

Advanced Exploration Systems Water Architecture Study Interim Results

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The mission of the Advanced Exploration System (AES) Water Recovery Project (WRP) is to develop advanced water recovery systems that enable NASA human exploration missions beyond low Earth orbit (LEO). The primary objective of the AES WRP is to develop water recovery technologies critical to near-term missions beyond LEO. The secondary objective is to continue to advance mid-readiness-level technologies to support future NASA missions. An effort is being undertaken to establish the architecture for the AES Water Recovery System (WRS) that meets both near- and long-term objectives. The resultant architecture will be used to guide future technical planning, establish a baseline development roadmap for technology infusion, and establish baseline assumptions for integrated ground and on-orbit Environmental Control and Life Support Systems definition. This study is being performed in three phases. Phase I established the scope of the study through definition of the mission requirements and constraints, as well as indentifying all possible WRS configurations that meet the mission requirements. Phase II focused on the near-term space exploration objectives by establishing an International Space Station-derived reference schematic for long-duration (>180 day) in-space habitation. Phase III will focus on the long-term space exploration objectives, trading the viable WRS configurations identified in Phase I to identify the ideal exploration WRS. The results of Phases I and II are discussed in this paper.

Nomenclature

<i>AES</i>	=	Advanced Advanced Exploration Systems
<i>CDS</i>	=	Cascade Distiller System
<i>DCaL</i>	=	Distiller Calcium Limiter
<i>DRM</i>	=	Design Reference Mission
<i>ECLSS</i>	=	Environmental Control and Life Support Systems
<i>FOST</i>	=	Forward Osmosis Secondary Treatment
<i>ISS</i>	=	International Space Station
<i>LEO</i>	=	low Earth orbit
<i>MABR</i>	=	Membrane-Aerated Biological Reactor
<i>NEA</i>	=	near Earth asteroid
<i>NGLS</i>	=	Next Generation Life Support
<i>OD</i>	=	Osmotic Distiller
<i>PPP</i>	=	Precipitation Prevention Program
<i>SOA</i>	=	state of the art
<i>TRL</i>	=	Technology Readiness Level
<i>UPA</i>	=	Urine Processor Assembly
<i>UPIX</i>	=	Urine Processor Ion Exchange
<i>VCD</i>	=	Vapor Compressor Distiller
<i>WCS</i>	=	Waste Collection System
<i>WPA</i>	=	Water Processor Assembly
<i>WRP</i>	=	Water Recovery Project
<i>WRS</i>	=	Water Recovery System

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I. Introduction

THE mission of the Advanced Exploration Systems (AES) Water Recovery Project (WRP) is to develop advanced water recovery systems that enable NASA human exploration missions beyond low Earth orbit (LEO). The Water Recovery System (WRS) recycles water by turning wastewater generated by the crew and vehicle systems into potable water for the crew, and technical water that can be used again by the vehicle. Recovery of potable water from wastewater is essential to the success of long-duration human spaceflight, particularly for deep space missions where there is no logistics supply chain as is currently afforded on the International Space Station (ISS).

The purpose of this study is to establish the reference architecture for the AES WRS and the most promising options. The goal is to have this architecture established by the NASA water community and have stakeholders engaged in its development. The impact of new technologies, particularly a change in the wastewater stabilization method, on an ISS-derived system will be evaluated. The results of this study will be used to guide future technical planning, establish a baseline development roadmap for technology infusion, and establish baseline assumptions for integrated ground and on-orbit life support systems definition.

II. Analysis Scope

NASA experts in water recovery and life support systems stakeholders were consulted to establish the scope, ground rules, and assumptions for this analysis. It was determined that, to best support the agency's mission to travel to a near Earth asteroid (NEA), this study would focus on water recovery in microgravity mission phases. The scope of this analysis does not include short-duration mission water management where there is no closed-loop water management system, nor would it consider partial gravity/surface systems (e.g., Mars or moon habitation).

Fig. 1 shows a process flow diagram for a generic water recovery system; the white, non-shaded, blocks are considered part of the WRS.

