the mass of condensate collected.

IV. Results and Discussion

A. Single Batch Processing

Single-batch testing was conducted over 25 hours of BRIC operation beginning in mid-July 2011 and ending in early September. Testing included system checkout with DI water and sodium chloride solutions (data not shown), and process runs with the ELS and ISS type brine waste streams described above. Representative photographs of the drying process from each of the three brine types are shown in Figure 3. Specifically, for each test run, the figure shows, per solution type, from left to right (1) 300 to 350 g of liquid brine material loaded into the BRIC evaporation chamber at the start of testing, (2) the dried brine residual contained in the solids collection assembly at the end of the cycle, and (3) collection of a dried solid residual sample, by scraping with a metal spatula at the end of the test run. Detailed observations from the single-batch brine drying process were made. In general, four types of brine residuals were observed. Examples of each representative brine could be found within a single-batch drying run suggesting the observed differences are associated with the level of dehydration and/or temperatures achieved during processing. The four types of brine residuals were described as follows: (1) Wetted crystalline solids, light yellow to orange in appearance. These crystalline solids appeared to exhibit the least amount of relative adhesiveness and exhibited more flow-like characteristics. (2) Thick brown to black solids with a molasses or tar-like consistency. These thicker solids exhibited little to no flow and were observed to be highly sticky. (3) Hard crusted black solids exhibiting no flow. These hard solids could be flaked off of the teflon container surface and did not appear to exhibit a high degree of adhesion once removed from the residual surface. These solids are believed to have been caused by excessive temperatures, resulting in charring



Figure 3. Examples of the single-batch brine drying process. Frames: Left to Right – brine influent, dried brine residual, collected solid sample.

of the brine material. (4) Dark green to black runny solids, similar in consistency to Elmer’s glue. These green runny solids were only observed for the ISS UPA brine. The color of these solids are believed to result from the chromic acid stabilizer added to the UPA-like waste stream. The general observation for all brine types, was that the residual dried masses all exhibited characteristics believed favorable to proposed concepts of BRIC operation, i.e., the residual masses were generally low to non-flowing and tended to adhere to surfaces. Efforts are currently underway to quantify the surface force properties of the brines and dried brine residual materials.

For the single-batch testing, processing conditions remained relatively similar. Data on the system mass balance of the process streams, solids, and water recovery estimates are shown in Table 2. A summary of chemical data collected for the brine influent and condensate product water is shown in Table 3. In general, for the single-batch brine runs, reductions in the average heater power were steadily implemented from batch to batch to help control observations of boiling and over-heating of the brine material. Specific energies remained largely unchanged. The average heater power across the test series was 129 ± 60 W and average production rates were 0.08 ± 0.04 kg/hr. The average time of processing was 4.5 ± 2.5 hours. The average specific energy, calculated based heater power as the energy input, was 1680 ± 110 W-hr/kg. The average brine water recovery estimates were determined to be 96.4%, and mass balance data for the three brine process streams, influent, condensate and residual solid, were within $100 \pm 5\%$. Contaminant removal efficiencies between the influent brine and recovered product water were greater than 98% for most of the major contaminants, including conductivity, TOC, TN, anions and cations by IC, turbidity, and Total Dissolved Solids (TDS). Some contaminant parameters with lower average removal efficiencies were hydrogen ion concentrations < 98%, and the summed metals, < 75%. These findings may suggest possible corrosion of metal components within or downstream of the evaporator chamber. Trace amounts of ammonium and chloride ion showed evidence of disproportionate carryover relative to other ions in the brine present at significantly higher concentrations. The former may suggest a small amount of urea breakdown. The latter in conjunction with the lower pH water may suggest carryover of hydrochloric acid.

