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Beyond LEO: Life Support Requirements and Technology Development Strategy

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This paper reviews basic Life Support Systems requirements for a conceptual Earth-Moon Libration Point-2 (EML-2) orbiting facility and conceptual early stage Lunar and Mars bases, highlighting commonalities and unique challenges for each. Recommendations are made for both near-term and long-term key technology development investments in a progressive approach to technology development that supports needs of the above missions and aligns with the current fiscally constrained environment. This approach leverages available commercial-off-the-shelf (COTS) hardware and already developed space-flight hardware, while providing the rationale for a corresponding modestly elevated risk posture intended to bring down development costs, and to prioritize which technologies unavailable through COTS are in highest need of development. The recommendations provide guidance for Life Support Systems technology development planning activities.

Nomenclature

ACS	=	Atmosphere Control & Supply
AR	=	Atmosphere Revitalization
CAMRAS	=	CO_2 and Moisture Removal Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CFR	=	Carbon formation Reactor
CHX	=	Condensing Heat Exchanger
CME	=	Coronal Mass Ejection
COTS	=	Commercial off the shelf
CRD	=	Cascade Rotary Distillation
ECLS	=	Environmental Control and Life Support
ECLSS	=	Environmental Control and Life Support Systems
EEE	=	Electrical, Electronic, and Electromechanical
EML	=	Earth-Moon Libration Point
EVA	=	Extravehicular Activity
FDS	=	Fire Detection and Suppression
G	=	Earth's surface gravitational acceleration (9.8 m/s, 32 ft/s)
GC	=	Gas Chromatography

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GC-QMS	=	*Gas Chromatograph – Quadruple Mass Spectrometer*
HEPA	=	High Efficiency Particle Air
HTCO	=	High Temperature Catalytic Oxidation
Hx	=	Heat Exchanger
IR	=	Infrared
ISS	=	International Space Station
LEO	=	Low Earth Orbit
MPAM	=	Multi-Platform Air Monitor
OGA	=	Oxygen Generation Assembly
PEM	=	Proton Exchange Membrane
RS	=	Russian Segment
TCCS	=	Trace Contaminant Control System
TCM	=	Trace Contaminant Monitor
THC	=	Temperature & Humidity Control
TRL	=	Technology Readiness Level
UPA	=	Urine Processing Assembly
USOS	=	United States Operational Segment
UWMS	=	Universal Waste Management System
VCD	=	Vapor Compression Distillation
VRA	=	Volatiles Removal Assembly
WM	=	Waste Management
WP	=	Water Processor
WPA	=	Water Processing Assembly
WRM	=	Water Recovery & Management
WW	=	Waste Water

I. Introduction

While human spaceflight targets Mars, there are multiple venues and vehicles which are under consideration for incremental maturation and risk reduction towards that end goal. Potential destinations include the Moon, Libration points, and asteroids with surface habitats, rovers, transit, and ascent and descent vehicles. Each of these destinations/vehicles present unique challenges and opportunities for the Environmental Control and Life Support Systems (ECLSS), from the high radiation encountered in deep space to dust contamination and partial gravity environments on the surface of both the Moon and Mars.

Historically, spaceflight hardware has been extremely costly due to requirements for reliability and minimum risk in unique and challenging environments. Current fiscal constraints place the development of ECLSS to support future human exploration to destinations beyond Low-Earth Orbit (LEO) at a critical juncture, emphasizing the need for an affordable architecture that can satisfy a wide range of missions

A closed-loop ECLSS recovers oxygen and water from what would otherwise be waste fluids vented overboard. Regenerative ECLSS systems on-board the International Space Station (ISS) include urine processing, water processing, carbon dioxide removal, oxygen generation and carbon dioxide reduction to form the basis for a mostly-closed-loop ECLSS that significantly reduces logistics up mass. Similar systems could be used for surface habitats and long-duration transit vehicles. The international ECLS community goal is to leverage ISS ECLSS as much as possible in the development of next-generation regenerative ECLSS for deep space, both for affordability and risk reduction. However, as missions venture further from LEO, reliance on relatively frequent resupply and dissimilar redundant systems (e.g., as provided by the Russian Segment on ISS) are no longer practical. Investments are needed now to address gaps with the current ISS systems and needs as mission complexity increases. Scalable and/or modular designs allow application of a single technology across multiple vehicles, maximizing the return on the investment. Balancing allowable risk posture and mass penalties for logistics for a given mission may enable reduced costs through the use Commercial off the shelf (COTS) hardware or heritage hardware.

