National Aeronautics and Space Administration (NASA) Environmental Control and Life Support (ECLS) Integrated Roadmap Development

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Abstract

Although NASA is currently considering a number of future human space exploration mission concepts, detailed mission requirements and vehicle architectures remain mostly undefined, making technology investment strategies difficult to develop and sustain without a top-level roadmap to serve as a guide. This paper documents the process and results of an effort to define a roadmap for Environmental Control and Life Support Systems (ECLSS) capabilities required to enhance the long-term operation of the International Space Station (ISS) as well as enable beyond-Low Earth Orbit (LEO) human exploration missions. Three generic mission types were defined to serve as a basis for developing a prioritized list of needed capabilities and technologies. Those are 1) a short duration micro-gravity mission; 2) a long duration microgravity mission; and 3) a long duration partial gravity (surface) exploration mission. To organize the effort, a functional decomposition of ECLSS was completed starting with the three primary functions: atmosphere, water, and solid waste management. Each was further decomposed into sub-functions to the point that current state-of-the-art (SOA) technologies could be tied to the sub-function. Each technology was then assessed by NASA subject matter experts as to its ability to meet the functional needs of each of the three mission types. When SOA capabilities were deemed to fall short of meeting the needs of one or more mission types, those "gaps" were prioritized in terms of whether or not the corresponding capabilities enable or enhance each of the mission types. The result was a list of enabling and enhancing capability needs that can be used to guide future ECLSS development, as well as a list of existing hardware that is "ready to go" for exploration-class missions. A strategy to fulfill those needs over time was then developed in the form of a roadmap. Through execution of this roadmap, the hardware and technologies intended to meet exploration needs will, in many cases, directly benefit the ISS operational capability, benefit the Multi-Purpose Crew Vehicle (MPCV), and guide long-term technology investments for longer duration missions

I. Introduction

The next steps taken in human exploration beyond low earth orbit (LEO) will require changes to Environmental Control and Life Support Systems (ECLSS) as structured today. Higher reliability is a key mission enabler for long-duration missions, as are lower total mass (system + spares) and performance. Although the National Aeronautics and Space Administration (NASA) has considered a number of future human space exploration mission concepts, detailed mission requirements and vehicle architectures remain mostly undefined, making technology investment strategies difficult to develop and sustain without a top-level roadmap to serve as a guide. This paper documents the process by which a roadmap was prepared to guide development of the ECLSS capabilities required to enhance the long-term operation of the International Space Station (ISS) and enable beyond Low Earth Orbit (LEO) human exploration missions. Three generic mission types were defined to serve as a basis for developing a prioritized list of needed capabilities and technologies. Those are 1) a short-duration micro gravity mission; 2) a long-duration microgravity mission; and 3) a long-duration surface exploration mission. To organize the effort, ECLSS was functionally decomposed into the three major functional groups (manage atmosphere, manage water, and manage solid waste) with each broken down into sub-functions. NASA subject matter experts (SMEs) then

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assessed the ability of existing state-of-the-art (SOA) technologies to meet the functional needs of each of the three mission types. When SOA capabilities were deemed incapable of meeting the needs of one or more mission types, those "gaps" were categorized according to whether the corresponding capabilities were enabling (essential for mission success) or enhancing (provides an improvement over the SOA) for each of the mission types.
The result was a list of enabling and enhancing capability needs that can be used to guide future ECLSS development, and is mapped to current projects and development efforts attempting to address those needs. A strategy to complete development to fulfill those needs over time was then developed in the form of a roadmap.

II. Activity Description

Formulation of the strategic ECLSS capability roadmap consisted of the following activities:

1. Decomposition of the functions typically performed by ECLSS, down to a level of detail sufficient to link the sub-function to flight hardware which has performed or is performing that function
2. Definition of three general exploration mission types, defined by duration and gravitational environment as the primary mission drivers to encompass the range of system capabilities likely to be needed to support human exploration objectives
3. A qualitative assessment by NASA subject matter experts of the ability of today's SOA ECLSS components and subsystems to meet the needs of the three representative exploration mission types
4. Qualitative characterization of the capability gaps identified in Step 3 in terms of whether the associated functions enable or enhance the representative mission types.

