

# Honeywell Cascade Distiller System Performance Testing Interim Results

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The ability to recover and purify water through physiochemical processes is crucial for realizing long-term human space missions, including both planetary habitation and space travel. Because of their robust nature, distillation systems have been actively pursued as one of the technologies for water recovery. The Cascade Distillation System (CDS) is a vacuum rotary distillation system with potential for greater reliability and lower energy costs than existing distillation systems. The CDS was previously under development through Honeywell and NASA. In 2009, an assessment was performed to collect data to support down-selection and development of a primary distillation technology for application in a lunar outpost water recovery system. Based on the results of this testing, an expert panel concluded that the CDS showed adequate development maturity, TRL-4, together with the best product water quality and competitive weight and power estimates to warrant further development. The Advanced Exploration Systems (AES) Water Recovery Project (WRP) worked to address weaknesses identified by The Panel; namely bearing design and heat pump power efficiency. Testing at the NASA-JSC Advanced Exploration System Water Laboratory (AES Water Lab) using a prototype Cascade Distillation Subsystem (CDS) wastewater processor (Honeywell International, Torrance, Calif.) with test support equipment and control system developed by Johnson Space Center was performed to evaluate performance of the system with the upgrades. The CDS will also have been challenged with ISS analog waste streams and a subset of those being considered for Exploration architectures. This paper details interim results of the AES WRP CDS performance testing.

## Nomenclature

$\Phi$	=	coefficient of powered operation
$\% R$	=	percent recovery as distillate collected divided by feed processed
$G_p$	=	change in distillate collection tank weight during processing
$G_f$	=	change in influent feed tank weight during processing
$k$	=	conductivity
$R_p$	=	production rate
$R_c$	=	consumption rate
$R.I.$	=	refractive index
$S_e$	=	specific energy
$t$	=	time
$V$	=	volume
$W$	=	watts

## I. Introduction

NASA's Advanced Exploration Systems (AES) Water Recovery Project (WRP) is chartered with developing advanced water recovery systems that will enable NASA human exploration beyond low Earth orbit (LEO). The goal of AES is to increase the affordability of long-duration life support missions, and to reduce the risk associated with integrating and infusing new enabling technologies required to ensure mission success. Because of

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the robust nature of distillation systems, the WRP is pursuing development of the Cascade Distillation Subsystem (CDS) as part of its technology portfolio. The CDS is a multi-stage vacuum rotary distiller system designed to purify water from spacecraft wastewater. A high fidelity prototype of the system shown in Figure 1 was co-developed by Honeywell International and the NASA Johnson Space Center (JSC). This system was used a distillation down-select test conducted in 2009 where it was compared to like spacecraft distillation technologies by an independent panel of experts. The panel concluded that the CDS showed adequate development maturity, produced the highest product water quality, and provided competitive weight and power estimates to warrant further development as a potential exploration life support technology.

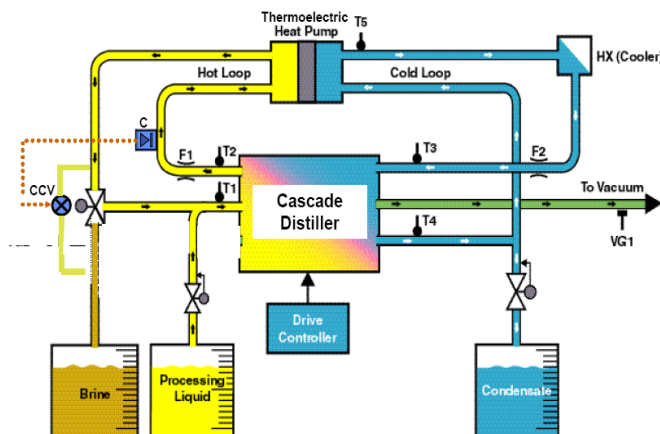
Through the AES WRP, Honeywell and the NASA-JSC are continuing their collaboration effort to develop a CDS flight system that could serve as a payload demonstration on the International Space Station (ISS) as early as 2017. Under the current design cycle, the development objectives include: (1) upgrade and test of the CDS prototype, (2) redesign and optimization of the CDS thermoelectric heat pump (TeHP), (3) upgrade and functional test of the CDS control system, and (4) development of a distillation compatible low-toxicity urine stabilization method. This report details the interim results associated with the upgrade and test of the CDS prototype, objective (1), with specific focus on demonstrating ability to process relevant ISS and exploration wastewater streams.