With limited funds for technology development each year, prioritization of enabling technologies is necessary to provide robust, reliable and cost-effective small, lightweight hardware in time to support the missions indicated above. As seen through the activation and utilization of regenerative ECLSS on-board the ISS, unintended interactions and integration issues often arise with the deployment of new technologies. A focused technology development effort will be required to mature these systems from ground development to ISS on-orbit test-beds to reliable hardware capable of safely sustaining deep space explorers for many years in hostile and unforgiving environments.

Against these envisioned habitation requirements, a preliminary evaluation identified technologies requiring near term investments based on the earliest mission need dates, mission complexity, etc. This study examines the requirements and potential hardware required to meet EML-2, Lunar and Mars surface habitat ECLSS needs.

II. Requirements Assessment

The requirements for mission-specific advanced life support systems are shaped by multiple variables including high-level mission objectives such as destination, duration and total number of crewmembers and are further constrained by available mass, volume and power. From these mission objectives and requirements the ECLSS engineer must design a robust and reliable life-support system.

For much of the last 50 years of human spaceflight, life support systems have tended to be open loop systems. The relatively short durations of early human space missions, from Vostok/Mercury to the Space Shuttle program, did not require recycling of consumables such as air and water. Instead all necessary life support consumables for total mission duration were loaded onto the spacecraft prior to launch. The use of open loop systems has the advantage of being highly reliable, but becomes mass prohibitive for longer duration missions.

The development of space stations in the 1970s and 80s provided the opportunity for the testing of partial closed-loop life support systems from low Earth orbit. Both Skylab and the early Salyut used open-loop systems, but early experiments were conducted with closed-loop systems beginning with the Mir space station. The ISS has significantly expanded the testing of regenerative life support systems and now includes partial regenerative oxygen and water systems.

Using the ISS as a baseline, **Error! Reference source not found.** provides a comparison of key requirements for missions to the lunar surface, the Earth-Moon Libration points, and the surface of Mars. The authors developed this table as a basis of comparison for the technology review.[1] All three missions will require partial, or fully, closed loop systems ECLS systems.

Duration: Of all the mission requirements, three key drivers are destination, mission duration and dormancy duration. ECLS systems requirements for a long-duration (+3 years) deep space mission to the vicinity of Mars are much more challenging than for those in cis-lunar. In general, ECLS systems for longer mission durations with limited resupply options will require a greater vehicle power, thermal, mass, and volume allocation. However, this can be somewhat offset with the use of regenerative closed-loop life support systems. Anticipated dormant periods between systems operations (i.e. visiting crews) on the order of months or years brings a new challenge to ECLS system performance requirements.

Cost: A key consideration in the fiscally constrained environment is to invest in only the necessary technologies to close the gap toward the goal of a human mission to Mars. Leveraging heritage technologies or COTS hardware can significantly reduce the investment required for each mission destination. Selection of mission architecture, whether a Moon first, or Mars without Moon approach, could also impact the development cost of ECLS systems. Without the incremental approach of returning to the Moon first, and the subsequent experience derived from operating on the lunar surface to test out systems, thereby reducing risk, development of reliable ECLS systems for multi-year long missions would require significant development and testing on the ground or ISS.

An EML-2 platform could be used as a starting point to leverage ECLS system technology from ISS, while lunar and Mars bases will require development of more reliable ECLS systems.