A. Functional Decomposition

The ECLSS is a complex system of systems that perform many critical functions. The top-level, primary functions performed by the ECLSS, illustrated in Figure 1, are Atmosphere Management (AM), Water Management (WM), and Solid Waste Management (SWM). While defined as separate functions, they are very interdependent in an operational vehicle and must be properly integrated to maintain balance at the higher ECLSS functional level. The degree of interdependency, and therefore the difficulty, in maintaining that balance increases directly with the degree of resource recovery performance required of the ECLSS to meet specific mission objectives.

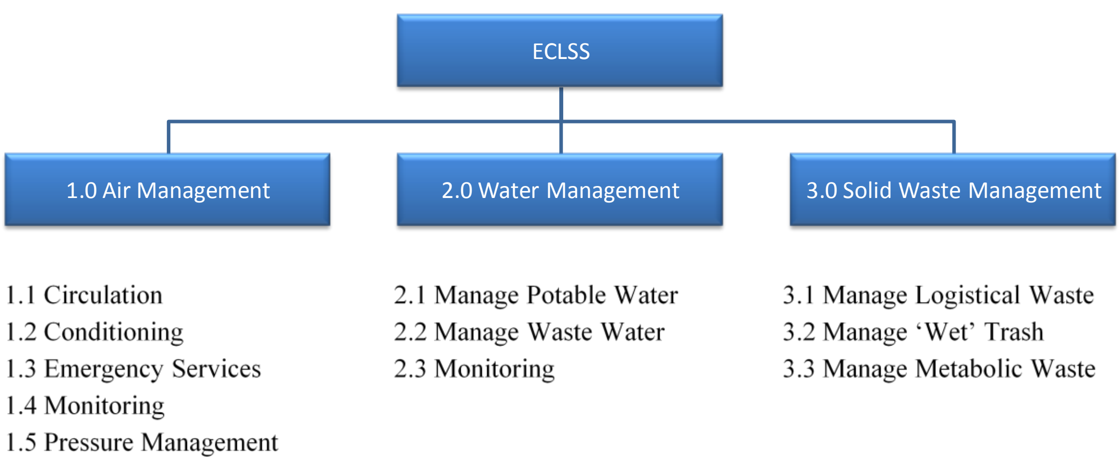

Figure 1. ECLS Top-Level Functional Decomposition

Each of these primary functions include many sub-functions (i.e., CO_2 removal, atmospheric pressure control, smoke detection & fire suppression, etc. for atmosphere management) A full decomposition to the component level is included in Reference 1.

B. Representative Mission Types

Generally speaking, ECLSS requirements dictate one of two distinct design approaches: one that supports short-duration missions (up to a few weeks), the other that supports long-duration missions (months to years). The distinction between the two lies in the difference in launch mass and volume required to support the defined mission duration. The total mass and volume of air and water (and the associated system hardware) required to support crew metabolic needs for short-duration missions is typically less than the mass and volume of just the hardware required to reclaim and reuse those same resources.

Open-loop ECLSS designs (e.g. Apollo and Shuttle) that operate based on resource consumption without re-use of metabolic waste products are therefore more appropriate for the shorter-duration missions. These designs are also less complex and interdependent, and have been matured to a very high level of reliability vs. usage time. A basic depiction of the open-loop versus closed-loop mass trade is shown in Figure 2, where the mass lines represent hardware mass plus total consumables. The thickness of the bars indicates a level of uncertainty associated with each mass estimate. This uncertainty is based on assumptions with respect to technologies or mission requirements.