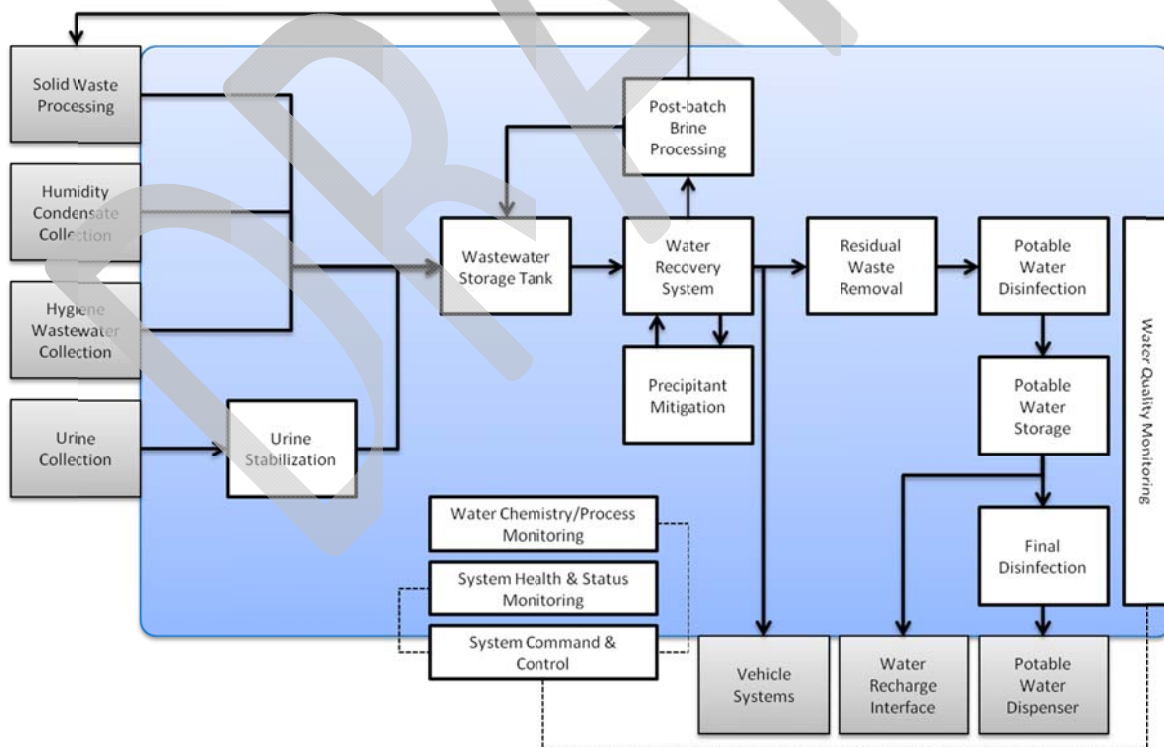


Figure 1. Water Recovery System architecture.

The current regenerable WRS used on the ISS is considered the baseline for the trades performed within the study. It is also considered the state of the art (SOA) for water recovery systems.

This study focuses on the following processes: Urine Stabilization, Primary Processor, and Precipitant Mitigation. These are highlighted in Fig. 2. Also highlighted in this figure are the Hygiene Wastewater Collection and Urine Collection processes. The impact of including hygiene wastewater processing on the various architectures considered will be evaluated. Compatibility of the various architectures assessed with the SOA Urine Collection technology will be assessed.

