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Water Recovery Trades for Long-Duration Space Missions

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Water recovery in life support systems is critical for long-duration space missions. Potential sources of recoverable water include humidity condensate, urine, feces, and wet trash. Water can also be recovered from metabolic carbon dioxide when hydrogen is available as a byproduct of oxygen generation. A trade study was performed for a 1000-day-class deep-space mission that considers water recovery from all of the above sources. A crewmember water balance based on a proposed exploration exercise protocol was used as a baseline. Consideration of deep-space missions without significant extravehicular activities allows evaluation of surplus recovered water scenarios and their potential for providing dissimilar redundancy and increasing life support system reliability. Results are presented in terms of overall life support equivalent system mass as a function of potable water balance. A mission-duration-dependent water cost factor is estimated for each technology that allows an assessment of technology breakeven time. An assessment of fecal waste processing and water recovery is initially presented to provide a basis for its trade against a baseline storage option.

Nomenclature

AES = Advanced Exploration Systems
ARC = Ames Research Center
BO = Bosch
BPA = Brine Processor Assembly
CDR = Critical Design Review
CM = crewmember
CO_2 = carbon dioxide
CWC = Contingency Water Container
ECLSS = Environmental Control & Life Support System
EMC = Evolvable Mars Campaign
ESM = Equivalent System Mass
EVA = Extravehicular Activity
FWVDC = Fecal Waste Vacuum Drying & Compaction
HIDH = Human Integration Design Handbook
HMC = Heat Melt Compactor
ISS = International Space Station
IVA = Intravehicular Activity
JEFS = Joint Environmental Control & Life Support Functional Strategy
JSC = Johnson Space Center
LR = Logistics Reduction
LRR = Logistics Reduction & Repurposing
MEFDSW = Microwave Enhanced Freeze Drying Solid Waste System
MP = Methane Pyrolysis
MPSWS = Microwave Powered Solid Waste Stabilization & Water Recovery
O_2 = oxygen
OBF = Odor/Bacteria Filter
OGA/OG = Oxygen Generation Assembly
ORBITEC = Orbital Technologies Corporation
PMWC = Plastic Melt Waste Compactor
PTFE = polytetrafluoroethylene
R = reliability
SA = Sabatier
SBIR = Small Business Innovative Research
SNC = Sierra Nevada Corporation
STM = Shuttle Training Menu
TGA = Thermogravimetric Analysis
TtG = Trash-to-Gas
UPA/UP = Urine Processor Assembly
UWMS = Universal Waste Management System
WPA/WP = Water Processor Assembly
WRS = Water Recovery System

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I. Introduction

WATER requirements are substantially greater in total than those of any other life support consumable. They include water for direct crew consumption and usage as well as for use in oxygen generation by electrolysis. The latter generally trades well for long-duration missions because of the potential for surplus recovered water due to water present in supplied food and metabolically generated water as well as the lower mass penalty associated with water storage compared to oxygen storage. Water is also used as an expendable coolant during extravehicular activity (EVA). The overall life support water balance is thus an important driver in life support architecture and technology selection. As noted in a 2007 Life Support Technology Seminar section titled "Closing the Air Loop – CO_2 Reduction Technologies," *It's really about water*.[1] The same can be said for optimizing life support systems for long-duration space missions.

A. Crewmember Water Balance

It might be assumed that a nominal agreed-upon crewmember (CM) water balance for design purposes would be established; however, that is not the case. As crew exercise requirements, water intake recommendations, food systems, and hygiene systems evolve toward longer duration space missions, so does the water balance. In addition, there are uncertainties due to microgravity and person-to-person variations. The baseline crewmember water balance assumed in the current study is shown in Figure 1.

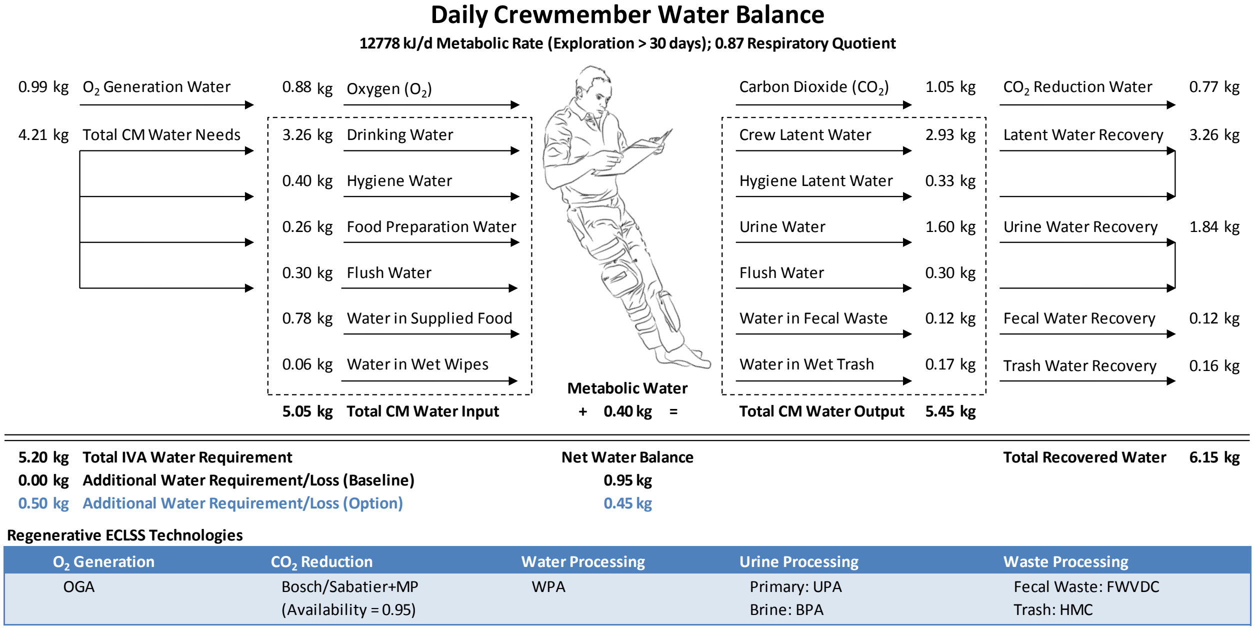

Figure 1. Baseline crewmember water balance with additional water requirement/loss option.

This figure includes crewmember water inputs and outputs as well as recovered water quantities assuming the indicated technologies. Sources and assumptions behind the input and output quantities are indicated in Table 1. Options considered in the study are also indicated.

