

# Results and Interpretation of the WFRD ELS Distillation

## Down-Select Test Data

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Testing of the Wiped-film Rotating-disk (WFRD) evaporator was conducted in support of the Exploration Life Support Distillation Down-Select Test. The WFRD was constructed at NASA Ames Research Center (ARC) and tested at NASA Marshall Space Flight Center (MSFC). The WFRD was delivered to MSFC in September 2009, and testing of solution #1 and solution #2 immediately following. Solution #1 was composed of humidity condensate and urine, including flush water and pretreatment chemicals. Solution #2 was composed of hygiene water, humidity condensate, and urine, including flush water and pretreatment chemicals. During the testing, the operational parameters of the WFRD were recorded and samples of the feed, brine, and product were collected and analyzed. The steady-state results of processing 414L of feed solution #1 and 1283L of feed solution #2 demonstrated that running the WFRD at a brine temperature of 50°C gave an average production rate of 16.7 L/hr. The specific energy consumption was 80.5W-hr/L. Data Analysis shows that the water recovery rates were 94% and 91%, respectively. The total mass of the WFRD as delivered to MSFC was 300 Kg. The volume of the tests stand rack was 1m width x 0.7m depth x 1.9m height or 1.5 m<sup>3</sup> of which about half of the total volume is occupied by equipment. Chemical analysis of the distillate showed an average TOC of 20ppm, a pH of 3.5, and a conductivity of 98 µmho/cm. The conductivity of the distillate, compared to the feed, decreased by 98.9%., the total ion concentration decreased by 99.6%, the total organics decreased 98.6%, and the metals were at or below detection limits.

### Nomenclature

ARC	=	Ames Research Center
°C	=	degrees Centigrade
CDS	=	Cascade Distillation System
ECLS	=	Environmental Controls and Life Support
ELS	=	Exploration Life Support
ELSDDST	=	ELS Distillation Down-Select Test

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gm	=	grams
Kg	=	kilograms
$\text{kJ/m}^3\text{ }^\circ\text{C hr}$	=	kilojoules per cubic meter per degree centigrade per hour
JSC	=	Johnson Space Center
L	=	Liter
L/hr	=	Liters per hour
lb	=	pounds
m	=	meters
$\text{m}^3$	=	cubic meters
ml	=	milliliters
$\mu\text{mho/cm}$	=	reciprocal ohms per centimeter
ppm	=	parts per million
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
pH	=	the negative log of the hydrogen ion activity
REMS	=	Regenerative ECLS module simulator
std. dev.	=	standard deviation
TDS	=	Total Dissolved Solids
TIC	=	Total Inorganic Solids
TOC	=	Total Organic Solids
TSS	=	Total Suspended Solids
the VCD	=	the VCD system being developed by MSFC
VCD	=	Vapor Compression Distillation
VPCAR	=	Vapor Phase Catalytic Ammonia Removal
WFRD	=	Wiped Film Rotating Disk
W	=	watts
W-hr/L	=	specific energy, watt – hours per liter
wt.	=	weight

## I. Introduction

This Wiped Film Rotating Disc (WFRD) was assembled, modified, and upgraded as part of a 9 month program to support the ELS Distillation Down-Select Test (ELSDDST). The Wiped Film Rotating Disc WFRD test hardware delivered to MSFC was a refurbished older unit that was constructed in the early 1990's as a component part of the original Vapor Phase Catalytic Ammonia Removal (VPCAR)<sup>1-2</sup> system. The original VPCAR system had been dissembled and surplused in the late 1990's during the development of the 2<sup>nd</sup> generation VPCAR system and is now being reassembled (minus the oxidative reactors) as the WFRD<sup>3-5</sup>.

The stand alone WFRD is configured as a vapor compression distillation system. A WFRD system is a particularly energy efficient water distillation process. A flow diagram of the WFRD system is provided in Figure 1. The WFRD process derives its efficiency through the recycling of the latent heat of evaporation. In the WFRD cycle, a waste stream is introduced into the WFRD evaporator where energy is transferred to the wastewater feed causing the evaporation of a portion of it. This vapor is then compressed to increase its saturation temperature and condensed on a common condensation/evaporation surface. The liberated latent heat of condensation is then transferred through the heat transfer surface and used as the energy source for further evaporation of the feed. The net energy required for the process is only that which is needed to drive the compressor, operate the liquid pumps and any other associated rotating equipment, and make up for any thermodynamic losses, i.e. heat loss to the environment and inherent thermodynamic irreversibility.

Figure 2 shows the complete assembly of the WFRD test stand that was tested at MSFC. This system was constructed specifically for the ELSDDST. In the past, the WFRD has been developed by NASA as a component of the VPCAR technology.