Total Pressure: Changes in total operating pressure and associated oxygen concentrations from heritage programs or ambient can limit the technology choices or drive significant efforts to evaluate hardware for acceptability. Projected changes in acceptable CO_2 partial pressure from those baselined for ISS adds challenges to CO_2 removal technology identification and selection.

Crew Size: At its core, the purpose of an ECLS system is to keep the crewmembers healthy and in such a condition as to safely complete all mission objectives. The human crewmember is central to any ECLS system, both as a user of the system and as a provider of waste products that can either be disposed of or re-cycled. **Error! Reference source not found.** shows the atmospheric and water requirements per day for an average crewmember, as well as the average waste created per day.

Mass: Depending on the overall mission requirements, vehicle trade studies will determine the ultimate overall mass allocation for the various subsystems, include the ECLS systems. The key requirements of the ECLS system, such as mission duration and number of crewmembers,

Table 1. Comparison of key requirements for missions to the lunar surface, the Earth-Moon Libration points, and the surface of Mars.

Key Characteristics	**Missions**				
	ISS	**Lunar Surface**	**Earth-Moon Libration Point 2 (EML2)**	**Mars Surface**	
Duration	20 – 30 years	5-10 years	5-10 years	~ 3 years	
Resupply Interval	~3 Months	6 Months	~1 year	~ 3 years	
Reliability	10 years +/- 5 years	Goal: 5 years +/- 1 year	Goal: 5 years +/- 1 year	Goal: 5 years +/- 1 month	
Emergency Return	Hours	~ 3 days or less	~ 3 days or less	Up to 2 years	
Crew Size	7	4	4	4	
Quantity of vehicle types	2	5	4	5	
Mass Penalty	1	4 (surface)	3	7 (Orbit)	10 (Surface)
Gravity	Microgravity	0.17 g	Microgravity	0.38 g	
Total Pressure	Sea Level Earth Normal	Exploration Atmosphere (10.2 psia)	Exploration Atmosphere (10.2 psia)	Exploration Atmosphere (10.2 psia)	
CO_2 Partial Pressure	5.3 torr	1.0 torr	1.0 torr	1.0 torr	
Dust	N/A	Yes	N/A	Yes	
Radiation	LEO Radiation	Deep Space	Deep Space	Deep Space	
Operational Profile	Continuous	Intermittent – Up to 6 Months Quiescent	Intermittent – Up to 6 Months Quiescent	Intermittent – Up to 2 years continuous (surface hab) and 2 years quiescent (deep space hab)	
EVA Intensity	Low - Moderate	High on surface	Low - Moderate	High on surface	
Future Development Cost	Low cost for ISS extension. Utilize existing technology with some demonstrators.	High w/some limited leverage of ISS technology. Potential use of COTS	Moderate - Extensive leverage of ISS technology adapted for L1 environment	Extremely High - advanced technology required.	
Risk Tolerance	High	Moderate	Moderate	Low	

Table 2. Atmospheric and water requirements per day for an average crewmember. *Source: ISS consumables requirements, SSP-41000*[2]

Average Atmospheric/ Water Requirements per Day per Crewmember	Average Human Waste (Solid/Liquid/Gas) per Day.
Oxygen = .84 kg	CO_2 = 1.0 kg
Drinking water = 1.6 kg	Respiration/Perspiration (water) = 2.28kg
Water in Food = 1.15 kg	Urine = 1.5 kg
Sanitary Water = 7.3 kg	Feces (solid) = .032kg

Dust: During the Apollo lunar missions dust contamination was found to be a significant problem. Crewmembers returning to the LM following lunar EVAs routinely brought in fine particles lunar dust which was introduced to the cabin atmosphere. Due to the short duration of the Apollo missions, the dust never significantly impacted the health of the crewmembers or hardware operation. But with longer missions to the lunar or Mars surface, dust contamination could pose a significant hazard, both to crewmembers health as well as to mission hardware.