Recovered water quantities in Figure 1 represent an estimate of the maximum recoverable water from each source using current or developmental technologies. For example, water recovery from urine (plus flush water) includes both a primary urine processor and secondary brine processor. Latent water (humidity condensate) and urine are the largest sources, followed by carbon dioxide (CO_2) reduction, and then by trash and fecal water. Alternative technology options and their cost factors (kg ESM/kg water) are discussed and compared later in this paper.

The baseline water balance attempts to capture the most current data and assumptions for deep-space exploration missions. Nevertheless, there is considerable uncertainty in many of these numbers. To assess the impact of this uncertainty, an additional water requirement/loss of 0.5 kg/CM-day on the baseline water balance was considered in the analysis and is indicated as an option in Figure 1. This additional water requirement could result from EVA or payload losses. An alternative water balance based on the 2014 release of the NASA Human Integration Design Handbook (HIDH)[2] was also considered in the analysis.

Table 1. Sources and Assumptions for Crewmember Water Balance

Water Balance Items	Sources and Assumptions
Metabolic Rate, Oxygen Consumption, and Crew Latent (Sweat and Respiration) Water	**Baseline:** Draft metabolic profile based on correlated Metabolic Man (Metman) software simulation of proposed exercise requirement for exploration missions greater than 30 days.[3] **Option:** Metabolic profile specified in HIDH 2014[2] (also based on Metman simulation).
Carbon Dioxide Production	**Baseline:** Calculated using diet-based respiratory quotient (molar or volumetric ratio of CO_2 production to O_2 consumption). Diet based on Shuttle Training Menu (STM) analyzed by Levri[4] and modified to replace 50% of rehydratable food with higher-moisture thermostabilized food. **Option:** Calculated using assumed respiratory quotient of 0.92 in HIDH 2014.[2]
Water in Supplied Food, Food Preparation Water, Metabolic Water	**Baseline:** Based on modified STM as noted above. Water in supplied food is similar to values reported by Ewert[5] and attributed to the JSC food lab. **Option:** Based on original STM. Values are similar to those specified in HIDH 2014,[2] JEFS 2011,[6] and Kulhanjian[7] (0.5 kg each) assuming 2007 ratio of thermostabilized, freeze-dried, and natural-form foods on ISS.
Hygiene Water	HIDH 2014[2]
Flush Water	JEFS 2011,[6] Kulhanjian[7]
Water in Wet Wipes	Derived from AES Logistics Project Exploration Waste Model v. 3.2.
Urine Water	Similar to 24-hour urine volume data from ISS nutrition studies[8] assuming ~60 g/day of urine solids.[9] Also similar to value reported in HIDH 2014[2] based on Skylab data.
Water in Fecal Waste	**Baseline:** 0.10 kg from feces (based on mean reported in Rose[9]) plus 0.02 kg from wet wipes. **Option:** 0.15 kg from feces[6,7] plus 0.02 kg from wet wipes.
Water in Wet Trash	Based on analysis of returned trash from four Space Shuttle missions.[10]
Hygiene Latent Water	Calculated by subtracting estimated amount in wet trash from hygiene water input. Estimated amount in wet trash determined by subtracting estimated contributions from food waste[4] and non-fecal wet wipes from total water in wet trash.
Drinking Water	Calculated from an overall water balance.

The total provided crewmember water from food and drink for the baseline water balance (4.3 kg/day), is higher than average values reported in a nutritional study by Zwart[11] for astronauts in-flight, but is similar to preflight values.

B. Fecal Waste Processing and Water Recovery

This study originated as an assessment of water recovery from fecal waste. The discussion below is a condensed summary of the findings and a description of the concept chosen to size and compare a fecal waste processing system in the overall life support system trade studies. Fecal waste processing for long-duration space exploration missions can potentially be justified as part of an approach to stabilize the waste for safe long-term storage, as part of an approach to reduce the mass and volume associated with fecal waste storage, and as part of an overall water recovery strategy to increase system closure or reliability.

1. Baseline Fecal Waste Management

Processing of fecal waste is expected to be closely tied to the method used to collect fecal material and associated consumables such as toilet paper, wipes, and gloves. Designs of both collection and processing equipment are likely to depend on the gravitational environment of the target mission application. For the current study, a deep-space microgravity application was assumed with fecal waste collection provided by the advanced-development Universal Waste Management System (UWMS).[12-14]

Fecal material is collected in the UWMS using single-use gas-permeable bags through which air is drawn during defecation. The bags are made of a microporous hydrophobic (PTFE/polyester) material that is breathable but retains liquid water.[15] All wet/dry wipes and gloves that are used are deposited in the same bag. The bag opening is sealed after defecation and the bag is placed in the fecal canister. Periodically, the deposited bags can be manually compacted after inserting a compaction plate on top.

The baseline design for the fecal canister is a rigid (hard) canister that is tapered to allow reduced-volume stacking during initial storage.[13,14] Each canister is assumed to hold 20 fecal bags corresponding to 20 defecations. Once full, the canister is removed and capped with an odor/bacteria filter (OBF) lid for long-term storage. A new canister is then installed in the UWMS. For a crew of four with an assumed average of two defecations per CM per day,[2] the canister would have to be replaced every 2.5 days. For a 1000-day mission, 400 canisters and lids would be required.

NASA is investigating soft canister concepts to reduce the mass and initial storage volume of the canisters as well as for potential use in fecal waste processing.[*] One such concept was included as a collection/storage option in the trade study analysis. The canister is assumed to hold the same number of defecations as the hard canister and to use the same OBF lid.

All technologies considered for fecal waste processing were assumed to start with the contents of a filled fecal canister in terms of the quantity and packaging of fecal wastes. Potentially compatible modifications of the canister design were considered.

2. Resource Recovery beyond Water

Recovery of resources beyond the water initially present in fecal waste is possible using technologies such as steam reforming, pyrolysis, combustion, and anaerobic or aerobic biodegradation. The AES Logistics Reduction and Repurposing (LRR) project (now LR project) conducted Trash-to-Gas (TtG) studies that investigated the conversion of trash (including fecal waste) to gaseous products for venting or propulsion.[16] Additional water of reaction can also be produced and recovered using these approaches. Technologies that chemically degrade waste are generally more complex than simple drying technologies and involve more system interactions. Although there are potential benefits to these approaches,[17] the current study focused on technologies that limit chemical degradation of fecal waste in order to minimize impacts on other systems. This includes minimizing gaseous byproducts and recovered water contaminants.