## II. Methodology

The testing methodology for the ELSDDST is documented in the "Exploration Life Support Water Recovery System Distillation Comparison Test Plan", JSC 47176, March 20, 2009.<sup>6</sup> The primary objective of this test was to generate data establishing the performance of the WFRD technology in support of the ELDDST. This performance evaluation was accomplished by processing two waste water solutions that represent potential lunar base waste-water streams. Solution #1 was a 30-day, 4-crew waste water stream composed of humidity condensate and

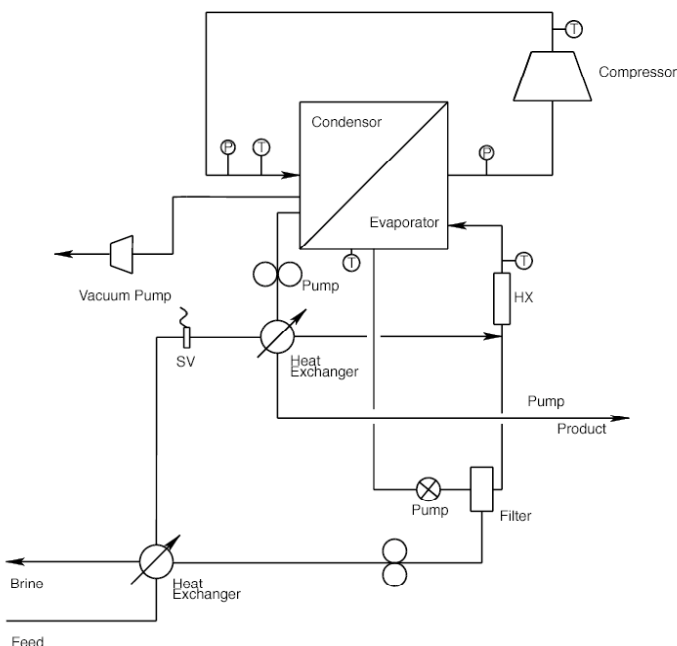


Figure 1. WFRD Flow Diagram

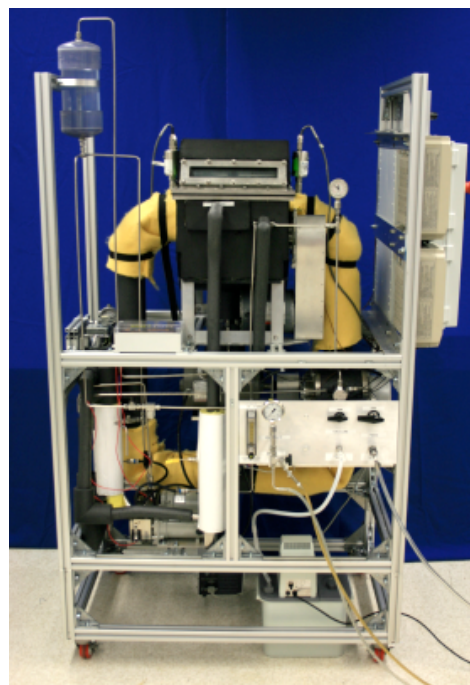


Figure 2. WFRD Test System as delivered to MSFC

pretreated urine. Solution #2 was a 30-day, 4-crew waste water stream composed of humidity condensate, pretreated urine, and hygiene waste waters.

The test objectives were as follows:

- Achieve a minimum of 93.5% water recovery of the Solution #1.
- Achieve a minimum of 90% water recovery of the Solution #2.
- Assess distillate quality and technology performance over the course of the test

Humidity condensate was generated to closely simulate the atmospheric contaminant load anticipated from a lunar surface mission. This was accomplished by collecting condensate from test subjects that exercise and performed hygiene activities in an enclosed facility, while also injecting contaminants to adequately represent the desired atmospheric quality. After the humidity condensate was collected, a pretreatment solution was added to maintain microbial control. This solution was comprised of 0.5 gm of oxone and 0.11 gm of sulfuric acid per liter of condensate.<sup>6</sup>

Urine was collected from volunteers and each liter was pretreated with 5 gm oxone, 2.3 gm sulfuric acid, and 250 ml of flush water. Hygiene was collected from volunteers using standard procedures (consistent with those implemented at Johnson Space Center for the evaluation of the Cascade Distillation System) to insure consistency. For Solution 1 (Table 1), hygiene activities were performed in the REMS (Regenerative ECLS module simulator) at MSFC, but the waste water was collected on hand towels and allowed to evaporate (to be collected with the humidity condensate). For Solution 2 (Table 2), waste water from the hygiene activities was collected for subsequent processing by the WFRD.

### **III. Results and Discussion**

Nominally the WFRD was operated at the minimum water recovery ratio (93.5% and 90.0%, respectively) for the duration of the testing with the exception of the initial startup of the first run where brine was not removed in order to quickly bring the brine to the appropriate water recovery concentration. A brine bleed was then taken for the duration of the run. The average feed flow into the WFRD equals the average distillate and brine flows out. The WFRD does not use a replaceable brine filter tank such as the ones used by the VCD and CDS use and thus has no regular re-supply requirements.

Vacuum was provided with a water aspirator pump maintained at nominally at 9°C with the WFRD operated at a steady-state heater temperature of 50°C. The aspirator pump was used to collect the liquid from the vacuum vent.

Treatment of each solution was analyzed and the results evaluated to ascertain the WFRD's performance during full-run, steady-state, and startup conditions.

#### **A. DATA SELECTION**

Data was analyzed for the start-up, steady-state, and full-run values.