Table 2. Brine Mass Data from Single-Batch Processing

BRINE MASS	ELS TS1 @ 90%	ELS TS2 @ 90%	PTAU Brine @ 70%
Brine (g)	300.6	352.9	302.4
Avail. Water (g)*	274.9	337.4	262.3
Condensate (g)	262.9	331.8	250.4
Dried Residual (g)	34.8	19.1	58.5
Recovery (%)**	95.6	98.3	95.5

*Brine mass less total solids.

**Expressed as condensate collected divided by available brine mass as water.

Table 3. Chemical Data from Single-Batch Processing

Parameter	Feed	Product	% Change
<u>ELS TS1</u>			
pH	1.83	6.41	> 98*
K (mS/cm)	112	1.3	>98
TOC (mg/L)	27950	217	>99
TN (mg/L)	16800	336	>98
TS (g/L)	146.3	0.15	> 99
Σ IONS (mg/L)	82134	71	> 99
Σ Metals (g/L)	8.2	0.1	> 75
<u>ELS TS2</u>			
pH	1.62	2.62	>90*
K (mS/cm)	66.7	1.3	>98
TOC (mg/L)	8200	165	>98
TN (mg/L)	4400	99	>98
TS (g/L)	46.1	0.04	> 99
Σ IONS (mg/L)	26161	208.6	>99
Σ Metals (g/L)	3.7	0.484	> 55
<u>ISS UPA</u>			
pH	2.42	4.44	>95*
K (mS/cm)	133.6	0.197	> 99
TOC (mg/L)	31400	75	> 99
TN (mg/L)	30200	26	> 99
TS (g/L)	154.9	0.04	> 99
Σ IONS (mg/L)	58377	29.2	> 99
Σ Metals (g/L)	3950	0.59	> 99

*Expressed as [H⁺]

Secondary observations, generally associated with issues of process control, were also noted during single batch testing. Such issues included uneven heating of the brine surface, challenges in maintaining control of vapor pressure equilibria, incidences of material boiling and splatter, and incidences of overdrying and overheating of the brine residual. Ultimately, improved control over the drying process will need to be developed and/or optimized. Also of note, was the observation of light deposition or hazing of brown and white material on the interior surfaces of the BRIC evaporator and vapor duct. Incidences of material deposition appeared to lessen as the processing temperatures were reduced over the course of testing. Samples were collected and chemical analysis of the material is planned.

B. Multibatch Testing

Multibatch brine processing was conducted over approximately 42 hours of BRIC operation using ELS Test Solution 1 type brine. In general, the primary findings observed for single-batch testing were also observed during the multibatch test runs. These observations included the formation of dried brine residual believed favorable for in-place drying applications, high recoveries of available water from the brine solutions and high contaminant removal efficiencies. Photographs of the brine residual mass accumulations as a function of batch number are shown in Figure 4. Similar to single batch testing, amber-colored solids tended to appear slightly wetted and crystalline in nature. Again, these solids could be scraped with relative ease from the Teflon containment surface, but also tended to cling to the metal spatula. Darker brown solids were observed to be more tar- or molasses-like in nature, exhibiting little flow, and requiring significantly more effort to scrape from the solid collection surface. Dark brown to black solids tended to be harder in nature, non-flowing and exhibited the highest levels of adhesion to the drying surface. One additional type of brine characteristic was also observed toward the end of processing. These solids are believed to result from the rehydration of dried brine material. This residual was dark orange and more gel-like in nature. At least one instance of the formation of a large crystal, approximately 7 to 10 mm in length, was found after one of the drying runs. The crystal provides evidence of the sticky nature of the solids, which could have the potential to obstruct/foul passages as they move through a brine dewatering system. A close-up photograph of the crystal is shown in Figure 5a. As a general observation of the proposed layering approach in early runs of batch testing, liquid dried brine residual appeared to mostly redissolve upon a fresh addition of a liquid brine layer. However, in the later rounds of testing, most of the salt-like crystalline formations seemed to redissolve, leaving a relatively thick layer of amorphous yellow to orange solids, which remained under the brine liquid surface. An example of the liquid/solid layering is shown in Figure 5b. Continued investigation into strategies for loading and collecting the solid brine residuals will be needed.