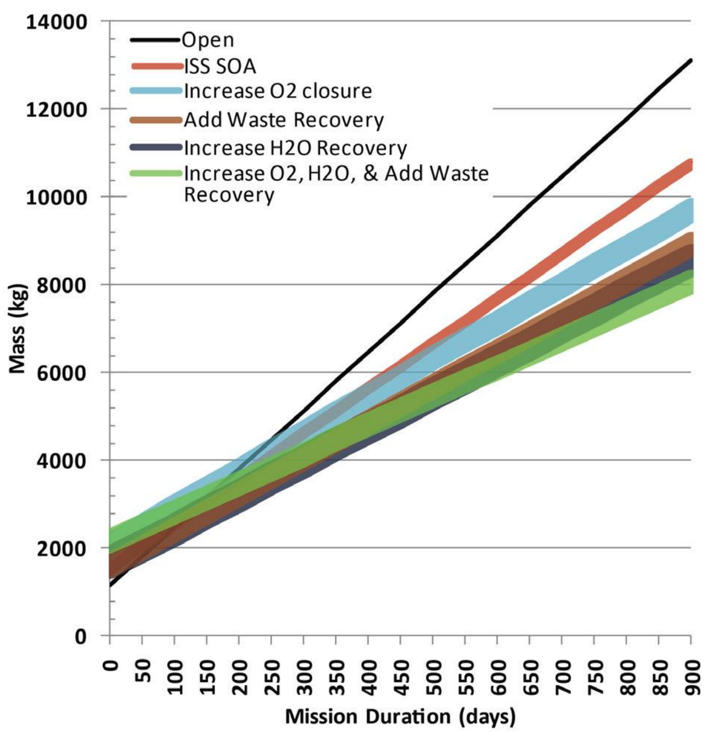

Figure 2. Representative Comparison of Mass Required by Mission Durations (Ref 2)

Increased recovery of air and water resources is important in longer-duration missions. As shown in Figure 2, mass and volume of an open-loop ECLSS increases linearly with mission duration, becoming prohibitively large for months-to-years-long missions beyond LEO. The absence of a nearby resupply source also increases mass and volume needs to carry adequate maintenance components and/or contingency supplies that enable crew self-reliance far from home. The distance from Earth is a driving factor, where ECLSS reliability becomes more critical the further we travel away from Earth. Unlike LEO missions where a safe return to Earth can be accomplished in hours, abort scenarios for missions beyond-LEO are much more challenging and thus require greater dependence on ECLSS for survival. Demonstrating the reliability needed to send crews on long-duration missions beyond LEO requires adequate testing and long duration on-orbit operations. Ground testing at the component, subsystem, and highly-coupled subsystem levels is a key component of affordable development for flight applications. A high-fidelity, fully integrated ECLSS test with humans in the loop on the ground is perhaps even more valuable to demonstrate the stability of the habitable environment under operational conditions. Compared to flight experiments, ground testing costs and risks are much lower because it is possible to stop the test, fix the problem, and restart much more easily than a flight experiment or demonstration. Ground testing of the integrated human, hardware, and operational system for durations approximating the intended missions is crucial to identify and control mission risks. In addition to a rigorous ground test program, targeted flight demonstrations are important for processes that are sensitive to microgravity. Long-duration on-orbit operations provide the confidence that resulting systems are sufficiently robust before deployment on a long-duration crewed mission far away from Earth. The balance between ground and flight testing is an important factor considered in the integrated ECLS roadmap.

Generic Mission Definitions

With a large number of design reference missions (DRMs) currently under evaluation and an absence of definitive mission needs, the NASA ECLSS technical community identified and characterized three generic mission types to facilitate the roadmap's development. The mission types were defined in broad terms to envelope the anticipated range of ECLSS capabilities necessary indicated by the wide range of missions that NASA teams were assessing. Care was taken to avoid over-defining the three mission types and focusing prematurely on too narrow a set of assumptions. The three representative mission types were defined to be: a short-duration, micro-gravity mission (referred to as Mission 1), a long-duration microgravity mission (Mission 2), and a long-duration surface mission (Mission 3). The assumed characteristics of each of these three mission types, along with examples, are summarized as follows:

Short-duration in microgravity (Mission 1): This mission type has a three to four week duration, with cabin pressures ranging from 8 to 14.7 psia. The entire mission would be conducted in micro-gravity. Extravehicular activity (EVA) capabilities would be supported through the use of an airlock or suitport. Some examples of exploration vehicles in this category include the Multi-Purpose Crew Vehicle (MPCV), Multi-Mission Space Exploration Vehicle (MMSEV), a Lunar Lander, etc.

Long-duration in microgravity (Mission 2): This mission type has a duration of 6 months or longer and occurs entirely in a micro-gravity environment. Vehicle cabin pressures range from 8 to 14.7 psia. Unique ECLSS challenges for this exploration mission type include a very limited or zero resupply capability and difficult mission abort scenarios. Examples of some vehicles in this category include Deep Space Habitats (DSH) and long-duration, deep space transit vehicles. The ISS is also an example, but is not as challenged by the harsh exploration constraints of little resupply or difficult abort scenarios.