##### **1. Determination of Steady-State Data**

Steady state was defined as operation after system temperatures stabilized. A heater in the brine recirculation loop is used to control the temperature of the evaporating feed. Although the WFRD was operated at a steady-state heater temperature of 50°C, the steady-state brine temperature fluctuated between 52 and 53°C for Solution #1. This discrepancy could be due to thermocouple inaccuracies or the normal mechanically generated self-heating of the WFRD. Only data collected after the brine temperature exceeded 52 degree C were kept for analysis as steady state, and the steady-state daily run was considered over when the production rate dropped below the steady-state value.

For Solution #2, the steady-state brine temperature fluctuated between 51.5 and 52.5°C and thus only data collected after the brine temperature exceeded 51.5°C were kept for analysis as steady state, and the steady-state daily run was considered over when the production rate dropped below the steady-state value.

Table 1. WFRD Daily Wastewater Generation for Solution #1

Wastewater	Water Quantity	Cleansing Agent
Humidity Condensate	15.6 kg/day (34.3 lb/day)	None
Handwash	16 per day, 55 ml/handwash	Water
Full Body Wash	2 per day, 55 ml/wash	Water
Wet Shave	1 per day, 55 ml/shave	Neutrogena Shave Cream
Oral Hygiene	4 toothbrush/day, 28 ml/activity	Arm & Hammer Dental Care
Pretreated Urine + Flush water	12.0 kg/day (13.2 lb/day)	N/A

Table 2. WFRD Daily Wastewater Generation for Solution #2

Wastewater	Water Quantity	Cleansing Agent
Humidity Condensate	15.6 kg/day (34.3 lb/day)	None
Handwash	64 per day, 125 mls/handwash	No-Rinse, 1.5 gm/handwash
Shower	8 per day, 6 L/shower	No-Rinse, 25 gm/shower
Wet Shave	2 per day, 150 mls/shave	Neutrogena Shave Cream, 0.8 gm/shave
Oral Hygiene	16 toothbrush/day, 100 mls/shave	Orajel for Kids, 1.0 gm/activity
Pretreated Urine + Flush water	12.0 kg/day (13.2 lb/day)	N/A

## 2. Determination of Startup Data

The startup data included all data from when the system was started and the brine temperature began increasing for the daily run up until the steady-state cut-off temperature (52.0 and 51.5°C, respectively) was achieved.

## 3. Determination of Full-Run Data

The full run data included all the startup and steady-state data.

## B. SOLUTION #1 DATA ANALYSIS

Table 3 shows a summary of the solution #1 data analysis.

### 1. Steady-State Data

Operating the brine loop heater at 50°C gave a steady-state brine temperature of about 52.7°C. This temperature gave an average production rate of 16.6 L/hr with a specific energy consumption of 80.1W-hr/L. The average power requirement was 1327 W with a standard deviation of 65 W at a pressure ratio of 1.27. The highest instantaneous peak power was 1551 W. The percent water recovery rate was 94.4% +/-0.6%.

## **2. Startup Data**

The average startup time was 82 minutes. For this period, the production rate goes from 0 L/hr to the steady-state value with an average production rate of 9.2 L/hr with an average specific energy consumption of 111.1W-hr/L. The average power requirement was 1025 W.

## **3. Full-Run Data**

The full run for each day took 5 to 5.5 hours. This timing was set by the operators and conformed to an 8 hr work day. For this period, there was a start up period of approximately 82 minutes followed by 3.5 to 4 hours of operations at steady-state. This resulted in an average daily production rate of 14.2 L/hr with an average specific energy consumption of 85.3W-hr/L at a pressure ratio of 1.25. Thus, the startup costs only increased the average specific energy consumption by 5W-hr/L. The average power requirement for a day's run was 1214 W. The percent water recovery rate was 91.9 +/-1.5%. At the end of each day's run the system was left containing the brine from the previous run.

## **C. SOLUTION #2 DATA ANALYSIS**

Table 3 shows a summary of the solution #2 data analysis.

### **1. Steady-State Data**

Operating the brine loop heater at 50°C gave a steady-state brine temperature of about 52.2°C. This temperature gave a production rate of 16.7 L/hr with a specific energy consumption of 80.6W-hr/L. The average power requirement was 1344 W with a standard deviation of 207 W at a pressure ratio of 1.33. The highest instantaneous peak power was 1743 W. The percent water recovery rate was 90.7% +/-0.4%.

### **2. Startup Data**

The average startup time was 80 minutes. For this period, the production rate goes from 0 L/hr to the steady-state value with an average production rate of 9.2 L/hr with an average specific energy consumption of 116.2W-hr/L. The average power requirement was 1066 W.

### **3. Full-Run Data**

The full run for each day took 5 to 5.5 hours. For this period, there was a start up period of approximately 80 minutes followed by 3.5 to 4 hours of operations at steady-state. This resulted in an average daily production rate of 14.7 L/hr with an average specific energy consumption of 86.4W-hr/L at a pressure ratio of 1.32. Thus the startup costs increased the average daily specific energy consumption by 6W-hr/L. The average power requirement for a day's run was 1267 W. The percent water recovery rate was 89.9 +/-0.2%.

Table 3. Summary of WFRD operational data.