3. Solid Waste Processing Technologies

In the first decade of this century, NASA supported the development of several technologies for recovering water from solid wastes including fecal waste. These efforts were performed through Small Business Innovative Research (SBIR) grants and in-house activities monitored and conducted by Ames Research Center (ARC). More recently, the AES LR project has supported the continued development of the Heat Melt Compactor (HMC) technology for processing spacecraft trash, and the development of the Torrefaction technology for processing fecal wastes. A brief description of each of these technologies is provided below. In general, microbial stabilization and waste volume reduction are central goals of these technologies in addition to water recovery.

Development and testing of a Lyophilization (freeze drying) system for water recovery from fecal waste is described by Litwiller[18-20] and Yuan.[21] Lyophilization recovers water by freeze separation followed by vacuum distillation. A prototype unit was designed and built to replace the fecal canister and perform the lyophilization in-situ.[20] Processing rate was therefore a critical requirement. The unit incorporated compression of fecal bags to enhance heat transfer and a thermoelectric heat pump to improve energy efficiency. Issues with resistance to heat and mass transfer associated with the condenser were observed. A modeling study[21] was performed to address these issues, but no further development was reported.

Development and testing of a Microwave Powered Solid Waste Stabilization and Water Recovery (MPSWS) System is described by Wheeler,[22] Wignarajah,[23] and Fisher.[24] In the MPSWS process, wet waste is microwaved batchwise at ambient pressure on a turntable. Water vapor is picked up by a flowing air stream drawn from the cabin and subsequently condensed out using a condensing heat exchanger. A surface temperature cutoff of 80°C was programmed to avoid pyrolysis of the wastes and the release of volatiles.[24]

Development and testing of a Microwave Enhanced Freeze Drying Solid Waste (MEFDSW) System is described by Wheeler,[25] Wignarajah,[26] and Fisher.[24] As with the MPSWS process, wet waste is microwaved batchwise on a turntable. With the MEFDSW process, however, vacuum is used to remove water vapor. The water vapor is condensed as ice on a Peltier condenser and subsequently melted for recovery after the drying cycle. Testing of the prototype indicated that the Peltier condensation system was undersized.[26,24] The MEFDSW process can operate in

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[*] McKinley, M., and T. Cox, personal communications, October 23, 2018 - January 17, 2019. This work is being supported by the Advanced Exploration Systems (AES) Logistics Reduction (LR) project and is currently in the feasibility assessment phase.

either a freeze drying mode or a vacuum drying mode depending on the level of vacuum. A surface temperature cutoff of 80°C was also programmed for the MEFDSW system.

Development and testing of a DRYER system is described by Hunter,[27] Apollo Arquiza,[28] and Fisher.[24] DRYER uses a closed air loop with a heat pump to recover water from fecal waste and wet cabin trash. Hot air is supplied to the wet waste to provide adiabatic heating. Water evaporates and is condensed from the recirculating air using a porous membrane condensing heat exchanger. In testing at ARC,[24] the DRYER condensation system had to be frequently primed. Using simulated feces and operating a nominal inlet air temperature of 60°C, little recovery of "inaccessible" water from within the waste matrix was observed after 10 hours of operation.

Development and testing of a Torrefaction system for fecal waste stabilization and water recovery is described by Serio.[15,29-32] During the process, the walls of a canister containing the waste are heated to a maximum temperature of 225-250°C. Heating is maintained until the center of the waste material reaches ~200ºC. During the process, initial water in the waste is evaporated and some additional water and other products are generated by a partial breakdown of the waste material. A condensing heat exchanger is used to recover the water. The final solid product is a dry char. The purity of the recovered water depends on the temperature at which the waste is processed. Operating at lower temperatures increases purity but may encourage microbial growth.[15] The system is being designed to be compatible with the UWMS canister size. A significant issue is the time required to process a full-size fecal waste canister using conductive heating. Predicted heating times are greater than 3000 min (50 hours).[32] Alternative designs that incorporate internal gas circulation or in-situ compaction to reduce the heating time have been considered.[32]

Development of a Heat Melt Compactor (HMC) for trash compaction, stabilization, and water recovery in space applications was initiated at NASA ARC in the early 2000s.[33] Since then, a second generation (Gen2) HMC unit has been developed and tested by ARC, and an SBIR Plastic Melt Waste Compactor (PMWC) has been developed and tested by ORBITEC/SNC. Development and testing of the Gen2 HMC is described by Turner,[34] Fisher,[35] and Lee.[36] Development and testing of the PMWC is described by Johnson,[37] Wetzel,[38] and Wignarajah.[39] A newer HMC design by SNC is described by Wetzel.[40] This unit is designed to evaluate the use of permeable bags to encase the trash during compaction.[41] Conceptually, the designs of the evolved HMC units are similar. Each can operate at partial vacuum to reduce the temperature required to evaporate water during the first stage of the compaction process. This results in improved water quality. During the second stage, the temperature rises and the plastic melts with densification of the final product into a tile.

Additional technology concepts for fecal waste processing are being solicited by NASA in 2019 as Phase I SBIR proposals under H3.02 subtopic Spacecraft Solid Waste Management focus area 'Water Recovery and Stabilization of Human Metabolic Waste (Feces)'.

4. *Fecal Waste Processing Considerations*

Processing conditions for fecal waste impact the degree of microbial stabilization achieved, the level of gaseous contaminants generated, and the quality of recovered water. The latter two aspects can impact other life support systems or impose additional "clean-up" penalties on the processing technologies. Information related to these considerations is reviewed below.

Microbial stabilization can be accomplished by dehydration and by heat treatment among other methods. Reducing the water activity level in the waste below 0.65 (equivalent to less than 65% relative humidity in equilibrium with the waste) is expected to stabilize the waste against microbial growth.[22] García-Bernet[42] measured the water activity level of various types of biowastes and digestates. For a water activity level of 0.65, the water content averaged about 0.07 gram water per gram dry mass. Assuming an average fecal water content of 75% (3 gram water per gram dry mass),[9] greater than 97% water removal would be required to achieve stabilization.

Temperature, time at temperature, and moisture content all play a role in the efficacy of heat treatments for microbial stabilization. Normal autoclave sterilization conditions are saturated steam at 121°C (15 psig) for at least 30 minutes. Fisher[35] states that at 150°C it takes about 3 hours at temperature to dry heat sterilize, and at 180°C it takes about one hour to dry heat sterilize. On the other hand, Feachem,[43] in a report on managing fecal pathogens, states that a few hours in the temperature range of 55-65°C is highly fatal to all pathogens.