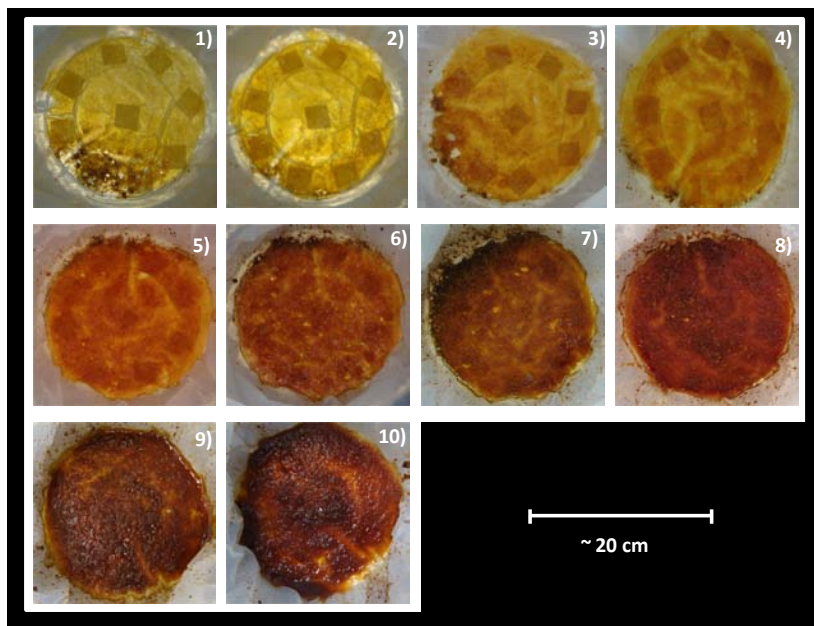


Figure 4. Accumulation of Residual Brine Solids: Batches 1 – 10

Dark brown solids were observed to be more tar- or molasses-like in nature, exhibiting little flow, and requiring significantly more effort to scrape from the solid collection surface. Dark brown to black solids tended to be harder in nature, non-flowing and exhibited the highest levels of adhesion to the drying surface. One additional type of brine characteristic was also observed toward the end of processing. These solids are believed to result from the rehydration of dried brine material. This residual was dark orange and more gel-like in nature. At least one instance of the formation of a large crystal, approximately 7 to 10 mm in length, was found after one of the drying runs. The crystal provides evidence of the sticky nature of the solids, which could have the potential to obstruct/foul passages as they move through a brine dewatering system. A close-up photograph of the crystal is shown in Figure 5a. As a general observation of the proposed layering approach in early runs of batch testing, liquid dried brine residual appeared to mostly redissolve upon a fresh addition of a liquid brine layer. However, in the later rounds of testing, most of the salt-like crystalline formations seemed to redissolve, leaving a relatively thick layer of amorphous yellow to orange solids, which remained under the brine liquid surface. An example of the liquid/solid layering is shown in Figure 5b. Continued investigation into strategies for loading and collecting the solid brine residuals will be needed.

In general, the processing conditions and thermodynamic responses over the 10 batch runs were relatively consistent. Table 4 provides data on the mass balances of the process streams, solids, and water recovery estimates for the ten batch runs. Table 5 provides a summary of the chemical data collected from the influent brine and product water condensate averaged across the ten batch runs. The average heater power and production rate over the ten runs was 76 ± 9 W and 0.04 ± 0.01 kg/hr, respectively. The average time of processing was 3.3 ± 0.5 hours and the average specific energy, based on heater power only, was 1798 ± 98 W-hr/kg. Like single batch testing, mass