	Full-run		Steady-state	
	Solution #1	Solution #2	Solution #1	Solution #2
<b>Temperature</b>	50 C	50 C	50 C	50 C
<b>Total Power<sup>a</sup></b>	1214 +/-289W	1267 +/-269W	1327 +/-65W	1344 +/-207W
<b>Production Rate<sup>a</sup></b>	14.2+/-4.8L/hr	14.7+/-4.7L/hr	16.6+/-1.6L/hr	16.7+/-2.6L/hr
<b>Specific Energy</b>	85.3 W-hr/L	86.4 W-hr/L	80.1 W-hr/L	80.8 W-hr/L
<b>Recovery Ratio<sup>b</sup></b>	91.9 +/- 1.5%	89.9 +/-0.2%	94.6 +/- 0.6%	90.7 +/-0.4%
<b>Startup Time</b>	82 min	80 min	N/A	N/A

<sup>a</sup> Average +/- std. dev. for all data, i.e., each 5 minute data point

<sup>b</sup> Average +/- std. dev. for the daily average

#### D. CHEMICAL ANALYSIS

Feed, brine, and distillate samples were collected and sent to an independent laboratory for chemical analysis. No more than one set of samples were collected per day, and normally they were collected every second day. This analysis included the TOC, TIC, pH, conductivity, turbidity, TSS, TDS, selected anions and cations, selected metals, and analysis for alcohols, aldehydes, organic acids, glycols, and ketones. This data is summarized in Table 4. Table 4 contains a statistical compilation of data for both feed solutions #1 and Solution #2.

The chemical analysis of the distillate produced the following major results: an average TOC of 20ppm, pH of 3.5, and conductivity of 98  $\mu$ mho/cm. The conductivity of the distillate compared to the feed decreased by 98.9%, the total ion concentration decreased by 99.6%, the total organics decreased by 98.6%, and the metals analysis was mostly “below detection limit”.

Table 4. Summary of chemical analysis – a compilation of data from all solutions

	Feed		Brine		Distillate		% Removal
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	
<u>CHEMICAL ANALYSIS</u>							
Total Particles, ppm	17509.4				180.026		>99
pH	2.31	0.02	1.83	0.1	3.5	0.19	
Surface Tension, dyn/cm	46.57	9.06	32.94	9.25	59.33	20.17	
TSS, ppm	17.14	11.6	334.3	152.58			
TDS, ppm	8931.43	7989.05	60360	48209.74			
Turbidity, NTU	10.95	5.55	453.7	367.93			
TOC, ppm	1367.98	563.95	10720	9941.31	20.03	4.26	98.5
TIC, ppm	12.91	3.77	8.56	4.81	BDL		>96
Conductivity, μmho/cm	8963.1	905.01	42376.6	23472.9	97.89	36.44	98.9
Total Ions, ppm	3879.1				16.97		99.6
Total Organics, ppm	3284.7				44.92		98.6
Total Metals, ppm	1.6213				0.2163		86.7

#### 1. Ion Analysis

A number of ionic species were selected for analysis. They included  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ , and  $\text{SO}_4^{2-}$ . Data analysis for Solution #1 and Solution #2 were grouped together since there was a limited number of data points for the analysis of many of the ions.

Most of the ions were removed at a level that was greater than 99% with the only exceptions being Ammonium (97.8%) and Chloride (98.9%). The ammonium removal is affected by the ability of ammonia to volatilize and move through the gas phase into the distillate. Total ions removed was greater than 99%

Table 5. Chemical Analysis for Ions

	Feed		Brine		Distillate		% Removal
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	
<b>TOTAL IONS</b>	<b>3879.1</b>				<b>16.97</b>		<b>99.6</b>
Sodium (Na+), ppm	474.05	83.86	4241.2	3894.98	0.73	0.16	99.8
Potassium (K+), ppm	101.46	10.24	930	614.09	BDL	N/A	>99
Ammonium (NH4+), ppm	65.7	9.75	175.33	5.51	1.47	0.55	97.8
Magnesium (Mg2+), ppm	BDL		201.33	118.85	BDL		
Calcium (Ca2+), ppm	BDL		326.8	123.4	BDL		
Chloride (Cl-), ppm	807.79	216.17	7224.2	8005.32	8.55	3.86	98.9
Nitrate (NO3-), ppm	75.87	13.78	572.67	374.01	0.78	0.37	99
Phosphate (PO43-), ppm	482.69	162.62	926	187.95	2	0.2	99.6
Sulfate (SO42-), ppm	1871.53	282.28	17284	14959.34	3.43	0.92	99.8

## 2. Organic Analysis

The WFRD removed 98.7% of the total organic concentration. The major constituent was urea, and it was removed at 99.8%. The reason for the difference is because of the preferential volatilization of several of the more volatile components. Organics such as methanol, ethanol, formic acid and acetic acid all have boiling points close to water and are thus transferred to the distillate in trace quantities through the vapor phase. The average product TOC is 20 ppm. The distillate's TOC for Solution #1 was 25.5 ppm while the distillate's TOC for Solution #2 was 17.9ppm.