Serio[15] saw no evidence of biological activity for canine feces processed at 175-250°C, but did observe some activity for a sample processed at 100°C.

Fidalgo[44] performed thermogravimetric analysis (TGA) of human feces and found that devolatilization started around 500 K (227°C). Yacob[45] conducted slow pyrolysis experiments with human feces and observed significant gas evolution and weight loss starting just below 200°C at higher heating rates. Serio[15] saw a significant increase in gas evolution between 200°C and 250°C using canine feces with a nitrogen carrier gas. Serio[29,15] also observed some CO_2 evolution starting just above 100°C.

Serio[29,30,15] measured total organic carbon (TOC) values greater than 7000 mg/L in recovered water from Torrefaction testing of a fecal simulant and canine feces at temperatures up to 250°C. Serio[15] also saw a significant increase in TOC between 200°C and 250°C. In testing of the MPSWS prototype, Wignarajah[23] measured TOC values less than 300 mg/L in recovered water using a fecal simulant with added water (maximum temperature assumed to be 80°C based on programmed cutoff). Wheeler[22,25] measured TOC values generally less than 400 mg/L in recovered water from testing of the MPSWS and MEFDSW technologies using refried beans as a fecal simulant (cutoff temperature < 90°C).

The evidence above suggests that gaseous product generation and recovered water organic contaminant levels increase dramatically as the fecal waste processing temperature is increased from less than 90°C to 200°C and above. For a deep-space application in which water recovery and volume reduction are primary goals in addition to stabilization, it is desirable from a risk perspective to minimize impacts on other systems. This implies targeting water recovery operations at lower temperatures (< 100°C).

There is also evidence from Torrefaction and DRYER testing that achieving high enough conductive and convective heat transfer to meet required processing times for a full-size UWMS canister will be challenging for these technologies based on their current designs. Although the microwave technologies can potentially solve the heat transfer issue, they face significant hurdles on scale-up to a full-size canister waste load and the lack of previous microwave heating applications on spacecraft.

5. *Fecal Waste Processing Concept for Trade Study*

Fecal waste has generally been excluded from consideration in HMC development, although aspects of current HMC designs appear favorable for fecal processing (separate from trash processing and without a plastic melting). The use of compaction to increase conductive heat transfer was included in the Lyophilizer design and was considered for the Torrefaction technology. Vacuum operation to improve recovered water quality is also in common with the Lyophilizer and MEFDSW technologies. The current consideration of using liner bags to encase the waste during HMC operation is a feature that would be appropriate for processing fecal waste.

Given the relative maturity of the HMC technologies in terms of overall system design (flight experiment prototypes have been designed and built), the current study considers a Fecal Waste Vacuum Drying and Compaction (FWVDC) technology that is based on current HMC designs and sizing. The FWVDC is considered as separate hardware from any HMC used for trash processing, although parts may be compatible.

A concept of operations for the FWVCD technology is outlined below:

1) The UWMS canister would be modified to include a microporous hydrophobic liner bag.
2) Once filled with fecal bags, the liner bag opening would be sealed, acting as secondary containment for the fecal waste.
3) The liner bag would be removed from the UWMS canister and placed in the FWVDC compaction chamber.
4) Vacuum and heating would be applied to allow water evaporation in the 60-80°C range.
5) Compaction would be set to enhance conductive heat transfer while minimizing the potential for leakage through the microporous liner (vacuum alone acting on the compaction piston would likely provide sufficient compaction).
6) When drying is complete, the compressed bag would be removed and placed in a fecal storage canister (identical with the UWMS canister) with an OBF-derived lid.

At any point while the bag is in the FWVDC, a temperature-hold period could be employed to maximize stabilization of the waste. As a conservative measure, storage of the dried product in fecal storage canisters (as designed for unprocessed fecal waste) would not require complete sterilization of the waste. The pore size of the bag material could also be selected to act as a bacterial barrier. Through volume reduction, the capacity of the storage canisters would be increased by an estimated factor of three. Lower storage mass options are likely possible but were not considered in the analysis.

II. Trade Study Analysis

The general approach used in the trade study analysis is similar to that reported by Lange.[48] The approach considers the impact of traded options on the Equivalent System Mass (ESM) of the entire life support system. Reliability impacts are included in ESM through the addition of component spares required to meet an assumed failure tolerance or system reliability criterion. ESM is a measure of launch mass, a critical quantity in mission planning and staging given the fixed payload capabilities of launch vehicles. Development and life cycle costs are also important, but were not addressed in this analysis.

A. Mission

Deep-space missions based on NASA Evolvable Mars Campaign (EMC) studies served as the target mission class for the trade study analysis.[46,47] A 4-person crew is assumed with a maximum crewed duration of 1000 days (including surface abort contingencies) and no scheduled EVAs. ISS-like food, clothing, and hygiene systems are also assumed. Derived volume, power, and cooling (thermal control) mass equivalencies (cost factors) are shown in Table 2. These equivalencies are based on a rigid habitat structure with solar panels and body-mounted radiators.

Table 2. Trade Study ESM Equivalencies

ESM Equivalency	Value	Units
Pressurized Volume Equivalency	35.1	kg/m^3
Unpressurized Volume Equivalency	18.6	kg/m^3
Power Equivalency	65.3	kg/kW
Cooling (Thermal Control) Equivalency	89.1	kg/kW

B. Technologies

Technologies included in the trade study are listed in Table 3 along with baseline and optional assumptions. Other required life support technologies included in the ESM analysis but not traded were based on ISS technologies. These additional technologies provide functions such as CO_2 removal and temperature and humidity control. Scaling of the ISS Water Processor Assembly (WPA) was included as a baseline to provide a water clean-up penalty for technologies that recover non-potable water (includes all other water recovery technologies). A baseline availability of 0.95 was assumed for all CO_2 reduction technologies based on the inability to store hydrogen. Other technologies were assumed to have an availability of 1 assuming storage and catch-up capabilities. In this context, availability corresponds to the average fraction of fully operational feed that is ultimately processed by the technology. FWVDC and HMC consumables included activated carbon beds (~ 25 kg/year each) for gas clean-up. Liner bags required for the FWVDC were included in UWMS consumables (~ 13 kg/year).