**Figure 1. The CDS test system in the JSC AES Water Lab.** The Cascade Distillation Subsystem (CDS) is contained in the blue box on right, and is supported by the AES Facility Support System contained in the silver racks on the left.

## II. Description of CDS Technology

The CDS is a multistage vacuum rotary distillation system used as a primary processor to recover water from spacecraft wastewater streams. Figure 1 shows a photograph of the CDS prototype test system installed in the AES WRP Water Lab at JSC. The CDS technology has been described in previous papers.<sup>1-3</sup> A simplified schematic of the CDS test stand is shown in Figure 2. The primary components in this system are the Cascade Distiller (CD) and its Drive Control Module (DCM), the thermoelectric heat pump (THP), the trimming heat exchanger, and the feed, product and brine tanks. It also includes various valves and flow switches to manage the flows within the system, a vacuum line condensate separator, liquid sampling fixtures, various filters, and basic instrumentation.



**Figure 2. CDS simplified schematic.** This simplified schematic highlights the major components of the CDS and the fluid paths, including the recirculating hot and cold loops.

Operation of the CDS involves evaporation and condensation of water from wastewater within a rotating drum. The drum is divided into five distillation compartments by means of specially designed baffles. Influent feed and recycled brine solutions are fed into the rotating drum at various stages in the distillation process. Vapor formed in each distillation chamber is condensed on the surface of the partition opposite the next

evaporation stage. Each of the five distillation compartments is maintained at a successively lower operating pressure and temperature, allowing the heat of vaporization to be recovered four times. A simplified model of the process stream flow in the five-stage distillation engine is shown in Fig. 2.

To enhance the liquid evaporation process, an external thermoelectric heat pump (THP) is used to provide heat energy to the hot side of the liquid recirculation loop. The THP also provides cooling energy to the cold recirculation loop. Cooling energy is used to remove the heat of vaporization not recuperated from the process. A trimming heat exchanger provides additional cooling energy to balance thermal inefficiencies common to THP technology. Operating at reduced pressure and recovering the latent heat of vaporization serve to reduce the CDS energy requirements.

The centrifugal forces produced during rotation of the drum assembly enable the distillation process in reduced microgravity. The CD centrifugal forces combined with management of pressures throughout the system provide the motive force by which to transport fluids through the system. This feature allows the CDS to forgo the added mass and complexity associated with using separate pumps. In addition to the core technology of the CDS prototype described in previous work, several upgrades to the system were implemented under the AES WRP as part of this latest phase of development. These upgrades included implementation of all ceramic shielded packed bearing design, intended to reduce bearing corrosion observed in previous development testing. Upgrades also included incorporation of new cold loop and product tank conductivity sensors, providing more accurate and precise measurement of distillate water quality during processing. Also replaced, were the hot and cold loop flow meters from gauge based visual Rotameters to new digital flow meters. The digital flow meters provide the capability for in-line data logging and a more measurement of loop flow that can be used to help close the systems thermodynamic balance. Finally, improved hot and cold flow switch technology was implemented as a more accurate control measure during filling of the two loops during autonomous operation.

### III. Materials and Methods

#### A. CDS Test Operations

General operation of the CDS was conducted according to procedures adapted from those provided by Honeywell at system delivery. The CDS test system (Fig. 1) operation was automated using the Three Tier (3T) Control System<sup>4</sup>.

In general, solution processing included a series of three consecutive batches for each unique test solution type. The CDS was operated in batch mode using the nominal operational settings listed in Table 1. A batch process includes system start up, waste stream processing, system shutdown and sampling. During start up, the distiller is spun to operational speed and the system is brought down to vacuum. The cold loop is filled with purified water, the hot loop is filled with the test solution and the THP is energized to transfer heat from the cold loop to the hot loop thereby initiating the distillation process.

During waste stream processing, also referred to as steady state operations, purified distillate evaporated from the hot loop is moved to the cold loop where it is condensed and removed to the product tank. Fresh influent test solution is continued to be fed to the hot loop at a rate equal to the rate of mass transfer of distillate to the cold loop. The wastewater brine containing the residual contaminants is recirculated through the hot loop becoming more and more concentrated as the batch progresses. System shutdown is initiated when the targeted batch size is achieved, as indicated by the feed tank weight. The batch size is a function of the targeted recovery rate which is established to maintain concentration of contaminants in the hot loop below the anticipated solubility limit for the solution under test.