balances were within $100 \pm 5\%$ and the average brine water recovery estimates were determined to be 96.5%. Also, like single batch processing, contaminant removal efficiencies for most of the major contaminants were observed to be greater than 98%, including conductivity, TOC, TN, anions and cations by IC, turbidity, and Total Dissolved Solids (TDS). Product water pH and metals data continue to suggest acid carryover and system corrosion. Like single-batch testing, trace levels of chloride and ammonium ion were found in the product water at disproportionate feed ratios relative to other ions measured by IC. Again, the presence of chloride ion could suggest specific carryover of hydrochloric acid. Similarly, trace levels of metal contamination, typically below 3 mg/L, were found in the product water. The metals included were Zn, Mn, Cu, Ni, Fe, and Cr. These elements are consistent with corrosion of stainless steel and brass. There was at least one brass fitting found at the outlet of the vapor trap. Another metal found at trace levels, 1 mg/L, was aluminum. Interestingly, the pan used to support the Teflon liner of the solid collection assembly was made of aluminum and did show some evidence of corrosion. Because the pan was removed for weighing and returned to the evaporator after every batch run, direct contamination of the product water during collection is suggested as one possible mode of transmission. Samples were taken from areas believed to show evidence of corrosion.

Secondary observations and issues during multibatch testing were also similar to those described in single-batch testing. Brine boiling and/or localized vapor eruption continued to be an issue. Similarly, achieving an evenly-spread liquid brine drying surface remained a challenge. Both phenomena contributed to continued observations of material splatter on the solid collection side wall and heat lamp. Overall for multibatch testing, overheating and overdrying of the brine material was felt to be better controlled compared to single batch testing. This was accomplished mainly by leveling the evaporation chamber and lowering the average power supplied to the heat lamp. The white haze material was also noted to accumulate during testing. The quantities of material were significantly less than those observed in the first single-batch test. Interestingly, the hazing phenomenon seemed to occur toward the end of each multibatch process run. The relative amount of material deposited seemed to increase as a function of batch run, and the onset of hazing was believed to have correlated to an estimated brine liquid/solid temperature of about 40 °C. Under the conditions of processing, concentrated hydrochloric acid, if present, may be expected to boil. Similar to the accumulation of the white haze, a concern during multibatch testing was the control of brine temperature as the concentration of solids in the brine continued to increase. Some evidence of this potential to overheat the brine solid was observed in the multibatch processing profiles for

temperature, heater power, and vacuum pressure (data not shown). The temperature profile across the 10 batch runs suggested that the brine material heated up faster with each successive batch run. This phenomenon, if real, is likely related to the increase in the solids content. Consequently, it was necessary to adjust the heater power in order to

Table 4. Brine Mass Data from Multi-Batch Processing

Batch #	Brine (g)	Avail. Water* (g)	Condensate (g)	Dried Residual (g)	Brine Recovery (%)
1	150.3	136.9	148.4	15.4	103.6
2	150.6	137.4	140.2	19.4	97.3
3	150.0	136.8	142.9	15.8	99.6
4	150.2	137.0	130.4	19.5	90.3
5	152.4	139.0	139.3	15.3	95.4
6	150.6	137.4	142.4	13.8	98.8
7	150.5	137.3	143.5	14.7	99.7
8	150.5	137.3	141.4	16.6	98.1
9	150.8	137.6	136.0	20.9	94.0
10	150.3	137.1	127.5	29.2	88.2

*Brine mass less total solids.

