

Development of an Enhanced Brine Dewatering System

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ABSTRACT

Water recovery is essential for long-duration space exploration transit and outpost missions. Primary stage wastewater recovery systems partially satisfy this need, and generate concentrated wastewater brines that are unusable without further processing. The Enhanced Brine Dewatering System (EBDS) is being developed to allow nearly complete recovery of water from Lunar Outpost wastewater brines. This paper describes the operation of the EBDS and discusses the development and testing of the major functional materials, components, and subsystems, including the wastewater brine ersatz formulations that are used in subsystem testing. The assembly progress of the EBDS full system prototype is also discussed, as well as plans for testing the prototype hardware.

INTRODUCTION

Extended duration Lunar and Mars missions will require the conservation and recovery of water to reduce launch mass and stowage volume. Primary stage water recovery systems can achieve over 90% recovery, but concentrate the wastewater into a brine that is potentially very corrosive with high potential for scaling, biofouling, and precipitation (Thomas, 2008a). The Enhanced Brine Dewatering System (EBDS) is being developed to recover 90-95% of the remaining water from these concentrated brines.

ORBITEC began preliminary concept development with Cornell University and continued development of EBDS under contract from Johnson Space Center (JSC) in

January 2007. The initial phase focused on subsystem development and component testing. The Phase 1 contract was completed in July 2007 and a Phase 2 contract began in January 2008. The goal of Phase 2 is to build and test a full-scale Lunar Outpost brine dewatering system. Additional component and subsystem research was completed along with the design, fabrication, and assembly of the system prototype. The system prototype will be tested with authentic wastewater brines generated by the Cascade Distillation System (CDS) and with several ersatz solutions that were developed by Dr. Jean Hunter's team at Cornell University's Department of Biological and Environmental Engineering. One of these ersatz solutions contains authentic pretreated urine brine generated by the CDS.

The EBDS concept involves a cycle of depositing brine onto a rotating solid substrate, evaporating the water from the brine, and scraping the residual solids from the substrate. This cycle repeats continuously as fresh brine is deposited after solids are removed from the substrate. The water that evaporates from the brine is then condensed and collected, with a portion of the heat of condensation used to reheat the air that evaporates the brine. The remaining solids are primarily made up of inorganic salts, organic salts, surfactants, and sulfuric acid, and are scraped off the substrate, drawn into a suction nozzle, and collected in a filter bag. A simplified functional system schematic is shown in Figure 1.