Long-duration in partial-gravity (Mission 3): This missions type is generally similar to Mission 2 with regard to duration, atmospheres, limited resupply, and challenging emergency abort scenarios. The principle difference is the partial-gravity environment on the surface of a celestial body such as an asteroid, Earth's moon, Mars, or its moons.

Because these mission types are very generally defined, aspects of one may apply to another depending on specific mission objectives and architecture. For example, a lunar lander operates in both microgravity and surface environments and must therefore include aspects of Missions 1 and 3. Similarly, a short-duration sortie-type vehicle which does not need to reclaim resources for its mission duration may be a component of a long-duration mission architecture which requires resource capture and return to its "home base" for processing. In addition, since the durations established were somewhat arbitrary, the results of the study also identified potential gaps that will require additional review for more "intermediate-duration" missions.

C. State of the Art (SOA) Assessment

Once the ECLSS functional elements and representative missions were fully defined, the ability of current and past flight heritage ECLSS hardware and/or mature technologies to perform each function or subfunction was assessed within the context of each mission type, utilizing three teams of engineers with experience in the primary ECLSS functional areas. The qualitative assessment included NASA engineers with a broad range of experience: system managers and sustaining engineers with intimate knowledge of the Space Shuttle, ISS, and MPCV Orion ECLSS systems; technology research and development subject matter experts; ECLSS analysts supporting NASA exploration study teams; and design, development and test experts.

The capability assessments were, by necessity, qualitative rather than quantitative since definitive mission requirements, constraints, and resource allocations were not available. Nevertheless, the breadth and depth of experienced engineering judgement provided a valuable set of information to work with.

Many of the current SOA ECLSS components and technologies were judged to be suitable for application in the representative missions. Substantial challenges in utilizing the SOA (hardware and/or technologies) on future exploration vehicles will occur due to packaging and layout constraints, material and parts obsolescence, mass and power budgets, etc. However, many of the future ECLSS functional needs could be satisfied utilizing copies and/or carefully derived versions of Shuttle, ISS, and MPCV equipment.

D. Functional Capability Gaps

For each ECLSS sub-function where SOA capabilities were judged to be either unavailable or insufficient to meet expected needs of one or more representative mission, a capability "gap" was identified. These gaps were qualitatively rated using two simple criteria. A functional capability gap the team believed must be filled to reasonably execute one or more mission type was rated as "Enabling". "Enhancing" gaps were those expected to provide valuable benefit to one or more of the mission types but would not likely prevent the missions from being executed if not filled. In some cases, particularly when considering mid-duration types of missions, the distinction between Enabling and Enhancing became difficult and highlighted the need for further focused assessments.

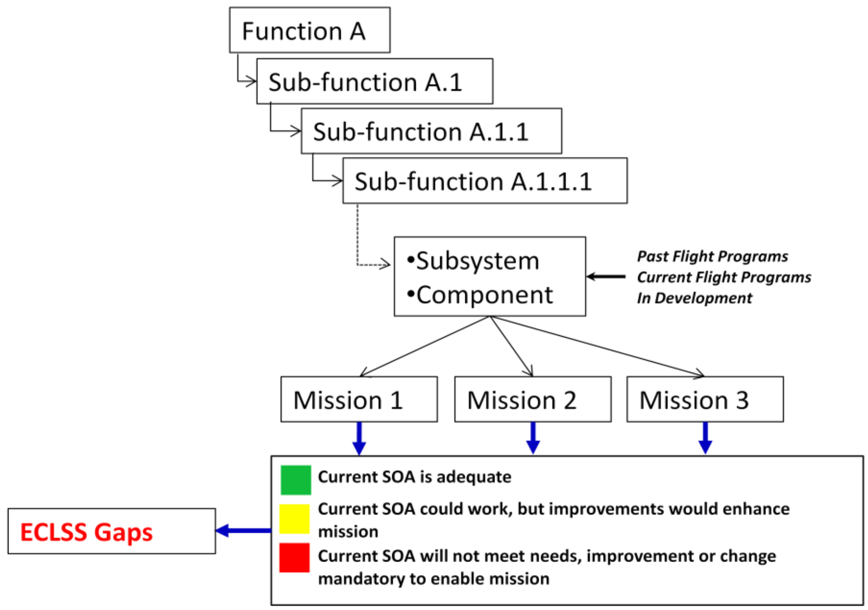

Figure 3. NASA ECLSS Functional Decomposition, Mission Need, and "Gap" Assessment Process

III. Summary of Results

Capability Gaps - Air Management

As shown in Table 1, twelve gaps in air management capabilities were identified as ‘Enabling’ in the assessment.