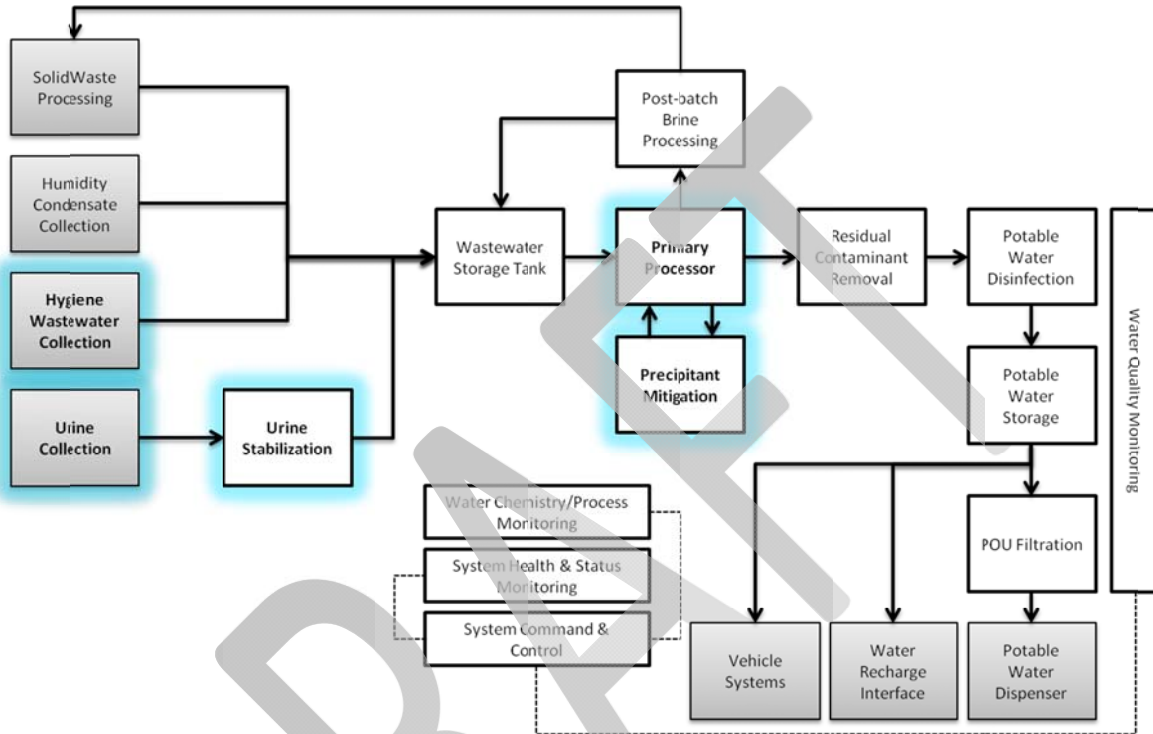


Figure 2. Architecture elements being traded.

Post-batch brine processing is specifically being excluded from this assessment. Though this process is considered critical to deep space human exploration missions, technology options will be evaluated as part of this effort. A separate assessment is being performed to evaluate these systems. Any requirements or constraints discovered from this assessment will be communicated to the brine processor technology downselect effort.

This assessment assumes that the systems downstream of the Primary Wastewater Processor will not change. The impacts to these systems (e.g., sizing and or consumables usage) will be evaluated.

III. Design Reference Mission

Three mission types were defined for development of Environmental Control and Life Support Systems (ECLSS) to enable deep space transportation and exploration: short-duration, long-duration microgravity, and long-duration with partial gravity. It is unlikely that short-duration missions would include a closed-loop water management system. Partial gravity operations is related to long-term habitation on the moon or Mars; this type of mission represents a small subset of the missions being addressed by AES. Long-duration microgravity operations is the most common aspect of deep space human exploration missions being considered. It was, therefore, the focus of this architecture study.

To provide more detail, the Design Reference Missions (DRMs) generated by the Human Spaceflight Architecture Team were reviewed. A full capability NEA mission was chosen. Per input from the AES Deep Space Habitat project, it was decided to add a requirement for cyclic manned/unmanned operations. This requirement

presents a specific challenge to life support systems and will likely be necessary if we are to consider, in-space construction and burn-in of a deep space exploration spacecraft. The resultant mission requirements are as follows:

- Provide potable water for four crewmembers
- Provide water for vehicle use
- Sustain operations for 388 days continuous without resupply
- Survive 842 days unmanned loiter prior to initial operation
- Be capable of cyclic operational cycles: 100 days manned/100 days unmanned
- Process Wastewater:
 - Urine
 - Humidity condensate
 - Hygiene water

This study focuses on the primary wastewater sources that are defined, to date. Other possible sources of wastewater not addressed by this study are: laundry, water recovered from brine processing, and vapor collected from heated solid waste compaction.

IV. Identification of Viable Architectures (Phase I Results)

Several options are available for each process; however, not all options are compatible with one another. The purpose of Phase I of this architecture study is to identify the viable architectures.

The variables defining those options are as follows:

- Waste Collection System (WCS)
 - Current technology with spin phase separation – these systems require urine stabilization agents to be added prior to the air/liquid phase separation to mitigate solids formation in the separator.
 - New technology that is tolerant of solids formation – this system would be operational without urine stabilization agents. There are currently no efforts to develop this technology.
- Primary Processor Technology
 - Physical distillation: water is recovered by evaporating urine – the steam is condensed to water and the non-evaporated liquid is brine. Due to the evaporation cycle, water recovery is generally limited due to salt precipitation.
 - Vapor Compressor Distiller: this is the SOA system used in the Urine Processing Assembly (UPA) on the ISS.
 - Cascade Distillation System (developed by AES): this is a mid-Technology Readiness Level (TRL) system being developed by the AES Water Project.
 - Membrane distillation: mass transfer across membranes is used as a means of separating water from the waste components. Membranes are susceptible to scale and biofouling that can coat the transfer surface or change the chemical properties of the membrane.
 - Osmotic Distillation: This is a low-TRL system being developed by the Next Generation Life Support (NGLS) project for processing urine.
 - Forward Osmosis Secondary Treatment: This is a low-TRL system being developed by the NGLS for processing hygiene water – it does not reject urea and is therefore not appropriate for urine processing
 - Biological wastewater processing: this system uses biological agents to consume the waste products to produce water. Additional systems are used to desalinate the water and remove residual organic content. The low pH of the SOA urine stabilization methods would kill the biological agents in this system; compatibility with the AES GreenTreats is yet to be determined.
 - Membrane-Aerated Biological Reactor (MABR) – this is a low-TRL system being developed by NGLS.
- Urine Stabilization Technology: Urine stabilization prevents the breakdown of urea (urea hydrolysis) into ammonia, a toxic gas at high concentrations. Second, it prevents the growth of microorganisms, thereby mitigating hardware and water quality issues due to biofilms and planktonic growth. Finally, it helps prevent solids formation in the SOA WCS.
 - ISS Pretreat: This is the SOA urine stabilization method where chromic and sulfuric acids are added to urine in the WCS.
 - Shuttle Pretreat: This is the heritage urine stabilization method used on the US Shuttle where Oxone and sulfuric acids are added to urine in the WCS.