Table 6. Chemical Analysis for Organics

	Feed		Brine		Distillate		% Removal
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	
<b><u>TOTAL ORGANICS</u></b>	<b>3284.7</b>				<b>42.03</b>		<b>98.7</b>
Urea, ppm	3233.33	372.27			5.4	1.4	99.8
Methanol	1.59	0.34			1.7	0.44	-7.2
Ethanol	23.9	6.38			13.12	12.41	45.1
Other alcohols	1.59	0.34			2.45	0.88	-54.5
Formaldehydes	0.17	0.04			0.31	0.27	-80.3
Other Aldehydes	0.17	0.04			0.31	0.27	-80.3
Ethylene glycol	3.25	1.98			1.25	0.06	61.7
Other Glycols	8.65	3.57			9.33	6.99	-7.9
Formic Acid, ppm	5.27	0.58			3.89	2.11	26.1
Acetic Acid, ppm	BDL	0			3.33	1.16	
Other organic Acids	4.33	0.5			0.44	0.36	90.0
Acetone, ppm	0.62	0.1			0.2	0.07	68.1
Other ketones	1.82	0.89			0.29	0.25	83.8

### 3. Metal Analysis

The metals analyzed can be divided into 3 categories: WFRD metals, BDL (below detectable limits) uncommon metals, and uncommon metals.

The WFRD metals are the metals making up the materials of construction of the WFRD which is primarily stainless steel (Fe, Ni, Mg, and Cr) and copper crush gaskets (Cu). These metals are present in the feed in relatively low concentrations but are also present in the brine in much higher concentrations than can be attributed to just the concentration effects due to operation at high water recovery rates. For example, the iron level increases 600 times from the feed to the brine. The high level of these metals in the brine is likely the result of corrosion of the internal stainless steel components of the WFRD. This was expected and is the result of the pretreatment used which reduced the pH of the feed to about 2. WFRD metals are also found in the product due to the low pH of the distillate. To prevent this corrosion will require constructing the WFRD out of a different material such as titanium.

The BDL uncommon metals are Ar, Ba, Cd, Pb, Hg, and Se. All of the BDL uncommon metals are reported as below detection limits in the distillate although three of these metals did have detectible concentrations in some of the feed samples.

The third group, the uncommon metals (such as Ag and Zn), are not found in the construction of the WFRD and have detectable quantities in both the feed and distillate. Ag and Zn have a percent removal of 96% to 97%, respectively.

It is therefore proposed that the distillation process removes >95% of the metals from the feed, with some of the WFRD metals being re-dissolved into the distillate

Table 7. Chemical Analysis for Metals

	Feed		Brine		Distillate		% Removal
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	
<b><u>TOTAL METALS</u></b>	<b>1.6213</b>				<b>0.2163</b>		<b>&gt;86.7</b>
WFRD Metals							
Cr	0.0154	0.0067	9.1936	4.8423	0.0285	0.02	-85.7
Cu	0.0332	0.0042	1.5002	0.326	0.0474	0.0183	-42.8
Fe	0.054	0.028	30.468	7.4832	0.0702	0.0683	-30.2
Mn	0.0262	0.0197	3.4532	3.2383	0.011	0.0124	57.9
Ni	0.0225	0.0055	1.5157	1.8175	0.0134	0.0096	40.4
BDL uncommon metals							
As	0.0087	0.0039	0.0383	0.0214	BDL		<b>&gt;94</b>
Ba	0.006	BDL	0.1124	0.0522	BDL		<b>&gt;91</b>
Cd	BDL		0.025	0.0184	BDL		
Pb	BDL		0.0445	0.0106	BDL		
Hg	BDL		1.1016	0.6485	BDL		
Se	0.1695	0.0163	0.4669	0.543	BDL		<b>&gt;94</b>
uncommon metals							
Ag	0.8399	0.1622	3.3664	3.7885	0.0342	0.0341	<b>95.9</b>
Zn	0.446	0.0382	1.4873	1.1309	0.0115	0.0007	<b>97.4</b>

E.

### PRODUCTION RATE

The average production rate for both solutions is 16.7 L/hr at steady state and 14.6 L/hr for a daily 5 hour run. Figure 3 shows that production rate is proportional to the brine temperature at which the WFRD is run. As the brine temperature increases at the beginning of each days run, so does the production rate. As the temperature drifts up and down at the steady-state condition, so does the production rate.