**Expressed as condensate collected divided by available brine mass as water.

Table 5. Chemical Data from Multi-Batch Processing

Parameter	Avg. Feed	Avg. Product	% Change
pH	1.77 ± 0.1	2.9 ± 0.5	> 90*
K (mS/cm)	111.2 ± 3.7	0.8 ± 0.5	> 99
Turb. (NTU)	34.6 ± 13.7	0.5 ± 0.2	> 98
TOC (mg/L)	16447 ± 1107	210 ± 76	> 98
TN (mg/L)	13575 ± 935	9.2 ± 2.6	> 99
TS (g/L)	100 ± 8	0.03 ± 0.04	> 99
Σ IONS (mg/L)	50635 ± 3442	83.6 ± 53.0	> 99
Σ Metals (mg/L)	8.9*	2.7 ± 2.5	< 70

*Expressed as $[H^+]$

prevent overheating of the brine surface. Also, for the multibatch data, there is some evidence in the individual batch chemical data, not shown, that carryover effects were exacerbated by increasing run time and average processing temperatures. For such runs, e.g., batch runs 6, and 7, pH, conductivity, and TOC, all appeared to exhibit slightly lower removal efficiencies, by 1 to 10%. Factors that may account for such observations could be the increase in heat absorption as the material became darker and/or more concentrated with solids, changes in the heat capacity of the material as it transitioned from liquid to solid material, or loss of evaporative cooling as the concentration of solid particles begin to dominate at the heating surface. The observation of these events highlights the interest in improving the understanding of the physical properties of the drying brines as part of the design and process development. Finally, as a demonstration of one potential mode of disposal for BRIC waste solids, Figure 6 shows the used BRIC solid waste collection assembly removed from the evaporation chamber, following testing, and sealed with a zip tie. The sealed bag and pan assembly were placed directly into a secondary laboratory solid waste collection container. The secondary waste container was sealed with a lid. No contact with the brine material was required during removal and disposal of the BRIC solids collection assembly.

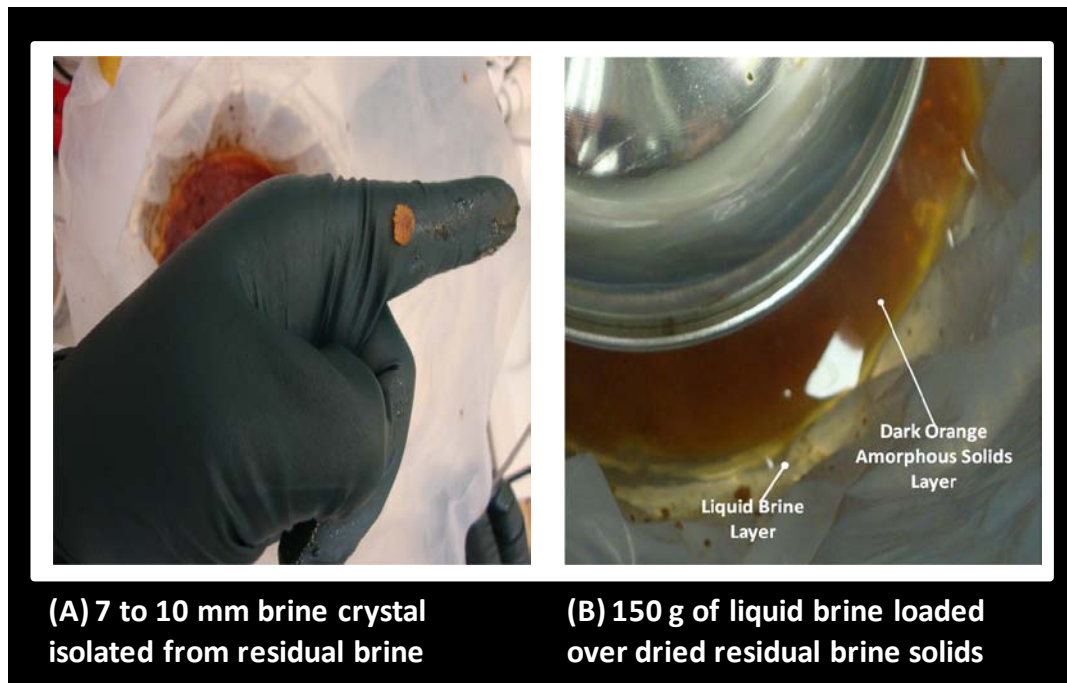


Figure 5. Examples of brine disposition during Multi-Batch Testing.