After system shutdown, approximately 100 mL were collected from the feed, product, and brine tanks from the sample port valve located at the base of the respective tanks. The contents from the vapor trap were also collected

**Table 1. Nominal CDS performance testing set points.**

<b>Parameter</b>	<b>Nominal Target Setting</b>
<b>Distiller Speed</b>	1200 RPM
<b>THP Power*</b>	300 W
<b>Temperature</b>	
Hot Loop	45° C
Cold Loop	22° C
Trim Cooling	18° C
<b>Flow Rate</b>	
Hot Loop	1.4 L/min
Cold Loop	1.5 L/min
Trim Cooling	2.8 L/min
<b>System Pressure</b>	0.35– 0.50 psia

\* This power setting correlates to a 4.0 kg/hr targeted processing rate.

per batch run. After sample collection, the tanks are drained and the test system is prepared for the batch. Between each test series and prior to testing with a new test solution, the CDS is cleaned by changing out the filter in the hot loop and processing with DI water.

## **B. Test Objectives**

The current phase of CDS development had two primary objectives. The first objective was to benchmark the performance of the CDS in its upgraded configuration. Solutions selected for benchmarking included feed streams that had been tested in previous CDS development work.<sup>3</sup> The specific benchmark solutions were DI water, 2% sodium chloride solution and a human-generated feed stream stabilized using an Oxone-based pretreatment formulation. The DI test solution was provided as baseline for thermodynamic performance of the system when processing without introduction of a contaminant load. The sodium chloride solutions were used to demonstrate phase separation and removal by distillation of dissolved salts using solutions with solids concentrations approaching that of urine waste streams. The sodium chloride solutions were also chosen as a simple and reliably generated standard for evaluating CDS performance trends over its test life cycle. Finally, the Oxone stabilized urine provided a performance benchmark when processing a complex waste stream containing a full urine-like organic and inorganic contaminant waste load. Testing with these solutions also allowed comparison of data to previous system performance, providing at least a rudimentary check that the upgrades made to the CDS prototype were not having an acute and/or significant impact on system performance. Once the system performance was benchmarked, the second objective of the test was to collect data that could be used to evaluate CDS performance when processing two previously untested ISS analogue urine waste streams. This latter testing with the ISS feed streams was considered a critical development step toward one day demonstrating the CDS technology as a payload on the ISS. In general, each of the five benchmark and performance test solutions selected were processed in a series of three consecutive batches. To minimize cross-contamination of the system between the unique test solution, the system was cleaned by changing out the CDS hot loop filter and processing with DI water to a pre-described cleanliness level after the completion of each test series. A brief description of each test solution is provided in Section C, below.

## **C. Test Solutions**

Benchmark test solutions included DI water, sodium chloride solution and an Oxone-based stabilized urine wastewater. Deionized (DI) was processed through ion exchange and provided directly from the AES Water Lab DI water system. Solutions of sodium chloride solutions were generated by dissolving 220 g of NaCl (Sigma Aldrich) into 11-L of facility DI water. Finally, Oxone stabilized urine, referred to as Oxone pretreated urine (PTU) was generated by collecting urine from human donors and to which was added 5 grams of Oxone, 2.3 g of concentrated sulfuric acid and 250 g of DI flush water per liter of raw urine.

The two ISS urine waste streams selected included a baseline formulation currently used to stabilize urine on the ISS. This formulation included the addition of 16.5 g of stabilizer solution and 250 g of flush water per liter of raw urine. The baseline stabilizer solution contained 9% chromium trioxide, 36.5% concentrated sulfuric acid, and 54.5% flush water. Use of this stabilizer allows up to 75% recovery of water from urine per the current target specification used for the ISS urine processor assembly (UPA). An alternative pretreatment formulation is also being developed and is planned for the ISS which will replace the sulfuric acid content in stabilizer solution with phosphoric acid. This latter alternative formulation is intended to reduce the risk of calcium sulfate precipitation in recovered urine brine process streams and will allow the stabilized urine to be processed back to the original UPA specification of 85% water recovery. Stabilizer concentrations for the alternative formulation are expected to be provided in the stabilizer solution at similar, but still to be verified, concentration provided for the baseline ISS formulation.