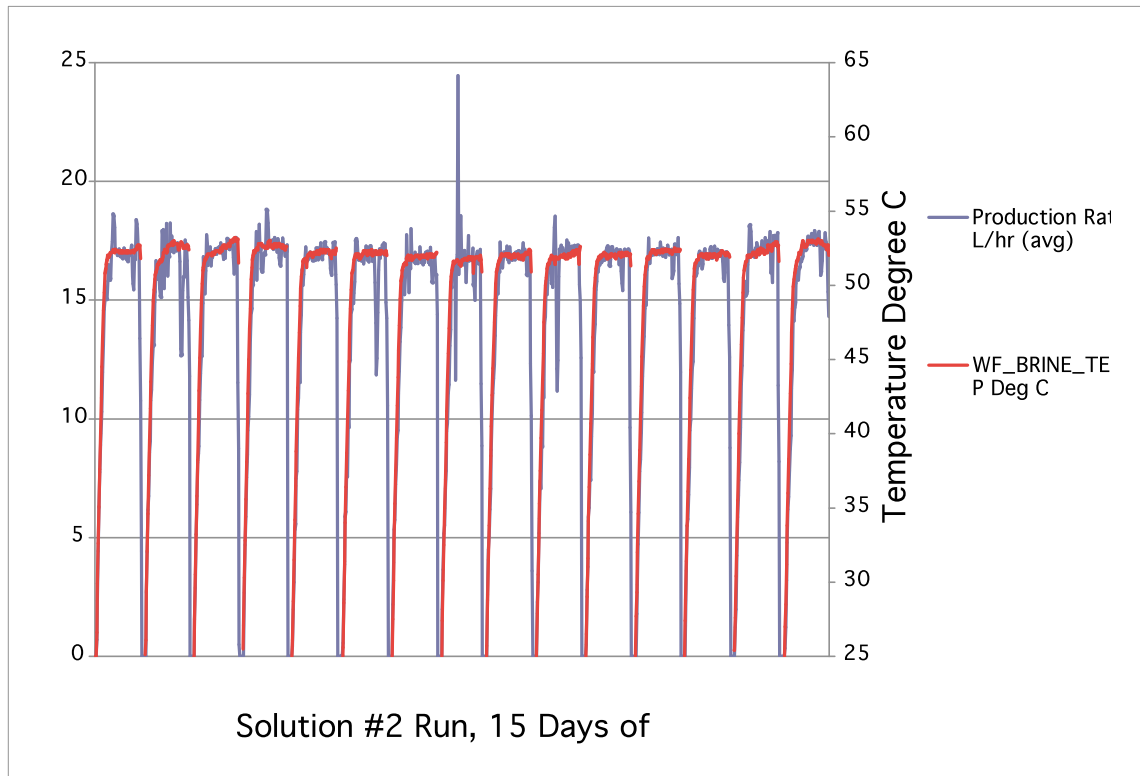


Figure 3. Plot showing the correlation between the brine temperature and the production rate of the WFRD. The noise within the production rate was smoothed by averaging the data point with the data that followed and preceded it, i.e., the 15 minute average.

**F.****MASS OF WFRD**

The total mass of the WFRD as delivered to MSFC was 300 kg. This includes the entire working systems hardware weight; the WFRD chamber, the pumps, the tubing, the control systems, the power analysis equipment, and the rack in which it is all mounted. The majority of the WFRD is built out of heavy stainless steel that is not optimized for weight. Notable exceptions are the rack which is aluminum and the compressor which is titanium. Table 8 provides a breakdown of all the component masses of the WFRD. A flight system would have to be made of titanium due to corrosion issues as noted in the metal analysis section above.

If titanium is used instead of stainless steel (40% wt. reduction), and if the WFRD chamber was weight optimized (not built out of 1/2" thick stainless steel, an over designed safety feature), the weight of the WFRD could be reduced to by over 50%.

Table 8. WFRD Component Mass (in kg)

<b>Item</b>	<b>Test Rig Mass, Kg</b>	<b>w/o support Mass, Kg</b>	<b>as titanium Mass, Kg</b>	<b>design optimized Mass, Kg</b>	<b>w/o motor Mass, Kg</b>
<b>WFRD Chamber</b>	64.68	64.68	36.87	18.43	18.43
<b>WFRD Rotor</b>	9.29	9.29	5.30	5.30	5.30
<b>2 1/2' Piping</b>	22.75	22.75	12.97	4.28	4.28
<b>Brine Loop Tubing</b>	2.20	2.20	1.25	0.63	0.63
<b>Brine Loop Filter</b>	7.91	7.91	4.51	1.13	1.13
<b>Misc Components</b>	2.88	2.88	1.64	1.64	1.64
<b>Misc Tubing</b>	1.20	1.20	0.69	0.34	0.34
<b>Motors and Pumps</b>	39.77	39.77	39.77	39.77	
<b>Framing and Mounting</b>	56.37				
<b>Power and Control</b>	92.76				
<b>Total Mass</b>	<b>300</b>	<b>151</b>	<b>103</b>	<b>72</b>	<b>32</b>

**G.****OFF NOMINAL OPERATIONS**

The WFRD ran reliably for the duration of the test with the exception of day 5 following a recirculation pump failure. This pump was removed and replaced and the run continued within the same day. Examination of the pump showed that it failed due to a defect in manufacturing.

On Day 13, there was a problem with the facility data analysis system that resulted in the system being shut down for a couple of hours.

For both of these issues, the non-steady-state data was removed from the analysis, and the rest of the data was analyzed normally.

It was noted that the flow to several of the wiper blades slowly decreased during the test. (The wiper blades ensure that the feed is spread evenly and continuously across the disc and help ensure that solids do not build up on the disc.) This is a problem that had been observed earlier during testing prior to shipment to JSC. The wipers were adjusted prior to shipping to MSFC in an attempt to mitigate this issue. It is believed to be caused by the deformation of the wiper material and the resulting constriction of the fluid flow paths in the wipers.

## **H. PRECIPITATION IN WFRD CHAMBER**

The WFRD was designed to run with some solids within the brine loop. The WFRD uses a wiped-film evaporator. This evaporator uses a wiper blade to add fluid feed and remove any solids that might build up on the evaporation surface. Our testing has shown that this wiper is effective against the build-up of most solids. The exception to this is scale forming solids such as calcium carbonate and calcium sulfate. These solids may not be removed by the wipers. The formation of scale solids typically limits the maximum water recovery ratio of the system for a given feed.