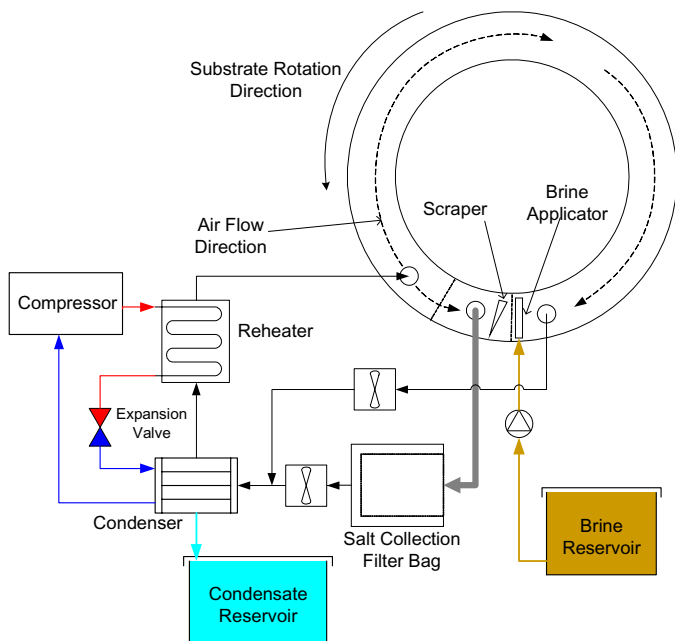


Figure 1. EBDS functional schematic

This paper summarizes the major component and subsystem development activity from Phase 1 and the first sixteen months of Phase 2. At the start of Phase 1, the goal was to develop a brine dewatering system that was capable of microgravity operation. At that time the type of mission, transit or outpost, had not been determined, nor had the composition of the brine to be processed. During Phase 1 the Lunar Outpost was established as the end goal of EBDS development; therefore, Phase 2 focused on development of a brine dewatering system that is dependent on gravity for both brine application and condensate collection. During Phase 2 significant research into the likely waste streams and primary water processing methods led to more advanced and accurate predictions of the composition of the EBDS influent brine. The EBDS design is not based on a specific reference mission duration, rather it is intended to be used for several years of terrestrial tests, with occasional maintenance. Through the course of the development described in this paper, we learned that the brine composition has a significant impact on determining the most effective hardware configuration.

PRELIMINARY SUBSYSTEM DEVELOPMENT

During the early stages of development we completed several subsystem investigations that are summarized below. These investigations included tests of the methods of brine application, chemical compatibility of brine application materials, salt removal methods, substrate materials, and salt collection methods, along with analysis of condensing/reheating thermal transfer methods

BRINE APPLICATOR TESTING – The primary goal for the brine applicator testing was to determine which of three proposed brine application schemes most evenly distributes brine across a substrate. The three methods of brine application included a spray nozzle, an applicator with multiple discrete drippers, and an applicator with one wide, thin dripper to deposit a film. All three methods were tested with and without a soft polyurethane wiper to assist in achieving uniform brine distribution on the surface of the substrate.

Initial brine applicator testing was performed with an ersatz that was developed with assistance from JSC engineers. During the early stages of EBDS development, testing was focused using only the concentrated urine component of the wastewater brine. This ersatz of the urine components consisted of the following components dissolved in deionized water:

- 114 g/L Sodium Chloride
- 38 g/L Urea
- 38 g/L Creatinine

The spray nozzle was intended to spray an even layer of brine on the substrate, but the low flow rate resulted in the brine dripping out of the nozzle, rather than spraying. The discrete dripper applicator created individual streams of brine that did not spread out to form an even layer unless it was used in conjunction with the wiper, which spread out the individual streams into a uniform film. The film applicator worked well without the wiper, since the applicator itself acted as a wiper. This testing showed that the design of the applicator nozzle was not critical as long as there was a wiper downstream to spread the brine evenly across the substrate.

Initial brine applicator testing proved feasibility of the EBDS brine application concept functionality and narrowed down the potential material and design options. The EBDS full system prototype incorporates an extremely simple applicator with a wiper downstream to create a uniform layer of brine on the substrate.

Brine Applicator Materials – When Lunar Outpost brine was established as the baseline EBDS influent, material compatibility was a major concern in development of the EBDS brine applicator, due to the acidic and corrosive nature of the pretreated urine. Long-term tests were conducted to confirm material compatibility by continuously circulating actual CDS pretreated urine brine (pH $\approx$ 2.4) through the tubing, fittings, and reservoir material. The items in the long-term material compatibility test are shown in Table 1.

Table 1. Long-duration brine applicator test materials

Component Description	Brine Contact Surface	Material
Pump Tubing	Inner Wall	Marprene
Tubing	All	Tygon 2075*
Tubing	All	Tygon SE-200**
Fittings	All	Kynar (PVDF)
Reservoir	Inner Wall	HDPE

* 2075 is Tygon's chemically resistant tubing formulation

** SE-200 is standard Tygon lab tubing with an inner FEP fluoropolymer liner

The long-duration materials compatibility test ran for six months, which is the baseline maintenance interval for the pump tubing. At the completion of the test none of the components showed any visible deterioration, but the tubing began to show some discoloration. The SE-200 showed substantial discoloration, especially around the barb connections. It appeared that some brine leaked between the FEP lining and the standard Tygon tubing and caused the discoloration of the inside of the Tygon tubing. The 2075 chemically resistant tubing showed no discoloration on the inside of the tubing. The sections of tubing that were sitting in relatively stagnant brine showed some discoloration for both tubing formulations. The outside of the standard Tygon portion of the SE-200 tubing turned a deep yellow color, similar to the brine, while the 2075 showed only a slight discoloration on one section of the tubing. The Kynar fittings and HDPE reservoir showed minimal discoloration. The Marprene pump tubing survived the test and showed no unexpected external wear. The inside of the Marprene tubing was discolored and the area of the tubing that was repeatedly compressed by the pump showed some wear as expected, but there were no signs of chemical breakdown of the material. Figure 2 shows the long-duration material compatibility test in progress.