The mitigation of the dust hazard can be addressed in a variety of hardware designs, from placing EVA spacesuits on external ports to reduce exposure of the internal cabin to dust, to airlock designs that contain the dust from the crew's primary living quarters. However, some level of dust must be assumed to be introduced into the cabin atmosphere, so the ventilation and atmospheric systems must be designed to filter it out. Maximum acceptable limits have yet to be determined but will have significant implications to system design.

Radiation: Protection from the space radiation environment is an important consideration in the design of the ECLS system. Space radiation primarily consists of high-energy charged particles, such as protons, alpha and heavier particles, originating from several sources, including galactic cosmic radiation, energetic solar particles from solar flares and trapped radiation belts. These particles are a constant threat to crewmembers. During extreme solar events, with large CMEs from the Sun, crewmembers will have to seek shelter in a pre-determined area of the spacecraft or surface platform, possibly for up to several days. The ECLS system for this shelter will have to be able to provide atmospheric, water and CO_2 removal while the crewmembers wait for the storm to pass.

Due to the atomic makeup of water, it has the potential of offering significant radiation protection for the crewmembers. The location, and subsequent management of the water tanks, could provide an effective low-mass alternative to heavy shielding in protecting the crewmember from space radiation.

EVA Intensity: For low intensity EVA operations, such as on the ISS or as would be anticipated on an EML-2 platform, EVA consumables have to be accounted for, but are not significant drivers for system design. For high intensity operations during surface operations (Moon/Mars) with limited resupply, regenerative ECLS systems become critical in replenishing consumables.

During a typical ISS EVA, the crewmember uses .63kg of O2, 5.4 kg of water (drinking water/suit cooling), and produces 2.9 kg of CO_2[3]. While ISS EVAs are infrequent (4 to 8 per year), surface EVAs on the Moon or Mars will occur on a much more frequent basis, with multiple EVAs per week. Therefore, use of an open-loop ECLS system for Lunar and Mars exploration is impractical, and drives the requirement for closed-loop systems that can replenish consumables expended during an EVA.

Emergency Return/Abort: Given the close proximity of the ISS to the Earth, emergency return/abort has not been a driver for the design of ISS ECLS systems. In the event of a catastrophic failure, the crewmembers can quickly enter the Soyuz capsules, separate from the ISS, and return to Earth. For missions beyond LEO, even to the relatively close EML-2, this is simply not an option. Emergency return/abort for deep space missions could range from days to months or years. As such, the ECLS system should be designed with emergency return/abort in mind, with specific requirements tailored to the worst-case emergency return/abort.

III. Conceptual Architecture

To inform the technology selections in this study, conceptual architecture were envisioned for the Moon, EML-2, and Mars, to assess the elements common to all destinations and thereby help guide the investments needed. By establishing this architecture, a review space was created in which to consider the advantages and disadvantages over various ECLS technologies and their dependent and independent aspects.

The ISS has provided a vast amount of experience for what it takes to live and work in space and many ISS technologies are directly applicable to deep space habitats. Unfortunately, having a habitable volume as large as the ISS is not an option for a deep space habitat or a lunar or Mars base due to the associated cost and required assembly. A more practical approach is isolatable habitation modules that could be launched and pre-positioned and activated when required. These modules would have to be capable of surviving long periods of dormancy with little to no re-supply for missions beyond the Moon.

The core architecture elements are Mars and lunar bases along with a platform at EML-2 to serve as a transportation node to the lunar base. This architecture then implies a lunar lander for transportation to the lunar surface and rovers for transportation on the surface. EVA suits are assumed to be a part of any future architecture and transportation to the EML-2 node is assumed to be Orion. The EML-2 vehicle would be most similar to ISS, maximizing reuse of technology to minimize costs and reduce risks through exposure of systems to deep space radiation and dormancy periods of six months or more. The lunar base would support crew stays of up to 6 months, with limited contingency duration, and can take advantage of aspects of the lunar environment that have similar challenges and benefits to the Mars environment such as partial gravity, regolith, and shadowing. Based on these aspects and the rapid return capability, the lunar elements can maximize the use of COTS hardware to minimize development costs associated with technologies not presently available on ISS or to enhance currently available ISS systems. The Mars base would then require some investment to increase the robustness and radiation protection of COTS hardware or development of new technology.