- AES GreenTreat: This is a “green” alternative to the SOA using food-grade preservatives with an organic, low-toxicity acid.
- Precipitation Prevention Program (PPP) Pretreat: This an alternative to the SOA that reduces the amount of sulfuric acid in order to mitigate calcium scale formation.
- None: No chemical or other stabilization technique is applied to the urine prior to being processed.
- Precipitant Mitigation Technology: Precipitant mitigation is needed for the physical distillation systems when sulfates are present in the urine stabilization method.
 - AES: Distiller Calcium Limiter (DCaL).
 - PPP: Urine Processor Ion Exchange (UPIX).
- Wastewater Composition.
 - Solution 1: Urine + humidity condensate mixture tested in the Distiller Downselect Testing.
 - Solution 2: Urine + humidity condensate + hygiene water mixture tested in the Distiller Downselect Testing.
 - Segregated Flow: this is the Solution 2 mixture where only urine is processed in the primary processor, humidity condensate is processed by the WPA and is currently done on ISS, and hygiene water is processed by a secondary processor assumed to be the Forward Osmosis Secondary Treatment (FOST) for purposes of this study.

Error! Reference source not found. The Viable Options Summary Table summarizes the viable technology combinations for this architecture study. This table shows that the two physical distiller technologies could be considered viable at this time, assuming the ISS or ISS-derived technology will be used. A precipitant mitigation system (two technologies were considered to perform this function) would be required for options where the urine stabilization method includes a sulfate. Biological and membrane systems may be considered with an alternate urine collection system (not currently being developed by any organization). The biological processor would not be compatible with a SOA system; membrane system compatibility has not yet been determined.

Table 1. Viable Options Summary Table

Urine Collection Device	Primary Processor	Urine Stabilization	Precipitant Mitigation
Phase Separation Technology (ISS WCS or Universal UCS)	Physical Distiller (AES-Cascade Distiller System [CDS] or ISS-Vapor Compressor Distiller [VCD])	ISS: CrO3+H2SO4	Precipitant Mitigation (AES DCaL or PPP Ion Exchange)
		Shuttle: Oxone	
		PPP: CrO3+H3PO4	None
		GreenTreat	None
	Membrane – OD	GreenTreat	None
Biological – MABR			
Solids Tolerant Waste Collection (Technology Gap)	Membrane – OD	None	None
	Biological – MABR		
	Membrane – OD	Green Treat	None
	Biological – MABR		

Note: The unshaded portion of the table represents 10 clearly viable WRS architectures.

These options are viable with both solutions tested during the ELS Distiller Down Select Study, Solution 1 consisting of humidity condensate and urine, and Solution 2 consisting of humidity condensate, urine and hygiene water. These options are also viable when considering separate urine and hygiene water flow streams where the urine is processed with the “Primary Processor A” and the hygiene water processed by a secondary processor; a FOST system will be the secondary processor evaluated for this study.

Four additional options (12 taking into consideration the three waste stream compositions being considered) may be viable pending further characterization of urine stabilization with “GreenTreat”. Another four architecture options (12 taking into consideration the three waste stream compositions being considered) would be viable given a solids tolerant WCS. No technology has been identified that is tolerant to solids formation in the collection system and no efforts are currently funded to address this technology gap.

V. Optimal Water Recover System Architecture(s) for Near-Term Missions (Phase II Results)

Phase II is focused on the clearly viable options involving physical distillers; the alternate biological and membrane processors do not have a high enough TRL to realistic support a short-term (within 10-20 years) mission.

Fig. 3 shows the trade space for the Phase II. Table 2 lists the components not taken into consideration in this Phase II evaluation.