Figure 6. Examples of brine disposition during Multi-Batch Testing.

C. Summary of Results

The primary finding from BRIC feasibility testing with the real brine solutions tested were that the dried masses all exhibited characteristics believed favorable to BRIC processing, i.e., the residual masses were generally low to non-flowing and tended to adhere to surfaces. Also important to these initial feasibility tests were the demonstration of high brine water recoveries, greater than 95% on average, and the high contaminant removal efficiencies, greater than 98% for most of the major brine contaminants. Secondary observations, also important to these early tests, were the issues of process control, including: uneven heating of the brine surface, the challenge of maintaining proper vapor pressure equilibrium, incidences of overheating and material splatter, corrosion, and potential off-gassing of brine products. These challenges present opportunities to further develop and refine the BRIC design and BRIC drying process. Of particular consideration in this development effort will be to understand the effects of microgravity and brine properties as related to these phenomenon. The source and identification of off-gas products, e.g., the white haze material observed during testing, should be further investigated, particularly with regard to any materials which may have implications for crew health/safety.

V. Conclusions

Design solutions implemented to recover water from wastewater brines must be compatible with, and take into account, the conditions associated with the brine dewatering process, including the physical properties and behavior of the three phases of the brine process stream, liquid, gas and solid. Preliminary feasibility testing of the BRIC concept continues to demonstrate the potential application of in-place drying for spacecraft brine dewatering. In particular, this round of testing successfully demonstrated brine liquid, vapor and solid phase separation, the retainment of a dried brine residual mass, high rates of water recovery and high contaminant removal efficiencies. Data from the current testing has also highlighted the need to further develop and refine the BRIC design and brine-drying process. Of particular consideration should be the development of design, control and drying strategies to prevent overheating, boiling, and evolution of the brine solids during processing. To accomplish these development goals for a space applications, it will be necessary to understand these phenomenon as related to the physical properties of brines and the effects of processing under conditions of microgravity. Forward plans for BRIC development include the continued investigation into the BRIC process and the drying properties and behaviors of brine solutions toward the development of a microgravity-compatible BRIC design.

Acknowledgments

The authors gratefully acknowledge Otto Estrada, Dean Muirhead, Chris Carrier, and Letty Vega of the Engineering and Science Contract Group, Julie Mitchell of the NASA Johnson Space Center for their contributions, and John Fisher, John Hogan, Lance Delzeit, Gregory Pace, Wignarajah Kanapathipi and Richard Alba of the NASA Ames Research Center for their contributions, insights, and support as related to BRIC development activities.

References

- ¹Barta, D. J., and Ewert, M. K., "Development of Life Support System Technologies for Human Lunar Missions," SAE Paper No. 2009-01-2483, *39th International Conference on Environmental Systems*, SAE, 2009.
- ²Barta, D. J., Ewert, M. K., Anderson, M. S., and McQuillan, J., "Life Support System Technology Development Supporting Human Exploration," SAE Paper No. 2008-01-2185, *38th International Conference on Environmental Systems*, SAE, 2008.
- ³Bagdigian, R. M., "Considerations Regarding the Development of an Environmental Control and Life Support System for Lunar Surface Applications," *38th International Conference on Environmental Systems*, SAE, 2008.
- ⁴ 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.
- ⁵McQuillan, J., Pickering, K.D., Anderson, M., Carter, L., Flynn, M., Callahan, M., Vega, L., Allada, R., and Yeh, J. 2010 "Distillation Technology Down-selection for the Exploration Life Support (ELS) Water Recovery Systems Element. Submitted to the *40th International Conference on Environmental Systems*, AIAA, 2010.
- ⁶APAH, 2006. *Standard Methods for the Examination of Water and Wastewater*, American Public Health Association, American Water Works Association, Water Environment Federation. On-line Edition www.standardmethods.org.