	Missions			
Capability	**ISS**	**1**	**2**	**3**
Suit loop fan		X		
Suit loop gas trap		X		
Suit loop pressure regulator		X		
Replacement for Halon & CO_2 for fire suppression	X	X	X	X
Smoke eater		X	X	X
Personal protection equipment filtering mask	X	X	X	X
Robust CO2 sorbent bed	X		X	X
High reliability O2 generation	X		X	X
O2 recharge for EVA	X		X	X
On-board trace contaminant monitor			X	X
Planetary surface dust pre-filter				X
Partial-g flammability testing				X

Table 1. Enabling Capability Gaps – Atmosphere Management

The baseline MPCV design includes a suit loop, which circulates and purifies 100% oxygen for the crew during pressure-suited operations. Air is circulated through the suit loop by a fan that is also used to circulate air through the cabin when the crew are not in their suits. Current SOA fans cannot meet the multiple flow rate and pressure drop operating points as well as the 100% oxygen compatibility required. The MPCV also has a suit cooling loop includes a venting gas trap to remove entrained gas resulting from umbilical connect/disconnect cycles and nominal leakage. A pressure regulator with a broad range of flow and pressure control capability is also required to satisfy both nominal and emergency “feed-the-leak” pressure control needs. Budgetary constraints have deferred the full development of the suit loop fan, gas trap, and pressure regulator flight designs, although some funding has been allocated to procure prototypes and perform some testing.

Current Halon fire suppressants must be replaced because they react to form toxic byproducts in the presence of high-temperature catalysts used in the trace contaminant control assemblies, and U.S. Environmental Protection Agency restrictions limit or prevent use. Carbon dioxide cannot be used as a suppressant in smaller crew cabin volumes without exceeding dangerous levels, and the ISS is also interested in a replacement for its CO2-based portable fire extinguisher. Therefore replacement of the current SOA fire extinguishers is necessary.

Due to the lack of quick, emergency return capability in missions beyond low earth orbit, all exploration vehicles will require an atmosphere cleanup device to use following a fire or contaminated atmosphere event, to avoid a depress/repress and loss of the air. Requiring the MPCV crew to don suits following such an event will likely expose the crew and suit loop atmosphere revitalization equipment to toxic gases. A much safer option is for the crew to don contingency masks while the cabin atmosphere is scrubbed to safe levels. While the ISS Russian segment currently has a deployable “smoke eater”, NASA has no equivalent hardware in use. Sorbents and catalysts which will remove the targeted contaminants can likely be selected, design of a deployable device utilizing an existing fan with the proper flow, head rise, and residence time may be challenging.

A contingency mask (mentioned above) donned by the crew in case of a fire or toxic spill is an enabling need that can be common for all inhabited exploration elements. The ISS currently uses an O_2–fed mask which, in small-volume vehicles, is hazardous due to O_2 enrichment/flammability concerns. For safety and commonality, a mask adapted from a commercial cartridge filtration mask is currently under development for ISS.

Current NASA regenerative CO_2 removal systems primarily employ zeolite or amine-based sorbent beds. These systems can be augmented to recover humidity and/or CO_2 for long-duration mission needs, but resource recovery is not as critical for short-duration missions. The MPCV and EVA suit Primary Life Support System (PLSS) baseline designs both utilize vacuum-desorbed amine swing beds for this function, but do not currently utilize a resource recovery capability. The ISS employs a zeolite bed regenerated by a combination of pressure and temperature desorption enabling downstream resource recovery via a Sabatier CO_2 reduction subsystem. Unfortunately, the current zeolite material has experienced breakdown and dusting issues on ISS. Robust, non-dusting sorbents, that are compatible with CO_2 recovery are required to enable reliable, long-duration missions.

The current NASA Oxygen Generator Assembly (OGA) and Russian Elektron onboard ISS are quite complex and have experienced reliability issues. In the OGA, the baseline electrolysis cell membrane material naturally leaches fluoride (causing corrosion issues) and is being phased out by the supplier and must be replaced. In addition, OGA reliability can be improved by reducing the system complexity of the first-generation OGA design. Oxygen generation is an enabling need for long-duration missions.