Table 3. Traded Technologies and Assumptions

Technology	Assumptions
Water Processor Assembly (WPA)	**Baseline:** ISS WPA scaled by required processing rate. **Option:** Unscaled ISS WPA.
Urine Processor Assembly (UPA)	Unscaled ISS UPA with 85% water recovery.
Brine Processor Assembly (BPA)	ISS BPA Flight Experiment (Ionomer Water Processor) with 80% water recovery.[49]
High-Pressure Oxygen (HPO2)	Based on Orion European Service Module O_2 tanks.
Oxygen Generator Assembly (OGA)	Unscaled ISS OGA.
Sabatier (SA)	**Baseline:** Unscaled ISS Sabatier. Availability = 0.95. **Option:** Availability = 1.
Bosch (BO)	**Baseline:** Preliminary sizing estimate based on developmental technology. Availability = 0.95. **Option:** Availability = 1.
Methane Pyrolysis (MP) (recovers hydrogen from Sabatier produced methane for recycle to Sabatier)	**Baseline** Preliminary sizing estimate based on developmental technology. Availability = 0.95. **Option:** Availability = 1. **Option:** Projected improvement in mass and volume.
Fecal Waste Vacuum Drying and Compaction (FWVDC)	**Baseline:** NASA Gen2 HMC or ORBITEC/SNC PMWC. Hard UWMS canister with OBF lid for dried fecal waste storage. 98% water recovery. WPA processes recovered water. **Option**: Soft UWMS canister. **Option:** 50% reduction in OBF lid mass.
Heat Melt Compactor (HMC) (for trash processing)	NASA Gen2 HMC or ORBITEC/SNC PMWC. 94% water recovery. WPA processes recovered water.
Universal Waste Management System (UWMS)	**Baseline:** UWMS CDR design with hard canister. **Option:** Soft Canister.

C. Failure Tolerance and Redundancy

Baseline calculations included spares for all major components to provide 2-failure tolerance for each technology except where dissimilar redundancy was present. Major components included pumps, separators, reactors, controllers, etc., at an ISS orbital replacement unit level or below. Dissimilar redundant technologies were provided 1-failure tolerance using component spares. A ranking algorithm automatically determined redundant combinations of water recovery technologies in cases with excess water production. The algorithm ordered technologies by recovered water quantity and evaluated minimum combinations that meet the total water requirement.

A more detailed reliability analysis based on assumed major component failure rates and a target system reliability was not performed in this study (as in Ref. 48) because there was no basis with which to evaluate component failure rates for the FWVDC or HMC. In addition, upgrades of ISS technologies for exploration missions are expected to address areas where failures have occurred in flight so that current failure rate estimates for those technologies may not be applicable.

III. Results

A. Architecture ESM Comparison

Figures 2 and 3 compare the ESM of different life support architectures (with component spares) as a function of overall potable water balance. Figure 2 corresponds to the baseline crewmember water balance presented in Figure 1, and Figure 3 corresponds to the balance with the additional water loss option. Results for a crewmember water balance based on HIDH 2014 fell between Figures 2 and 3 in terms of architecture ranking and are not shown.

In these figures, water processing options are indicated by symbol shape and oxygen supply/recovery options are indicated by symbol color. For each shape/color combination, there are four data points representing architectures with no fecal waste or trash processing, fecal waste processing and no trash processing, trash processing and no fecal waste processing, and both fecal waste and trash processing.

Each figure includes three cutouts of the minimum ESM region that indicate (by darkened symbols) architectures with fecal waste processing, trash processing, and dissimilar redundancy. Values for architectures with BO\SA+MP include the average ESM for the two maximum CO_2 reduction technology combinations, and the "error" bars represent the range. Values for architectures with FWVDC or HMC include the average ESM for Gen2 HMC and PMWC technologies, although in this case the "error" bars are contained within the symbols. Three example architecture cases labeled A-C are identified on each plot. These cases are further discussed later with reference to the baseline crewmember water balance.

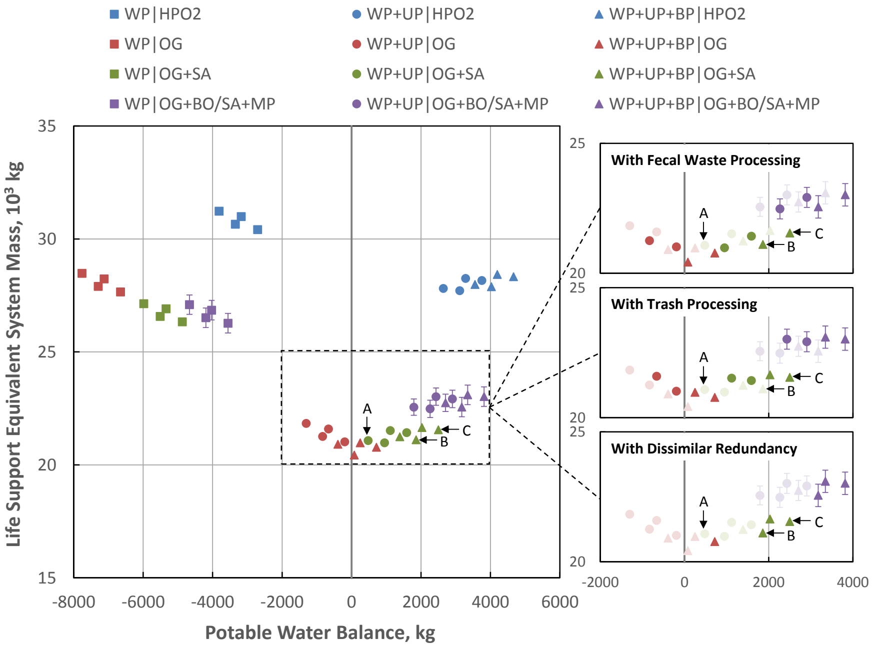


Figure 2. Relation between ESM and potable water balance for alternative life support architectures with baseline technology options and baseline crewmember water balance. Cut-out figures indicate additional architecture characteristics.