For both ISS urine test solutions, the human-generated urine was first augmented to match more closely the urine mineral content observed for in-flight ISS urine waste streams. The augmented solutions, once stabilized, are referred to ISS pretreated and augmented urine (ISS PTAU) and ISS alternative pretreated and augmented urine (ISS Alt-PTAU), respectively. A description of the augmented urine formulation can be found in Mitchell et. al.<sup>5</sup>. Finally, all test solutions were filtered to 100 microns by passage through a stainless steel filter prior to processing through the CDS.

## **D. Sample Analysis**

For each test series, water quality and thermodynamic performance data were collected. Data collected from inline sensors were logged by the 3T control system including: system pressures, system temperatures, tank masses, THP and DCM power, and distillate conductivity. All samples—brine, product, influent, and vapor trap—were

analyzed for pH, conductivity, and refractive index. Samples were sent to the AWRSDF analytical lab for analysis of anions/cations, total organic carbon (TOC), and total inorganic carbon (TIC), metals, surface tension, total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), and total nitrogen (TN), analysis pending.

### E. Analytical Instrumentation

Standard chemical analyses were obtained according to methods described in Ref. 6. These analyses included pH (4500-H +B) and conductivity (2510B). pH measurements were made using an Orion 3-Star pH meter (P/N 1112000) equipped with an Orion glass body combination 8102BN Ross pH electrode. Conductivity measurements were made using an Orion 3-Star conductivity meter (P/N 1114000) equipped with a 013005MD conductivity probe. All other planned analyses will be made using methods established in the AWRSDF analysis lab.

### F. Calculations

#### 1. Production Rate

The production rate in kilograms per hour is given by

$$R_p = \frac{G_p}{\Delta t} \quad (1)$$

where  $G_p$  is the weight of distillate measured by the product tank weight scale over time interval  $\Delta t$ .

#### 2. Consumption Rate

The consumption rate in kilograms per hour is given by

$$R_c = \frac{G_f}{\Delta t} \quad (2)$$

where  $G_f$  is the change in the weight of feed solution as measured by the feed tank weight scale over time interval  $\Delta t$ .

#### 3. Power Consumption

The power consumption in watts for the main components of the CDS test article is given by

$$W = W_{THP} \times \Phi_{THP} + W_{CD} \times \Phi_{CD} + W_{VAC} \times \Phi_{VAC} \quad (3)$$

where  $W_{THP}$ ,  $W_{CD}$ , and  $W_{VAC}$  are the average power consumed by the THP, CD, and vacuum pump, respectively, during batch operation, and  $\Phi_{THP}$ ,  $\Phi_{CD}$ , and  $\Phi_{VAC}$  are the respective ratios of operation over the batch run. Full batch processing was considered to be the time from distiller startup to distiller shutdown. The measured power draw for the CD and THP were used in this evaluation; an average power of 400 W was assumed for the vacuum pump.

#### 4. Specific Energy

The specific energy ( $S_e$ ) consumption watt-hours per kilogram of water produced is given by

$$S_e = \frac{W}{R_p} \quad (4)$$

#### 5. Percent Recovery Rate

The percent recovery, or condensate recovered from the initial solution processed, is given by

$$\% R = \frac{G_p}{G_f} \times 100 \quad (5)$$

where  $G_f$  and  $G_p$  are the weight of the feed consumed and total distillate produced, respectively.

#### 6. Batch Size

The maximum batch size, or targeted feed consumption, is given by

$$G_f^* = \frac{V_{HotLoop}}{(1 - \% R^*)} \quad (6)$$

where  $V_{HotLoop}$  is the hot loop volume, which is empirically determined based on the configuration of the CDS hot loop.

#### IV. Results and Discussion

AES FY14 performance testing began on May 29, 2014 and ended on July 2. Over this test phase, eighteen batch runs were performed and over 160 kg of influent test solution was processed, less DI water processed as part of test system checkout and cleaning cycles. A summary of system performance is provided in Table 2, highlighting for each test solution the average (n=3) and standard deviations for batch size, water recovery rate, mass balance, specific energy, feed consumption rates, and distillate production rates. In general, the thermodynamic performance of the CDS with all test solutions was acceptable, exhibiting relatively low specific powers and expected recovery rates.

The CDS performance remains consistent with previous testing where a similar Oxone PTU test solution was processed with an average specific energy of 100 W-hr/kg when processed to 84% recovery.<sup>6</sup> These results suggest CD bearing and test system updates have not had a significant impact on performance.