The capability to recharge high-pressure oxygen tanks enables EVA during long-duration exploration missions where earth-based resupply is prohibitive. Such a capability might be based on compressing oxygen delivered directly from an oxygen generator or from oxygen separated from a cabin air atmosphere and concentrated.

On-board trace contaminant monitoring was identified by the assessment team as an enabling capability gap for long duration missions beyond low earth orbit due to the lack of quick and affordable air sample return to earth-based analysis. A subsequent assessment is currently underway with members of NASA’s medical and environmental health communities to revisit the criticality and state of the art of on-board trace contaminant monitoring for human exploration space missions.

Common use of SOA High-Efficiency Particulate Air (HEPA) filters for particulate filtration across all Exploration vehicles is likely. Additional surface dust pre-filtering technology development is an enabling need for surface missions, as HEPA filtration alone will likely not be sufficient.

Limited material flammability testing in partial-gravity has revealed that this environment may be more challenging for fire suppression than in either normal or microgravity, as materials may burn in partial-g at lower O_2 concentrations. Additional testing in partial-g environments is necessary to understand this phenomenon prior to surface missions.

	Missions			
Capability	**ISS**	**1**	**2**	**3**
Quiet fans		X	X	X
Common bed core for CO2 removal		X	X	X
High reliability atmosphere major constituent monitoring reliability		X	X	X
Improved fire product sensors		X	X	X
Oxygen sensor accuracy improvements		X	X	X
Higher degree of CO2 reduction beyond Sabatier	X		X	X
Longer life/regenerable particulate filters			X	X
Advanced trace contaminant control catalysts & sorbents			X	X
Lower power water save for CO2 removal	X		X	X
Long life CO2 compressor	X		X	X
Smaller volume interim CO2 storage	X		X	X
Airborne microbial monitor	X		X	X
Fire detection with incidence to false alarms			X	X
Long life heat exchanger coatings				X
Surface dust particulate monitoring				X

Table 2. Enhancing Capability Gaps – Atmosphere Management

As shown in Table 2, 15 gaps in air management capabilities were identified as Enhancing. These gaps are summarized as follows:

Spacecraft cabins have historically had high levels of background acoustics emissions from ECLSS equipment. Cabin and equipment cooling fans often are the dominant sources of these emissions. Development of quiet fans can enhance exploration missions by not only reducing background noise levels and improving communication between crewmembers, but can also reduce the need for mass- and volume-adding acoustic foam insulation and in-line mufflers.

Substantial development, sustaining, and operational cost savings could be realized by developing a common CO2 bed component for use in Habitats, transit vehicles, and EVA suits. If feasible, such a bed component might be designed for use in building-block fashion in any exploration element, with or without upstream and/or downstream equipment to capture humidity and/or carbon dioxide for subsequent water and oxygen recovery.

The atmosphere monitoring function includes major constituents (nitrogen, O2, CO2, and water vapor), trace contaminants, and airborne microbial monitoring. The current SOA for major constituents is the mass spectrometer-based Major Constituents Analyzer (MCA) used onboard the ISS. This technology is considered sufficient for future vehicles; however, enhancements to improve reliability and O2 accuracy for tighter control at lower operating pressures would be valuable for future missions.

The MPCV will utilize an improved mass-spectrometer instrument that can be used for all exploration elements. A capability to monitor airborne microbial constituents may only be needed for long-duration vehicles and for planetary protection for surface vehicles and habitats. On ISS, crew time-intensive manual culture samples are utilized and frequently returned for ground-based analysis. Contingency sensors to detect combustion by-product gases (acid gases) and propulsion toxins (ammonia and/or hydrazine) can enhance the effectiveness of emergency detection and response in all exploration vehicles.

Oxygen recovery from CO2 is only foreseen as a need for longer-duration mission elements, and can leverage SOA ISS Sabatier technology at a minimum, which recovers approximately 50% of the O2 from CO2. Development of technologies for additional O2 recovery from CO2 beyond the Sabatier process can enhance longer-duration missions but could be enabling, depending on the mission architecture's ability to accommodate replenishment of consumables. Long life CO2 compressors and advanced technologies to reduce the volume of stored CO2 can also enhance exploration missions by reducing logistics and system volume.