At the end of the testing of solution #2 the WFRD Chamber was opened and the presence of solids was noted, see Figure 4. The circular stripes of white material shown in figure 4 are indicative of scale. However, it should be noted that prior to this inspection, the system was noted to be operating normally. Data recorded at the time indicated that production was unchanged. The power consumption for the last run did rise slightly at the end (see Fig. 5), and an increase in power consumption can be indicative of scale forming on the heat transfer surfaces.

A sample of the solid material was collected from each disk and was sent out for analysis. Energy dispersive X-ray spectroscopy (EDS) analysis was taken for solids samples for each disk and from a single disk where visual inspection indicated differences in chemical makeup. Figure 6 and 7 present the results of this analysis. From Figure 6 it is clear that the yellowish/orange samples (from disk 1) and brown samples (from disk 4) are primarily organic solids and should not pose a problem. From Figure 7 it appears that likewise the yellowish/orange samples (from disk 1) and white samples (from disks 2 and 3) are not calcium scales because they have low levels of calcium. This would not be expected if they were a scale solid. This is true for all but the white fibers taken from disk 2 which are indicative of a calcium scale due to their high calcium levels. The existence of some calcium scale in disk 2 indicates that the system is operating right at the limit to water recovery ratio and that if it was exceeded would cause problematic scaling.



Figure 4. Precipitation of solids on disks at end of test.



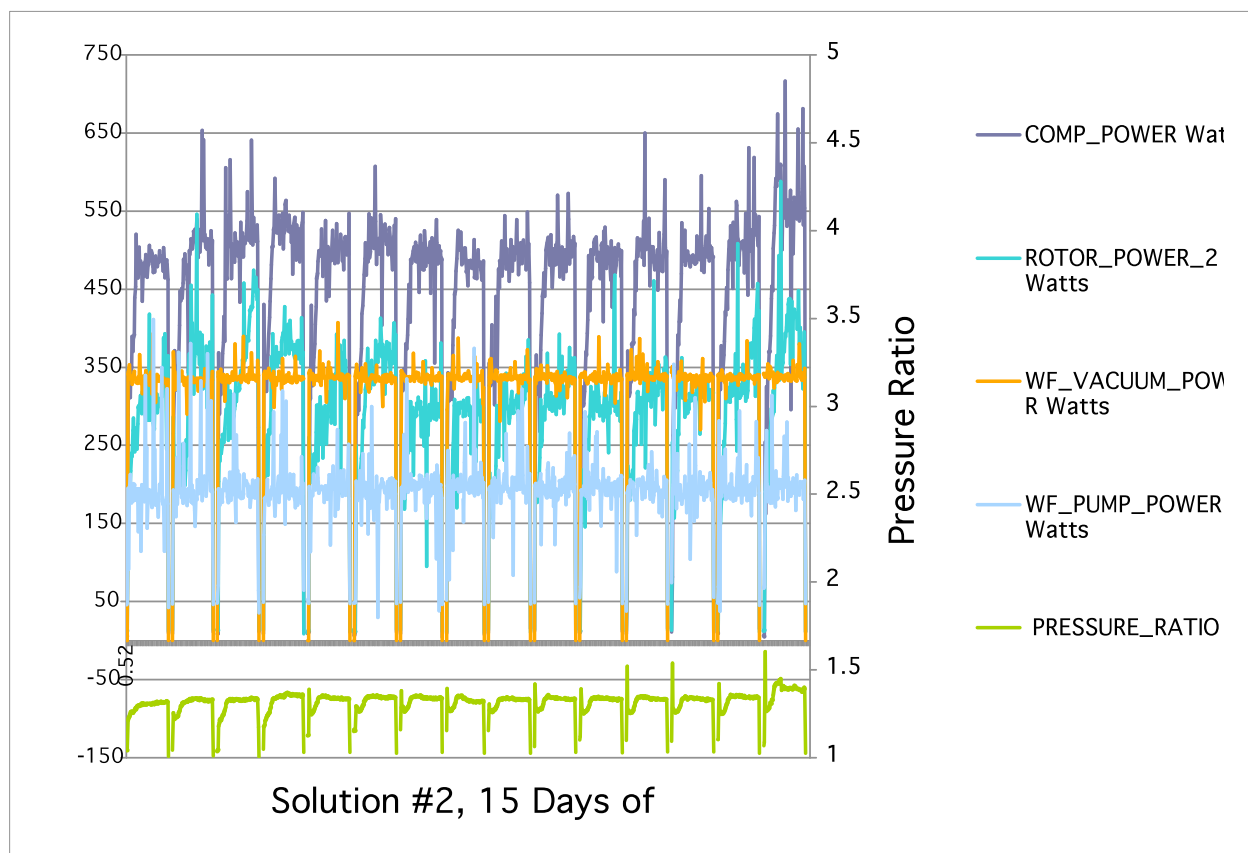


Figure 5. Power data for run with solution #2. Note slight power increase in compressor and rotor power during last day of the test. Also notice the slight increase in pressure ratio during the last day of the test.