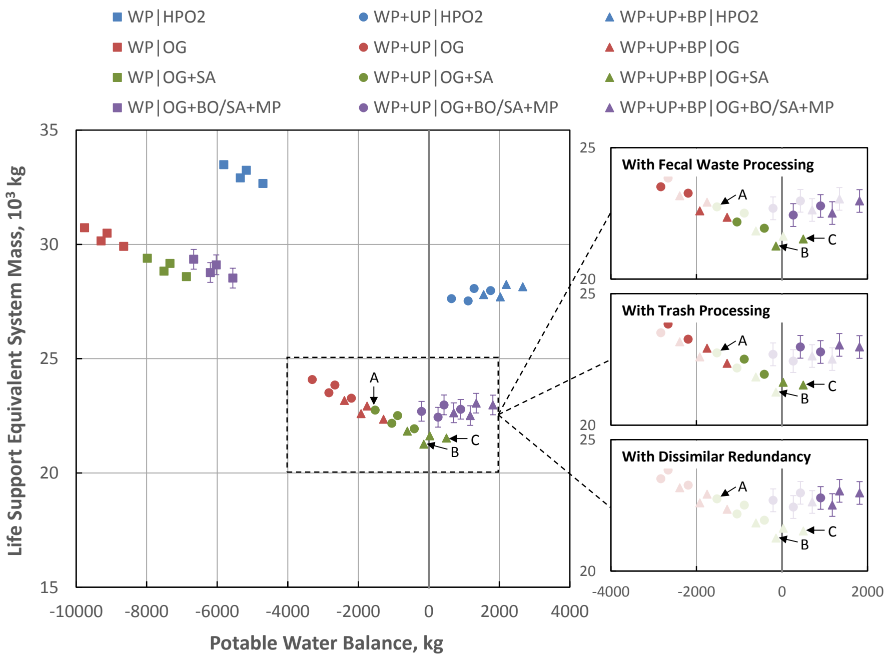


Figure 3. Relation between ESM and potable water balance for alternative life support architectures with baseline technology options and baseline crewmember water balance with additional 0.5 kg/CM-day water loss. Cut-out figures indicate additional architecture characteristics.

For this 1000-day class mission scenario, life support architectures that minimize ESM have a net potable water balance near zero. These architectures represent cases of intermediate system closure that include a full water processor (WPA+UPA+BPA), an OGA, and, depending on the crewmember mass balance, a Sabatier (SA). Each also includes water recovery from fecal waste (FWVDC) (first cutout). That said, architectures without a BPA or FWVDC can be identified that are relatively close to the minimum. The same can be said for architectures with water recovery from trash (HMC) (second cutout). Architectures with CO_2 reduction become more favorable as the surplus water potential decreases. With further reductions in surplus water potential, architectures with maximum CO_2 reduction eventually become competitive (results not shown).

The third cutout in each figure indicates architectures with dissimilar redundancy. These architectures are, by nature, on the positive side of the water balance. Other than reduced spares for the redundant technologies, the current ESM analysis includes no credits for generation of surplus water, but does include a storage penalty based on use of Contingency Water Containers (CWCs). Nevertheless, surplus water could provide increased system reliability and other benefits. These aspects are explored later for Cases A-C.

B. Water Cost Factors

The results in Figures 2 and 3 represent baseline assumptions for the technologies from Table 3. The impact of optional technology assumptions, optional crewmember water balances, alternative architectures, and mission duration is reflected in Figure 4 as "water cost factors" for each technology or technology combination. The water cost factor is defined as the change in system ESM (not including water storage) divided by the change in recovered water mass upon adding the technology (kg ESM/kg water). "Error" bars represent the range of values calculated under different combinations of architectures and assumptions, and symbols represent the midpoint. The water cost factor can be viewed as a technology breakeven measure with a value of one being the breakeven point. The inset figure expands the region of lower cost factors.

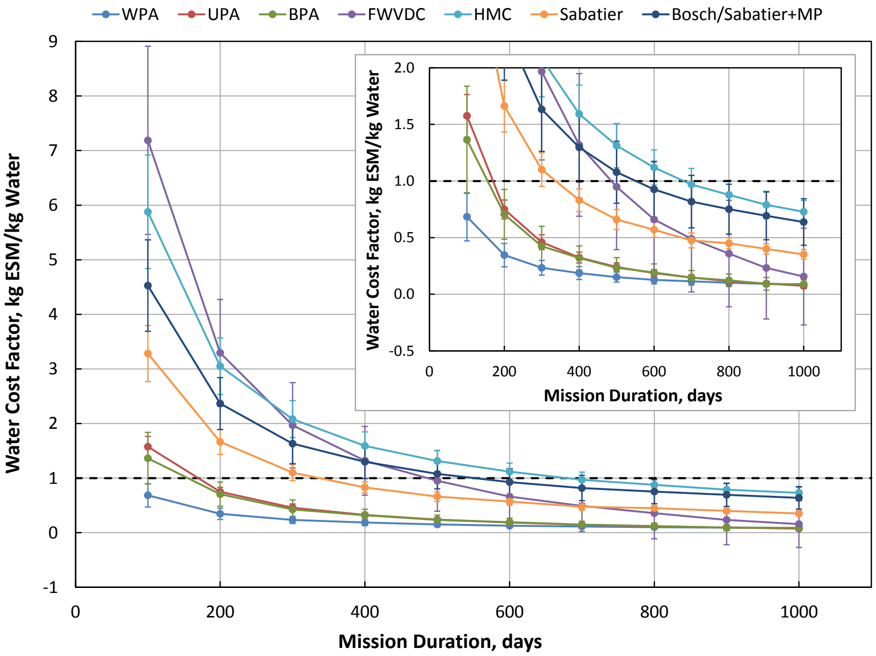


Figure 4. Water cost factor breakeven plot for different water recovery options. "Error" bars reflect range of values estimated over all considered mission and technology options. Inset shows expanded region near a cost factor of one.

For technologies such as the FWVDC and HMC that recover relatively little water, initial water cost factors are high compared to technologies that recover substantially more. Nevertheless, these technologies eventually payoff. In the case of the FWVDC, the water cost factor may even eventually become negative due to savings in UWMS consumables. In this case, the ESM savings in UWMS consumables exceeds the ESM of the FWVDC hardware and its consumables. Technologies that recover water directly from liquid wastes (WPA, UPA, and BPA) are also shown to have lower water cost factor than CO_2 reduction technologies that recover water through chemical reactions.

C. Case Studies

Cases B and C in Figure 2 represent architectures that provide a substantial increase in surplus water with a relatively small increase in ESM compared to the minimum case. Case B includes a full water processor (WPA+UPA+BPA) with OGA, Sabatier, and FWVDC. Case C adds HMC. Case A is an ISS-like case with WPA, UPA, OGA, and Sabatier. Both Cases B and C have dissimilar redundancy, with BPA+FWVDC or BPA+HMC (Case C) able to replace Sabatier and still meet the overall life support water requirement. Reliability and volume implications for these cases are compared and discussed below.

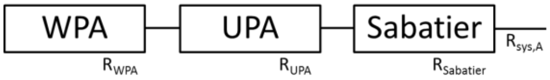
1. *Reliability Implications*

Reliability, in this case, is the probability that a technology will be operating successfully at a particular time. System reliability is the probability that a system is operating successfully at a particular time. System reliability depends on the reliability and the operating structure of the individual components within the system. A system with multiple components contributing to the same requirement can be more reliable than a system with only one. As such, bringing multiple types of water recovery technologies that recover water from different sources can create a more reliable system.