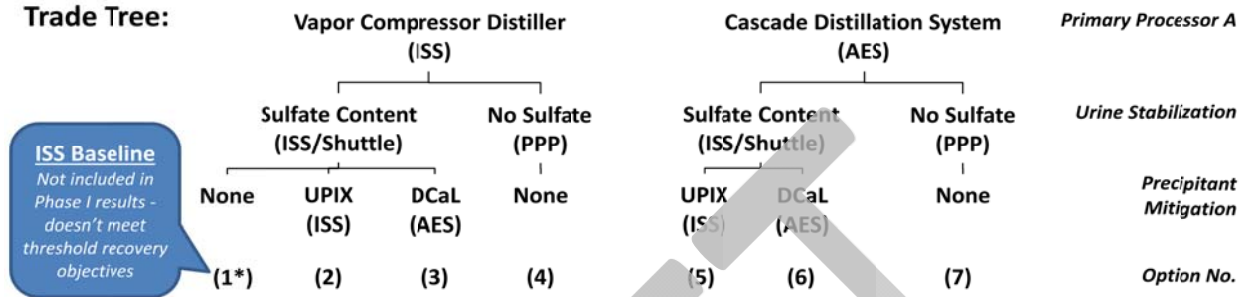


Figure 3. Phase II trade tree.

Table 2. WRS Components NOT in Phase II Trade Space

WRS Component	Comments
Wastewater Composition	ISS wastewater (urine + humidity condensate) will be assumed
Primary Processor B	Segregated flows will not be assessed
Commode Design	It is assumed that the ISS WCS or similar technology will used
Residual Waste Removal	Heritage ISS system assumed
Potable Water Processing	Heritage ISS system assumed
WRS Avionics	Assume heritage or AES monitoring; does not impact architecture
Post-batch brine processing	This trade is not in scope with this architecture study; no post-batch processing is assumed for Phase II. This does not impact the rest of the WRS architecture

Fig. 3 shows ISS and Space Shuttle urine stabilization methods as one option. These are also referred to as the Russian and US pretreats, respectively. Within the bounds of this Phase II assessment, there is no significant difference between the Russian and US pretreats, so there is no reason to treat them as two separate options.. The following table shows the resultant options for Phase II.

Table 3. Phase II Options

Option	Urine Stabilization	Primary Processor A	Primary Processor B	Calcium Remediation
1 *	Russian Pretreat	VCD	None	None
2	Russian Pretreat	VCD	None	UPIX
3	Russian Pretreat	VCD	None	DCaL
4	PPP Alternate	VCD	None	None
5	Russian Pretreat	CDS	None	UPIX
6	Russian Pretreat	CDS	None	DCaL
7	PPP Alternate	CDS	None	None

* Option 1 represents the current ISS configuration; it does not represent any option identified by the Phase I study since it does not meet the > 90% recovery objective. Options 2 and 4 represent options currently in work to recovery performance on the ISS UPA.

VI. Phase II Evaluations

A. Performance

Performance will be measure as a function of water recovered from urine (includes flush water and pretreat). The baseline option current recovers a max of 72% water from urine; systems that recover less than this would be considered viable options. Alternate pretreat (options 4 and 7) is expected to return system to spec performance at

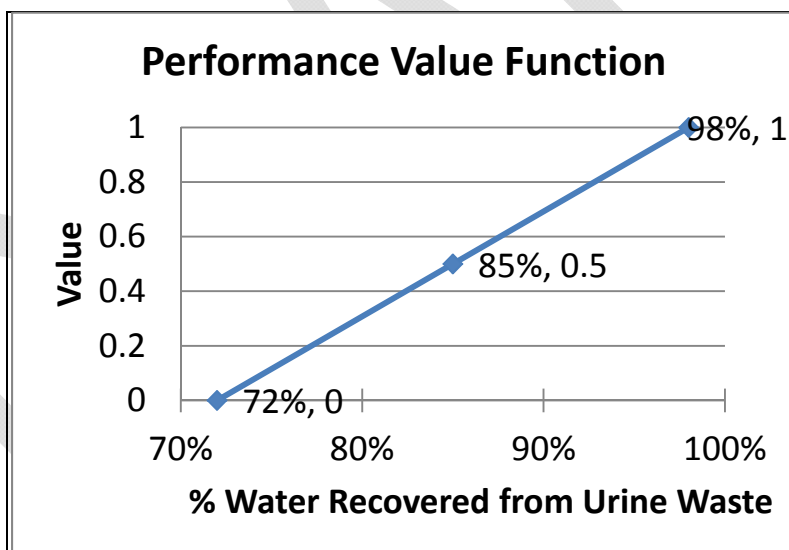


Figure 4. Performance Value Function.

85% recovery. The Performance Value Function is provided in Fig. 4.

UPIX and DCaL, being ion exchangers, have the potential to increase the minimum recovery by removing more solids and precipitating ions; expect these to enhance system performance by at least 5%. There is some controversy over this assertion, however. If the benefit of ion exchange performance is invalidated, then all options except one will have Recovery Rate 85% and Value 0.5. The following table shows the value and score for this figure of merit..