The data suggests that the complexity of the test solution drives system performance. In general, the urine test solutions exhibit the highest specific energies (Figure 2), likely resulting from the presence of non-condensable gases requiring more work to be performed by the vacuum pump. Production rates also trend toward lower values in order of contaminant load, with DI exhibiting the highest production rate and the ISS PTAU solutions the lowest.

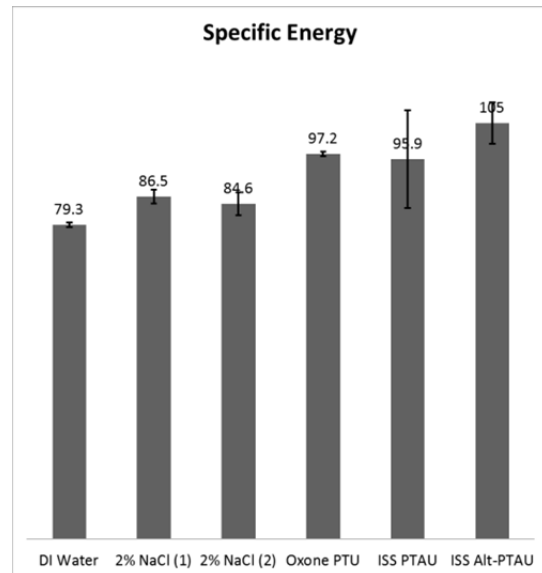
**Table 2. CDS Performance Summary**

Test Solution	Batch Size, kg	Water Recovery, %	Mass Balance, %	Consumption Rate, kg/hr	Production Rate, kg/hr	Specific Energy, W-hr/kg
DI Water	9.01 ± 1.39	84.6 ± 4.7	97.1 ± 2.9	4.69 ± 0.35	4.56 ± 0.11	74.8 ± 7.9
2% NaCl (1)	9.78 ± 0.02	85.3 ± 1.2	97.7 ± 1.5	4.40 ± 0.05	4.27 ± 0.03	86.5 ± 0.9
Oxone PTU	9.81 ± 0.01	83.1 ± 2.7	95.8 ± 2.8	4.54 ± 0.03	4.40 ± 0.04	97.2 ± 0.3
ISS PTAU	5.79 ± 0.03	78.4 ± 1.6	100.1 ± 1.9	4.01 ± 0.03	3.89 ± 0.00	95.9 ± 6.3
ISS Alt-PTAU	9.77 ± 0.03	84.4 ± 0.8	97.9 ± 0.8	4.17 ± 0.06	3.98 ± 0.04	105.0 ± 2.7
2% NaCl (2)	9.76 ± 0.02	83.0 ± 0.6	95.1 ± 2.8	4.42 ± 0.09	4.32 ± 0.09	84.6 ± 1.5

This trend might be expected across the urine based waste stream as the PTAU test solutions were augmented to increase the contaminant loads to better match the urine waste streams on orbit. The fact the Oxone is observed to have a production rate greater than that of 2% sodium chloride is likely due to the sodium chloride solutions having a larger salt content in the influent feed stream. The solids content for all test solutions will be verified through solids analysis (data pending).

Another item to note is that among the urine test solutions, the ISS PTAU exhibited a lower average specific energy. This may be attributed to the smaller batch size. At similar processing rates, the ISS PTAU required much less total time to process the batch amounting to a shorter duty cycle for the vacuum pump to maintain the system pressure within the prescribed limits over the shorter batch run.

Preliminary chemical analysis is provided in Table 3, including average values (n = 3) and standard deviations per test solution for pH, conductivity, and refractive index (R.I.). Overall, as a primary processor, the product water quality from the CDS was considered acceptable



**Figure 2. Average specific energy for test solutions processed.** This chart highlights the trend of increased specific energy with test solution complexity.