In order to meet the success criteria, the sum of the water recovery rates by the selected technologies must meet or exceed the water balance requirement. Once a viable combination of technologies has been determined, the reliability of that system can be determined using a reliability block diagram.

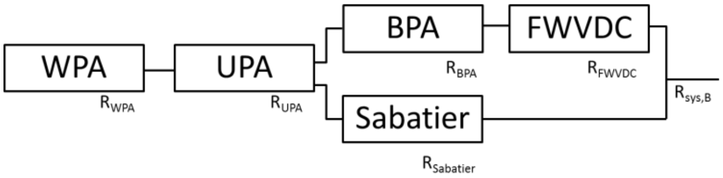
Figure 5 represents reliability block diagrams for Cases A-C. It is important to note that in a reliability block diagram, the paths represent possible ways to achieve the water balance requirement, not operational dependencies. "Success" in this instance indicates that each component required to meet the water balance requirement is operating successfully.

Case A



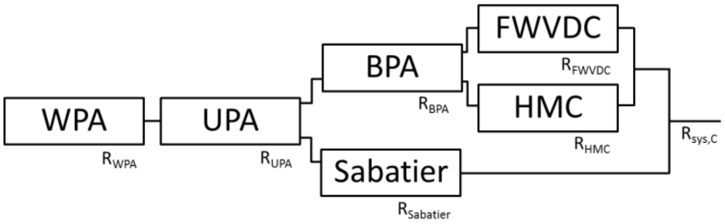
$$R_{sys,A} = R_{WPA}R_{UPA}R_{Sabatier}$$

Case B



$$R_{sys,B} = R_{WPA}R_{UPA}[R_{Sabatier} + (1 - R_{Sabatier})R_{BPA}R_{FWVDC}]$$

Case C



$$R_{sys,C} = R_{WPA}R_{UPA}[R_{Sabatier} + (1 - R_{Sabatier})R_{BPA}(R_{FWVDC} + R_{HMC} - R_{FWVDC}R_{HMC})]$$

Figure 5. Reliability block diagrams illustrating three architecture cases that achieve the water recovery requirement.

Each technology has an individual reliability, R. System reliability can be calculated if the reliability of each component is known. The reliability of components in series is equal to the product of the individual reliabilities. For components in parallel, the reliability can be found from the product of the probabilities of failure rather than the individual reliabilities.

Case A represents the system currently used on the ISS and is considered the baseline in this analysis. In order to achieve the water recovery requirement, the WPA, UPA, and Sabatier must all be operating successfully. Case B includes brine and fecal processing in addition to what is currently being used on the ISS (Case A). The combined water recovery of the BPA and FWVDC meets the water recovery requirement if the Sabatier fails, which is represented by a parallel path in the reliability block diagram. This introduces the concept of dissimilar redundancy. Case C includes every source of water recovery, creating a third path to success in the reliability block diagram. This system generates the largest water surplus, highest reliability, and highest ESM.

As a simple example, Table 4 compares the predicted reliability of each case with varying system spares. Only one component is considered per technology in this example and each is assumed to have a hypothetical uniform failure rate of $1{\times}10^{-5}$ hr^{-1}.[†] Sabatier, FWVDC, and HMC each have the same number of spares, while WPA and UPA spares are fixed at two each. Case A with one Sabatier spare is less reliable than Case B with no spares for Sabatier, BPA, or FWVDC. Without considering potential common-cause failures of spares, the reliability for each case becomes similar as the number of spares increases. Nevertheless, there are additional advantages to bringing dissimilar technologies. Instead of one path operating and being replaced with a spare in Case A, multiple paths will be operating simultaneously in Cases B and C. This will create a surplus in water production and the opportunity to store excess water. Each day the system operates successfully, a surplus of water will be added to the system. Eventually, the surplus will be large enough to result in failure protection of various technologies.

[†] A more rigorous analysis would consider failure rates associated with the major components of each technology. Sparing at a major component level was assumed in the ESM analysis (based on failure tolerance), but long-term operational data are needed to assess component failure rates for the FWVDC and HMC technologies.

Table 4. Example Reliability Calculation Showing Influence of Architecture and Spares

Case	Architecture	Water Recovered kg/CM-day	Reliability		
Spares for technologies other than WPA and UPA:			0	1	2
A	WPA+UPA+Sabatier	5.32	0.784	0.972	0.994
B	WPA+UPA+BPA+Sabatier+FWVDC	5.67	0.986	0.995	0.996
C	WPA+UPA+BPA+Sabatier+FWVDC+HMC	5.83	0.991	0.996	0.996

Figure 6 shows the surplus water stored for each case as a function of mission time. The open symbols on each "Nominal" line represent points at which a technology becomes failure protected, and dashed lines represent the water storage as the mission continues without operation of that technology.

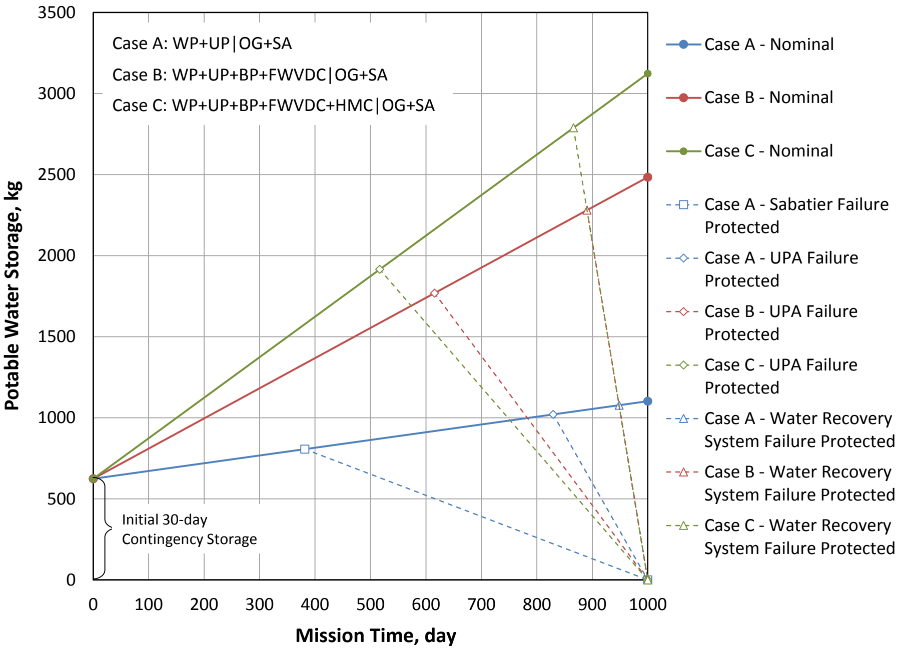


Figure 6. Comparison of failure protection provided by initial contingency water storage and excess water production for Cases A-C. Points represent minimum time at which protection occurs (resulting in sufficient water to last 1000 days without additional failures).