Table 4. Performance Scores

Option		Recovery Rate	Value
VCD	1 – Baseline	74%	0
	2 – UPIX	90%	0.69
	3 – DCaL	90%	0.69
	4– Alt. Pretreat	85%	0.50
CDS	5– UPIX	90%	0.69
	6 – DCaL	90%	0.69
	7– Alt. Pretreat	85%	0.5

B. Mass

Mass evaluation will be performed as a delta to the baseline mass. Up-mass water required to augment system (since it is not 100% closed) is not included in the mass evaluation – this aspect of the system is captured by the Performance metric. Urine Stabilization options do not incur an obvious mass delta, therefore only the mass of the primary processor and calcium remediation components for each option were evaluated. The following figure shows the Mass Value Function.

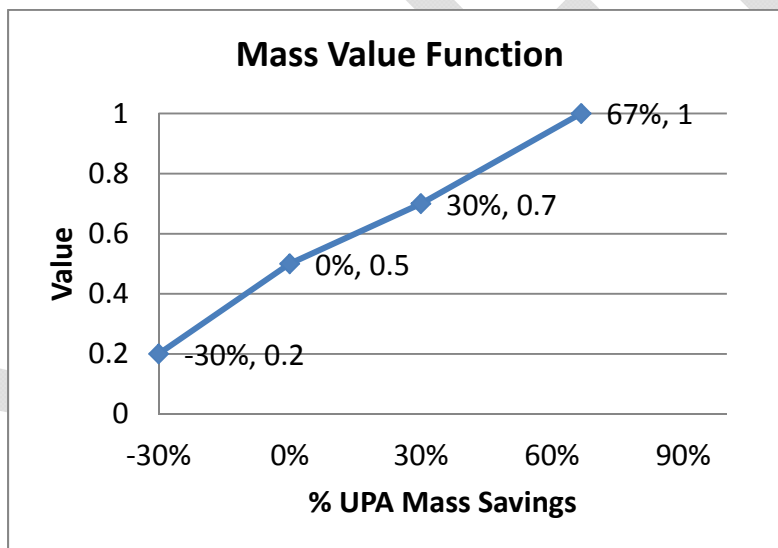
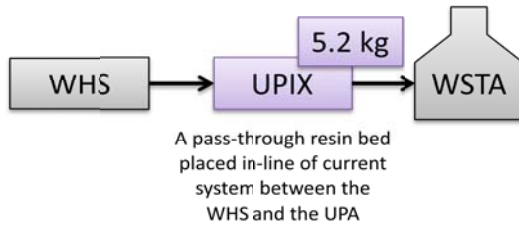


Figure 5. Mass Value Function.

1. Precipitant Mitigation Systems Mass:

The Precipitant Mitigation Systems are shown in the following figure.

- UPIX System Schematic



- DCaL System Schematic

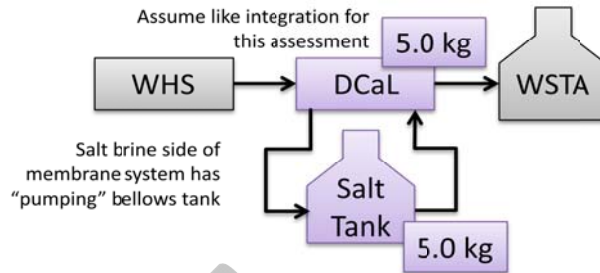


Figure 6. Precipitant Mitigation System schematics for infrastructure mass evaluation.

The consumables mass was evaluated for the DRM duration of 388 days, and for a shorter 180-day mission. The UPIX is a disposable ion exchange bed system. The DCaL is a membrane ion exchange system, which will require salt (e.g., NaCl) to be replenished.

2. Primary Processor

The changes that would be required to the baseline system were evaluated. To make relevant comparison between VCD- and CDS-based systems, the team evaluated a generic UPA to identify the common components. The delta mass was calculated by comparing the unique components.