**Table 3. Preliminary Chemical Analysis**

Parameter	Influent	Distillate	Brine	Vapor Trap	Recovery Estimate (%)	Contaminant Removal (%)
<b>DI Water</b>						
pH	5.71 ± 0.11	5.07 ± 0.01	5.59 ± 0.03	5.27 ± 0.06	--	--
Cond. (μS/cm)	1.25 ± 0.05	1.89 ± 1.23	2.56 ± 0.38	5.18 ± 1.67		
R.I.	1.3332 ± 0.01%	1.3331 ± 0.01%	1.3332 ± 0.00%	--		
<b>2% NaCl (1)</b>						
pH	5.58 ± 0.11	5.72 ± 0.04	5.07 ± 0.12	5.04 ± 0.51	83.7 ± 3.6	> 99.9
Cond. (μS/cm)	36,400 ± 1,550	2.39 ± 0.19	229,800 ± 4,905	10.9 ± 6.3		
R.I.	1.3360 ± 0.01%	1.3328 ± 0.01%	1.3524 ± 0.34%	--		
<b>Oxone PTU</b>						
pH	2.08 ± 0.03	4.05 ± 0.03	1.59 ± 0.11	4.63 ± 0.20	85.0 ± 3.9	99.8
Cond. (μS/cm)	21,770 ± 645	46.2 ± 6.3	150,400 ± 3,087	12.8 ± 2.2		
R.I.	1.3357 ± 0.01%	1.3327 ± 0.00%	1.3535 ± 0.34%	--		
<b>ISS PTAU</b>						
pH	2.39 ± 0.04	3.92 ± 0.30	2.23 ± 0.04	5.00 ± 0.24	77.7 ± 5.4	99.6
Cond. (μS/cm)	27,270 ± 1,329	100.4 ± 6.4	125,700 ± 2,191	10.9 ± 5.4		
R.I.	1.3406 ± 0.03%	1.3328 ± 0.00%	1.3610 ± 0.44%	--		
<b>ISS Alt-PTAU</b>						
pH	2.36 ± 0.03	3.74 ± 0.08	2.25 ± 0.04	4.77 ± 0.23	85.7 ± 3.3	99.7
Cond. (μS/cm)	22,780 ± 2,774	85.2 ± 10.1	162,500 ± 2,635	12.1 ± 6.2		
R.I.	1.3403 ± 0.07%	1.3328 ± 0.00%	1.3787 ± 0.62%	--		
<b>2% NaCl (2)</b>						
pH	5.56 ± 0.05	5.74 ± 0.14	4.13 ± 0.27	5.28 ± 0.37	83.2 ± 4.4	> 99.9
Cond. (μS/cm)	34,690 ± 4875	2.38 ± 0.36	217,800 ± 6960	7.40 ± 2.95		
R.I.	1.3357 ± 0.01%	1.3329 ± 0.00%	1.3504 ± 0.39%	--		

for all influent waste streams. In general, contaminant removal from feed to product process streams were estimated at greater than 99% for all non-DI test solutions, with concomitant loading of contaminants in the brines. In accordance with the thermodynamic performance data, the trending conductivity of the product water increases with complexity of the influent. The distillate generated from the Oxone PTU influent had conductivity that was 19 times greater than that of the distillate generated from the 2% NaCl influent. Similarly, the ISS analog solutions have about twice the average distillate conductivity than Oxone PTU. These results are corroborated in pH data that suggests higher carryover of volatile materials such as organic acids. The R.I. data also correlates well with the general trends in conductivity. Higher than expected conductivities in the vapor trap samples may suggest some low level corrosion of the vapor trap system. A fine red suspension was observed in a number of vapor trap samples and across a number of different feed streams. Ion chromatography and metal analysis, data pending, will be used to look for specific evidence of metal corrosion in that portion of the system.

Finally, average recoveries estimated from the feed and product conductivities correlate well with calculated estimates determined from tank masses above. More data on steady state batch operations are planned to look at recovery trends as a function continuous multi-batch operations using a single influent waste stream.

## V. Conclusion

During the current phase of CDS development testing, the system was operated as expected and with acceptable performance when processing the benchmark test solutions, DI Water, 2% NaCl and Oxone PTU. Preliminary comparison of the benchmark data to previous testing suggest the system upgrades made to the current CDS prototype, especially upgrade of the bearing design, have not shown any immediate impacts to system performance. Similarly, the current round of testing has shown the CDS to be capable of processing ISS analog waste streams and with performance values approaching those observed for the less complex baseline test solutions. This latter result is an important development step on the critical pathway toward demonstrating the CDS technology as part of an ISS payload. Testing of the CDS will continue to evaluate the updated THP, control system and low-toxicity urine stabilization method. In addition, CDS prototype will also continue to be used as a test bed for informing the design and operation of the flight-forward CDS system.

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