With increasing excess water production, technology failures become protected earlier in the mission, increasing system reliability. Sabatier failure protection for Cases B and C is provided from time zero by dissimilar redundancy. In the contingency situation where the crew spends an additional 500+ days in the deep-space habitat (resulting in the full 1000-day crewed duration), UPA failure protection and total water recovery system (WRS) failure protection are also provided at points along each line assuming no prior loss of function. For a nominal mission, failure protection would be provided much earlier in the mission.

2. *Volume Comparison*

Another benefit of including FWVDC and HMC technologies is the potential for waste volume reduction and increased habitability. Processing fecal waste and trash will result in substantial waste volume reduction. Figure 7 shows the estimated internal volume for various ECLSS components at (a) the beginning and (b) the end of the mission. Inset figures show the combined totals.

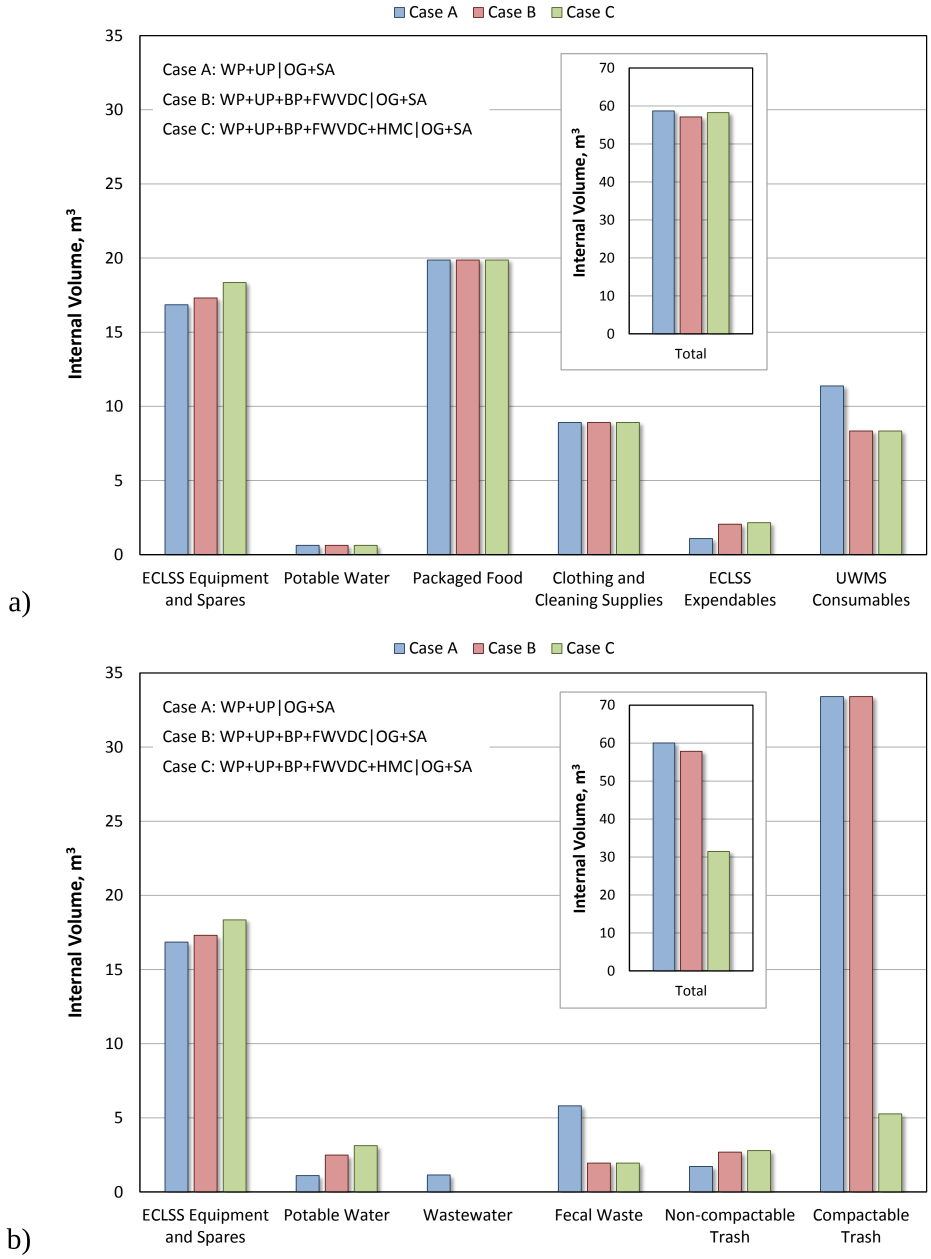


Figure 7. Estimated distribution of internal ECLSS volume for Cases A-C at (a) beginning of mission and (b) end of mission.

The addition of fecal water recovery, shown in Cases B and C, substantially decreases the storage requirement for fecal waste. This means that less UWMS consumables, such as canisters and lids, will need to be brought and the product will take up less volume. The addition of trash water recovery, shown in Case C, will lead to substantial volume reduction in compactable trash and substantial total end-of-mission volume reduction. Bringing additional water recovery technologies will also influence potable water storage volume by generating a water surplus that will need additional storage as time passes.

IV. Conclusion

For 1000-day-class deep-space missions, life support architectures predicted to minimize overall life support ESM have an intermediate degree of air/water-loop closure and a potable water balance near zero. With a modest increase in ESM, architectures exist that could provide a substantial surplus of potable water. These architectures offer the potential for increased system reliability through extended downtime/failure protection and, in some cases, dissimilar redundancy.

Water recovery from fecal waste and wet trash has the potential to increase habitability and system reliability. Fecal waste processing is predicted to result in an overall reduction in ESM relative to the storage baseline; however, additional development and testing are needed to better assess technology designs and sizing, system interactions, and crewmember interactions and acceptability. Lower-temperature operations are recommended to minimize recovered water contaminants and generated gases.

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