Operational experiences on the ISS have demonstrated the propensity for atmosphere particulates (lint, hair, etc) to accumulate quickly on filters protecting air circulation ducts and equipment ventilation fans. Rapid loading of these filters, combined with the difficulty in reaching them in densely packed equipment bays, contributes to substantial crew time demands for periodic filter cleaning. Technologies to extend filter life or provide a regeneration function can enhance exploration missions by reducing dependence on expendable filter elements and crew time for routine maintenance. Long-life filters can also allow for greater flexibility in packaging equipment volumes if routine maintenance is not required.

Trace contaminant control concepts for exploration elements could utilize Shuttle/ISS SOA sorbents and catalytic oxidation technology as-is, but could be enhanced by improved sorbents that would reduce the size and extend the life of these components.

The capability to reduce the power expended to capture and recover humidity separated from CO2 could enhance exploration missions. The silica gel desiccants utilized on ISS requires substantial heat input to recover the adsorbed water.

Obscuration-based smoke detectors are prone to false alarms, particularly in the particulate-laden environment of microgravity vehicles. Smoke detectors that are less susceptible to particulate-triggered false alarms unassociated with smoke or combustion events can enhance Exploration missions.

Hydrophillic coatings used to retard the growth of microorganisms on the wetted surfaces of condensing heat exchangers are prone material sloughing resulting in a loss of effectiveness. Over the course of long duration missions these characteristics can reduce the efficiency of cabin thermal control and/or cause contaminant-induced failures in components downstream. Durable, long life condensing heat exchanger coatings would therefore enhance the efficiency and reliability of long duration exploration missions.

The unique characteristics and potential health hazards associated with surface dust will require diligent controls to minimize introducing such dust into spacecraft and surface habitat cabins. The ability to monitor the airborne concentration of lunar dust particulates within cabin environments can enhance long duration surface missions by providing early warning of elevated particulate levels.

Capability Gaps - Water Management

Table 3 shows four 'Enabling' gaps identified in the Water Management primary function

	Missions			
Capability	**ISS**	**1**	**2**	**3**
Drink bags, launched full		X		
Additional water recovery from urine or urine brine	X		X	X
Laundry wastewater recovery			?	X
Reduced water processing expendables			X	X

Table 3. Enabling Capability Gaps – Water Management

Outfitting initial Orion vehicles without fixed metal bellows storage tanks has been considered as a cost savings measure. In lieu of tanks, drink bags filled with water prior to launch might be used to support crew members during the short duration test flights. Crew water for use in the postlanding mission phase must be stored in bags and survive landing loads. However, today's drink bags are certified only to be launched dry and filled on-orbit. Drink bags that have the integrity to be launched and landed full is an enabling need for early MPCV missions.

The ISS Urine Processor Assembly (UPA) was designed to recover up to 85% of the water contained in urine. For long duration (typically $\geq$ 6 months) missions beyond low earth orbit, the additional system mass for recovering more water from urine or urine brine begins to trade favorably. Similarly, longer-duration missions may also benefit from the ability to launder and re-use clothing, provided that the resource (weight, power, and volume) impacts of a laundry system itself and water recovery system does not negate the clothing savings. The potential benefits of recovering additional water from urine and launder clothing were both identified by the community as enabling needs for long-duration exploration missions.

Reducing water recovery system life cycle mass is considered an enabling need. In this context, equipment life cycle mass includes the initial system mass plus the mass of hardware replaced either due to failure or because the useful service life of the hardware had expired. For reference, the life cycle equipment mass "utilized" and potable water "produced" by the ISS SOA WRS is shown in Figure 3. As shown in the figure, from its initial activation through March 15, 2012, the WRS produced over 21,000 lb of potable water. During that time, the cumulative mass of equipment "utilized" had been 5,461 lb, including the initial system mass of 3,042 lb plus 2,419 lb of additional equipment changed out due to either hardware failures (722 lb) or service life expiration (1697 lb). The mass of potable water produced represented approximately 88% of the overall water content available in crewmember urine and humidity condensate combined.