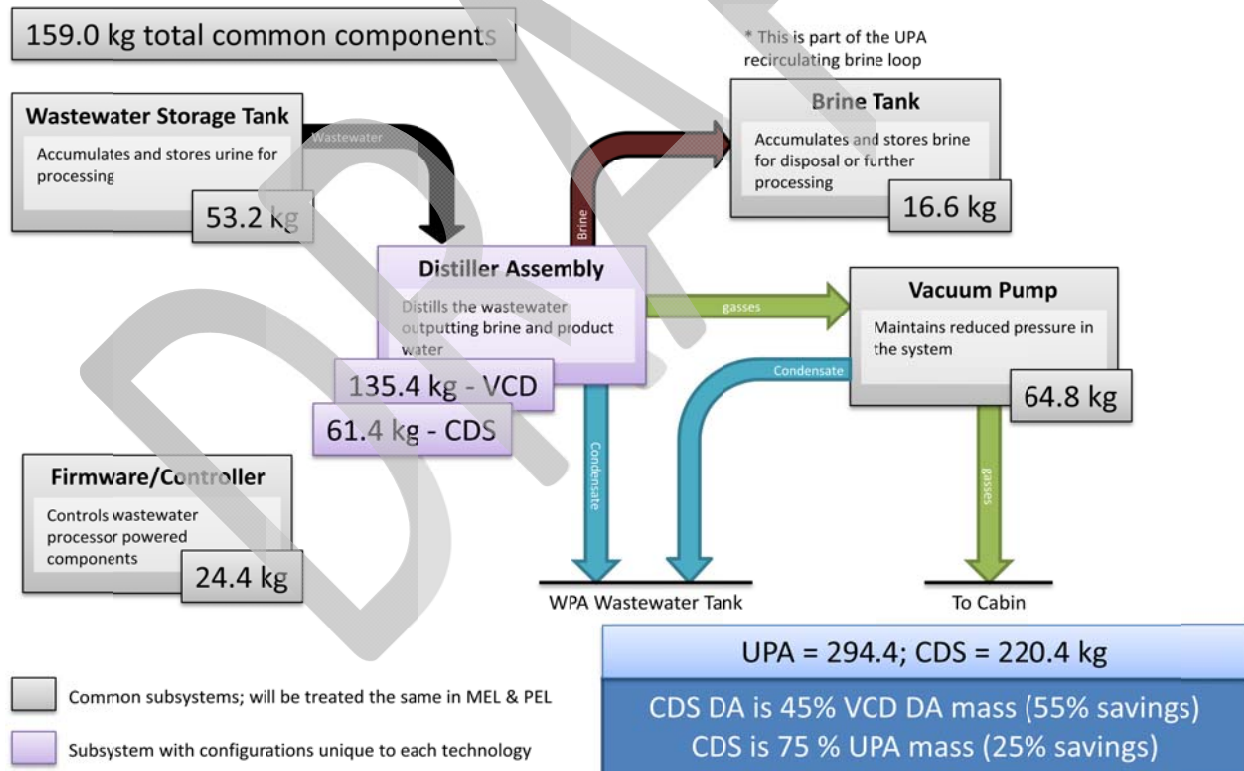


Figure 7. Primary Processor Assembly.

C. Power

The value function for power is shown in the following figure:

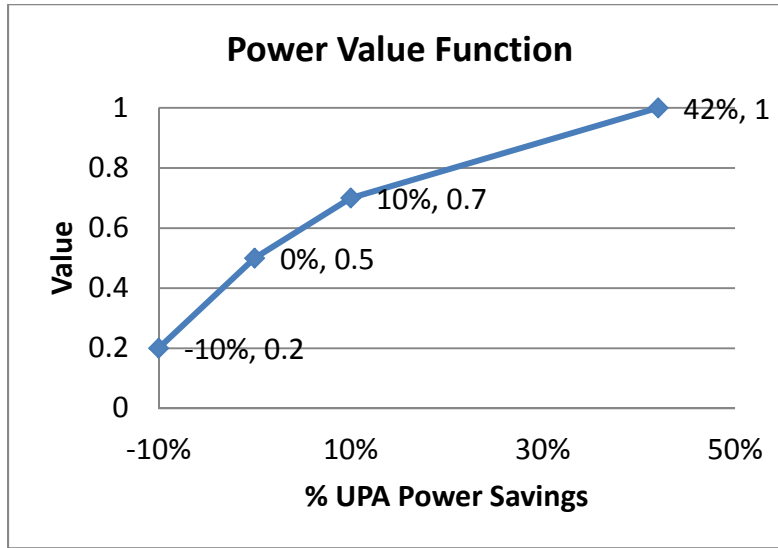


Figure 8. Power value function.

Pretreat alternatives do not require any additional powered equipment. The Primary Processors have similar specific power:

- VCD specific power = 188 W-hr/kg
- CDS specific power = 108 W-hr/kg

The UPIX, being an unpowered system, has an advantage over DCaL, which uses electricity to drive ion exchange through the membranes; this system also includes pumps that require power.

D. Flight Readiness

Flight readiness was evaluated as a function of technology readiness and level of development required. The value function is as follows:

- 0 - Low TRL w. extensive design, development, test & evaluation or tech challenge
- 0.2 - Low TRL w. minimal tech challenge
- 0.4 - TRL soon w. extensive design, development, test & evaluation or tech challenge
- 0.6 - TRL soon w. minimal tech challenge
- 0.8 - TRL now w. minimal upgrades
- 1.0 - TRL now or no change