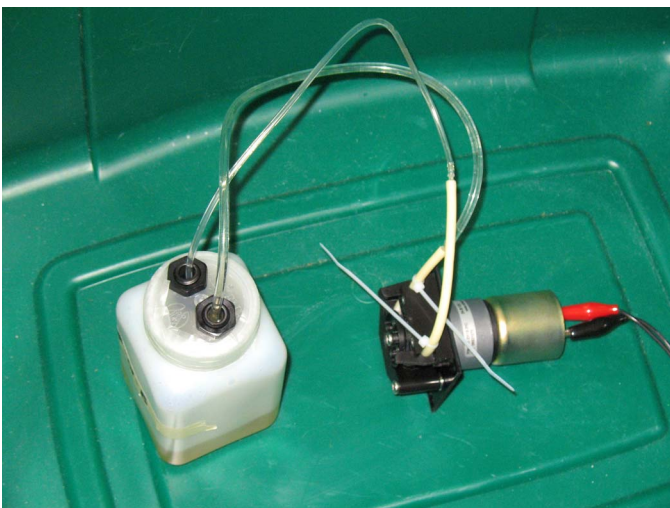


Figure 2. Long-duration materials compatibility test

Based on these results, all materials used in this test are suitable for use in the EBDS with Lunar Outpost brine. The EBDS prototype will incorporate Marprene tubing in the peristaltic pump and will use Tygon 2075 tubing throughout the rest of the system, since 2075 showed less discoloration than the SE-200 tubing.

SALT REMOVAL TESTING – Two initial methods of salt removal were investigated, a scraper and a rotating brush. For the rotating brush method, the test variables included brush material, rotational speed, and distance of the axis of the brush from the surface of the substrate. For the scraper method, the test variables included scraper angle and force. A variety of brine application substrate materials and surface treatments were tested as well. All initial salt removal testing was performed using the concentrated urine ersatz described earlier.

The ersatz was manually applied to each substrate and then evaporated in an oven. The following substrate materials were tested:

- Anodized 6061 Aluminum
- 304 Stainless Steel
- Nylon 6/6
- Neoprene Rubber
- Ultem

All scraper testing was performed with a custom designed Delrin scraper so the nylon, neoprene, and Ultem substrates would not be damaged by the scraper.

Testing showed that a scraper angle of 20° from perpendicular was more effective than a 40° scraper angle, and that salt removal capability reaches a maximum at 9 lb of scraper force. Salt removal capability increased with increasing scraper force up to 9 lb, but showed no noticeable increase at forces above 9 lb. These valuations are qualitative, based on visual observation of the scraping operation, and are fairly consistent for all of the substrate materials that were tested.

Two brush materials were tested, nylon and tampico. Rotational speed and the distance of the axis of the brush from the surface of the substrate were varied. The nylon brush appeared to be too soft and did not observably remove any salt at any speed or distance. The tampico brush removed most of the salt from the substrate, but also caused surface damage to all tested substrate materials except neoprene, which allowed nearly complete removal of the dried salts.

Since the scraper was more effective than the brushes for a wide range of substrate materials, the EBDS prototype features a scraper mounted 20° from perpendicular with a downward scraping force of approximately 9 lb.

SUBSTRATE MATERIAL TESTING – Two rounds of testing were performed on potential substrate materials.

The substrate material testing performed during Phase 1 included a variety of metallic, plastic, and rubber materials. The Phase 2 testing included anodized aluminum, the best performer from the Phase 1 testing, and two titanium samples.