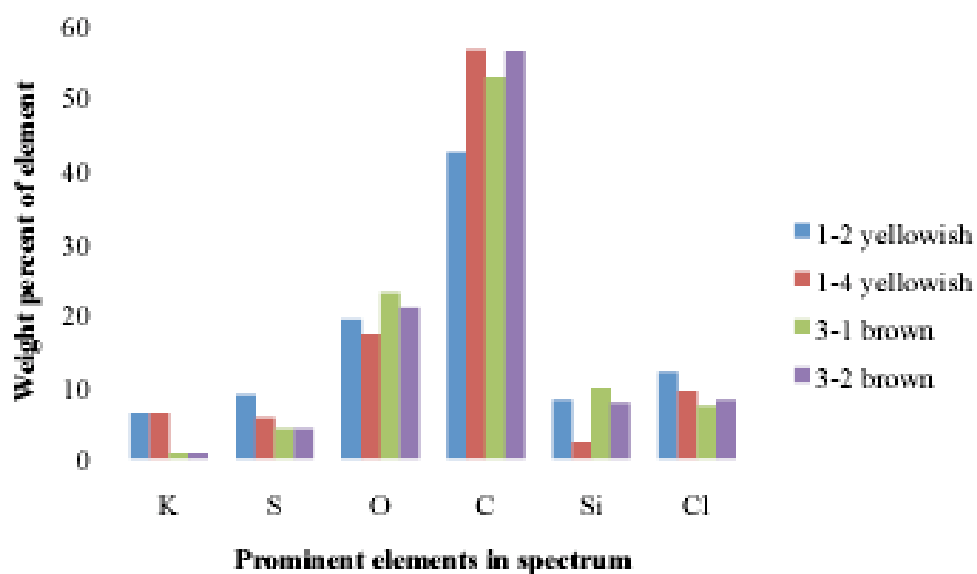


Figure 6. Correlation between yellowish/orange samples (from disk 1) and brown samples (disk 4)

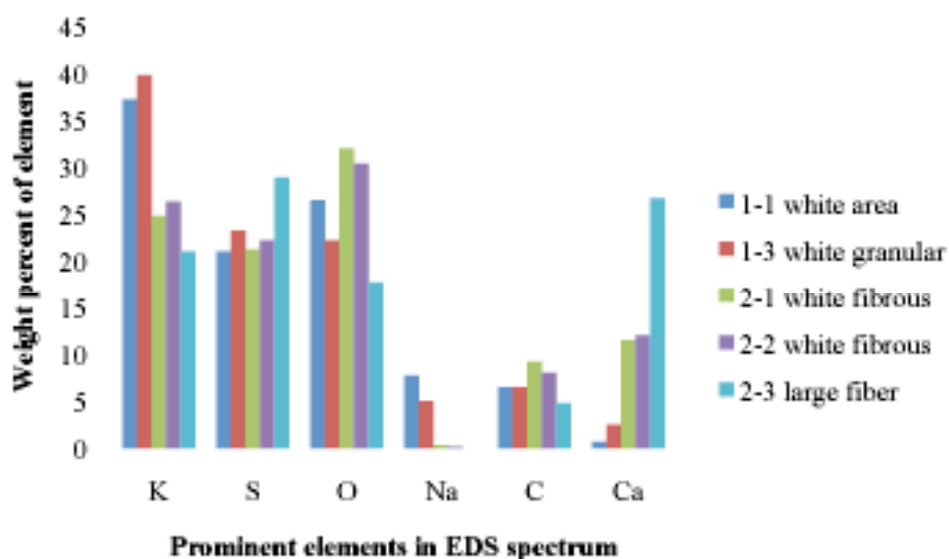


Figure 7. Correlation between yellowish/orange samples (from disk 1) and white samples (disks 2 and 3)

#### IV. Conclusions

Development and testing of the WFRD in support of the Exploration Life Support Distillation Down Select test has been successfully completed. The WFRD was constructed at Ames Research Center (ARC) and was tested at Marshall Space Flight Center (MSFC). The WFRD was delivered to MSFC in September 2009 with the beginning of testing Solution #1 starting on Sept 15 and with Solution #2 immediately following. During the testing, the operational conditions of the WFRD were recorded and samples of the feed, brine, and product were collected and analyzed.

Analysis of the data collected during the testing showed that running the WFRD at 50°C gave an average production rate of 16.6 and 16.7 L/hr, respectively, for the two solutions tested. The specific energy consumption was 80.1 and 80.6 W-hr/L, respectively. Data Analysis for the steady-state operating condition shows that the water recovery rates were 94% and 91% respectively. When the full 5 hour daily run was analyzed, the specific energy consumption increased to 85W-hr/L, this value includes all startup power costs. The total mass of the WFRD as delivered to MSFC was 300 Kg. The volume was 1.5 m<sup>3</sup> of which about half was occupied by equipment.

The chemical analysis of the distillate showed that the average TOC is 20ppm, the pH is 3.5, the conductivity decreased 98.9%, the total ion concentration decreased by 99.6%, the total organics decreased 98.6%, and the metals analysis results were predominantly below detection limits.

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<sup>6</sup>“Exploration Life Support Water Recovery System Distillation Comparison Test Plan”, JSC 47176, March 20, 2009.