VI. Phase II Results

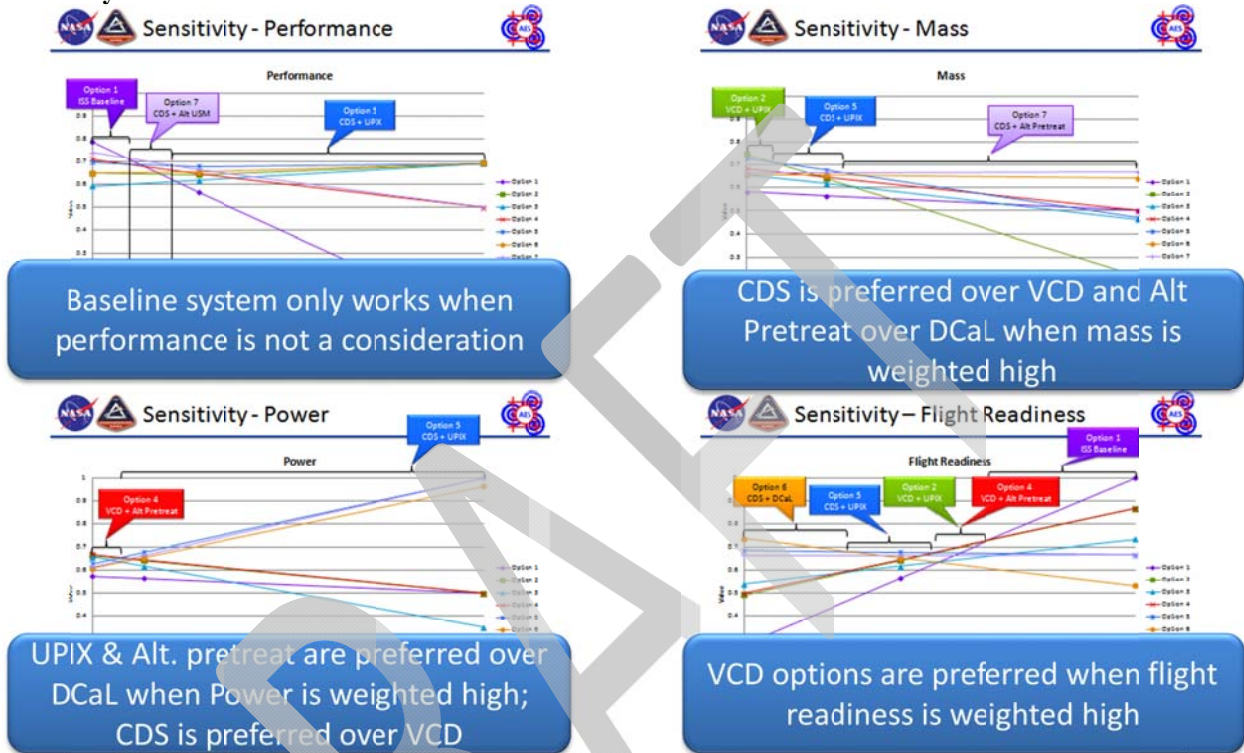
The results for a long-duration mission as defined in the DRM is as follows:

Measure	Wt	1 - ISS Baseline	2 - VCD + UPIX	3 - VCD + DCaL	4 - VCD + Alt. Pretreat	5 - CDS + UPIX	6 - CDS + DCaL	7 - CDS + Alt. Pretreat
Performance	0.27	0.00	0.69	0.69	0.50	0.69	0.69	0.50
Mass Savings	0.20	0.50	0.22	0.46	0.50	0.47	0.64	0.67
Power Savings	0.13	0.50	0.50	0.35	0.50	1.00	0.96	1.00
Flight Readiness	0.40	1.00	0.87	0.73	0.87	0.67	0.53	0.67
Raw Score		2.00	2.28	2.24	2.37	2.83	2.83	2.83
Weighted Score		0.57	0.64	0.62	0.65	0.68	0.65	0.67
Without IX Benefit		0.55	0.60	0.57	0.65	0.64	0.60	0.67

The highest scoring option for both DRMs is use of the CDS with the UPIX. All options except 1 (VCD) and 3 (VCD + DCaL) are within 10% of top score for all cases. The current ISS system is not recommended for near-term missions. DCaL, as specified in this analysis, is not recommended for near-term missions.

Use of alternate pretreat is preferred if the performance benefit of ion exchange not accepted. In this case, Option 7 – CDS w/ alternate pretreat scores the highest. Option 4 – VCD + Alt Pretreat is within 10% of Option 7 score.

A. Sensitivity



B. Conclusion

Option 5, CDS with UPIX, was the highest-scoring option. No option stands out as being significantly better than or worse than the others, with exception of the baseline system; use of DCaL with the VCD does not trade as favorably as the other options. Work to mitigate calcium precipitation in distiller systems is needed to meet performance needs. The plan to fly a VCD with some means of mitigating calcium scale is valid for a near-term Gateway mission. Resource allocation to developing CDS is also validated

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