Phase 1 Substrate Material Testing – The goal of the substrate testing was to evaluate the performance of different substrate materials and surface treatments. Characteristics of interest included creation of a uniform brine layer on the surface, and ability to remove dried salts from the substrate after evaporation.

At the time of this testing potential EBDS design concepts included both a solid substrate and a flexible belt substrate, so the following substrate material types were tested:

- Anodized 6061 Aluminum
- 304 Stainless Steel
- Nylon 6/6
- Neoprene Rubber
- Ultem

Each material listed above was tested in an untreated condition, and also with a commercial hydrophilic surface treatment applied. At the time of this testing, the EBDS was still potentially a microgravity application, so a hydrophilic surface was desired. The hydrophilic coating was applied by Surmodics, Inc. and is generally intended for medical devices. This coating was selected based on availability and schedule with the goal of providing general insight into the effect of a hydrophilic surface on system performance.

The Phase 1 substrate material testing was performed with the sodium chloride, urea, and creatinine ersatz that was described earlier. A prototype brine applicator applied brine to a moving substrate, similar to the application process in the EBDS. The brine applicator used in this testing incorporated discrete drippers and a wiper to spread the ersatz into a uniform film. The combination of ersatz application rate and substrate speed resulted in a film thickness of 0.014 cm. After the ersatz was dried, a Delrin scraper positioned at 20° from perpendicular removed the residual salts.

All substrate samples with hydrophilic coatings achieved more uniform brine distribution than the untreated samples. Unfortunately, the hydrophilic coating also resulted in greater salt adhesion, which made removal of the dried salts more difficult. Of the untreated samples, nylon and anodized aluminum enabled a fairly uniform brine application, while Ultem, stainless steel, and neoprene exhibited pooling of the brine on the substrates. Stainless steel also showed significant corrosion after two cycles of brine application and evaporation.

Of all substrate materials tested, only anodized aluminum with no hydrophilic treatment allowed

acceptable quantities salt to be removed by scraping. Over multiple cycles of brine application, evaporation, and removal, only the anodized aluminum substrate reached a steady state at which the quantity of salt removed was equal to the quantity of salt applied.

Phase 2 Substrate Material Testing – The knowledge gained during Phase 1 regarding the corrosive nature of the liquids that will potentially be inside the EBDS led to the determination that a titanium substrate sample should be tested, due to titanium's extreme corrosion resistance. The Phase 2 substrate material testing included three materials:

- Anodized 6061 Aluminum
- Titanium
- Anodized Titanium

This aluminum-titanium substrate material testing was performed using a new aluminum scraper positioned at 20° off perpendicular, the same concentrated urine ersatz formula from previous tests, and an ersatz film thickness of 0.10 cm, which is approximately 6.5 times more ersatz than in previous testing.

The ersatz spread more uniformly on the two titanium substrates than on the aluminum substrate, which showed some pooling of the ersatz. The untreated titanium substrate allowed a fairly uniform ersatz layer, although some areas remained uncovered after ersatz application. The ersatz spread very evenly on the anodized titanium substrate, although there was some minor pooling near the edges of the substrate.

The increased quantity of ersatz and the use of an aluminum scraper allowed much more salt to be removed by the scraper, compared to previous tests with the Delrin scraper. As the salt was removed with the scraper, it formed granules and small flakes. Some portions of the salt layer had small amounts of liquid underneath the salt.

The amount of salt remaining on the anodized aluminum substrate after each scraping pass was consistently higher than on the titanium substrates. Of the two titanium substrates, the anodized substrate had slightly less salt remaining on the surface over repeated application and removal cycles. All samples appeared to reach a steady state at which the quantity of salt removed was equal to the quantity of salt applied.

Upon completion of the test, both the untreated and anodized titanium substrates showed no visible damage when examined under a microscope. The salt samples scraped from the anodized aluminum substrate had a bluish gray tint as shown in Figure 3, which indicates that some of the anodized layer was removed. After the test, damage caused by scraping on the anodized aluminum substrate was clearly evident to the naked eye. Under magnification the anodized aluminum substrate appeared to have lost some of the anodized layer.