Note that the dominating hardware mass consumed in the ISS WRS has been the replacement of UPA Recycle Filter Tank Assemblies (RFTAs). Originally designed to minimize on-orbit crew time and potential exposure to hazardous urine brine, RFTA replacements have exceeded replacements of other failed hardware by about a 2-to-1 ratio (based on mass). The ISS Program has developed an Advanced Recycle Filter Tank Assembly (ARFTA) that allows crewmembers to manually transfer brine waste to the Temporary Urine and Brine Stowage System (TUBSS) and the hard-shelled Russian liquid storage containers (EDVs) for eventual disposal, thereby reducing the logistical mass penalty associated with RFTA replacements.

As shown in Table 4, six gaps in water management capabilities were identified as Enhancing.

	Missions			
Capability	**ISS**	**1**	**2**	**3**
Replacement biocide		X	X	X
Backup urine separator		X	X	
Alternate pretreatment	X		X	X
Reliable urine processing	X		X	X
In-line water monitoring	X		X	X
Biological water monitoring			X	X

Table 4. Enhancing Capability Gaps – Water Management

The capability to add, monitor, and reduce or eliminate depletion of silver biocide in potable water is an enhancing capability. Although the Russians have the capability to add silver in-line, that capability has not yet been developed by NASA.

Three enhancing needs were identified relative to managing wastewater. These include developing an alternate urine pretreatment formulation that mitigates precipitation of calcium sulfate and is non-toxic. Precipitation on orbit has occurred at lower levels of urine recovery (about 70%) than on the ground due to higher levels of calcium concentrations in urine thought to be from supplements taken by crewmembers to offset bone loss. Improving urine processing reliability and its tolerance to precipitates, as well as developing a back-up to a urine spin separator for more robust redundancy are also enhancing capability gaps.

Two water monitoring capability gaps were determined to be enhancing. An in-line capability to monitor organic and inorganic species in water can enhance exploration missions beyond low earth orbit where the return of water samples for ground-based analysis will not be possible. Similarly, an on-orbit capability to quantify and identify microorganisms in water samples can also enhance long duration missions by providing an autonomous capability to detect and correct contamination events and assess resulting risks to the crew.

Capability Gaps – Waste Management

Only one gap in waste management capability was identified as Enabling. Long-term (and perhaps indefinite) stabilization of fecal and trash wastes is expected to be required to meet planetary protection requirements for future surface missions. As the specific requirements are not yet defined, the team believed that mass constraints on the return flight from other celestial bodies will be require crews to leave waste products behind on the surface, thus making the stabilization capability mandatory (enabling)

	Missions			
Capability	**ISS**	**1**	**2**	**3**
Wet trash jettison			X	
Trash compaction & dewatering			X	X
Metabolic waste packaging			X	
Odor & trace contaminant control			X	X
Metabolic waste water recovery (trade-dependent)			X	X

Table 5. Enhancing Capability Gaps – Waste Management

As shown in Table 5, five enhancing needs were identified, including the capabilities to compact, dewater, and jettison wet trash, package metabolic solid waste for the MPCV application, manage odors released from waste management equipment, and recovering water from metabolic solid wastes for missions in which such capability would trade favorably.

IV. Conclusion

The ECLSS technical community has developed a general roadmap framework summarized herein to pursue short-duration operations through development of the MPCV ECLSS and long-duration operations by utilizing ISS-derived ECLSS capabilities. This will be achieved through an effective combination of both ground and flight testing, regardless of destination. The framework is not the answer to all ECLSS needs, but a living tool which can be tailored and applied to specific mission requirements to inform appropriate investments to meet NASA's objectives for human exploration going forward. Specific requirements such as crew size, mission duration, EVA requirements, and the availability of resupply can dramatically affect the selection of system designs and technologies.

In the current NASA environment, completing the MPCV ECLSS hardware development, performing targeted ISS demonstrations to address existing reliability issues and add capabilities, and pursuing a rigorous ground testing program will drive us to effective solutions for the next steps of human exploration beyond low earth orbit.

The preparation of this whitepaper was guided and supported by the NASA Thermal/ECLSS Steering Committee (TESC), which is made up of technical discipline management representatives from each NASA center, including JPL. In addition, two NESC technical fellows act as ad-hoc members of the TESC. ECLSS technical subject matter experts from each of the centers and NESC provided the material and support that culminated in the NASA whitepaper that this paper is based on.

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