The ECLSS in each of the elements provides the functions necessary to support human habitation and exploration along with basic safety capability. The return scenario combined with mass penalties for each destination drives the necessary fault tolerance and contingency provisions. The amount of volume required per crewmember is driven by duration of occupancy, resulting in larger habitable volume allocations for Mars missions.

For all destinations, the ECLSS must be configurable to enable activation and scrubbing of the atmosphere prior to crew ingress. This implies increased command and data capability over that currently available on ISS.

Each vehicle must have egress and ingress paths, with dust mitigation functions included for lunar and Mars and defined spaces for crew sleep, hygiene, food preparation and science.

The regenerative ECLSS technologies would reside predominantly in the base elements, or habitats, where the crew would generally reside. The "base" is the largest habitable element, facilitating crew occupation for longer durations and thereby requiring the greatest volume of ECLSS hardware. Sleep stations for both EML-2 and Mars missions require more radiation protection due to the exposure to deep space, which drives the layout of the hardware and/or water and waste storage. On the Moon, where the main radiation concerns are Solar Particle Event, detection elements combined with hardware configurations that provide appropriate shielding may be preferable while for Mars, the use of deployable water walls could both provide storage for potable water for crew consumption and can be replenished via water recovery.

Mars habitats will include both showering and laundry capability, which has implications on multiple systems, including water recovery management. Neither the moon nor EML-2 requires laundry capability according to the envisioned crew stay duration and the ability to transport sufficient supplies.

Several ECLS Systems would need to be included in the core architecture with distribution across vehicles/bases according to the mission needs and profiles. These systems include:

- Water Recovery
- Oxygen Generation
- Waste Management
- Atmosphere Pressure Control
- Atmosphere ventilation and temperature control
- Humidity Control
- CO_2 Removal
- Fire Suppression
- Air monitoring
- Trace Contaminant Control

When laying out options for each module, several factors must be considered. One of the challenges will be the lack of "free volume". Supplies and equipment take up the majority of volume on the ISS. The modules that were selected for the ISS have a fixed volume and cannot be easily re-configured for multiple uses.

IV. Technology Review

Based on the conceptual architectures from Section 3, detailed systems hardware can be reviewed and compared. ECLS systems and technologies are available for consideration from several sources: ISS, Shuttle, Orion, Commercial Crew vehicles, and COTS. A quick study of these program platforms is warranted and provides a framework to use when considering new or COTS devices.

Shuttle Orbiter ECLSS hardware included many non-regenerative systems that were light and robust, including fans, heat exchangers, smoke detectors, pressure control system components, tanks for oxygen, nitrogen, potable and waste water, cryogenic oxygen and hydrogen, and a commode for collection of liquid and solid waste. Almost all systems were hard-wired and had no computer controls and none of the Shuttle ECLSS hardware was designed for in-flight maintenance. While the designs (and some residual hardware) still exist, many companies are out of business and/or their products are obsolete.

The ISS has successfully operated for more than 15 years, providing the best data for operational life for long-duration microgravity systems. ISS ECLSS hardware generally reflects next-generation upgrades for computer controls, interfaces and in-flight maintenance compared to the Shuttle, but it was based on having the Space Shuttle deliver and return hardware with a goal of minimizing crew maintenance time. This resulted in big and complex Orbital Replaceable Units (ORUs) that are not conducive to deep space systems packaging or sparing. Additionally, it is getting harder to build replacements without running into EEE parts obsolescence issues.

Orion ECLSS hardware currently under development[4] will more closely resemble Shuttle hardware than ISS hardware. It will need to be small, light and non-regenerative, with the exception of CO_2 removal. The hardware will likely have more computer controls than Shuttle ECLSS hardware and no obsolescence issues for years to come. Orion will also incorporate atmosphere monitoring of major constituents, a capability that was not present in Shuttle. Like its Shuttle Orbiter predecessor, its ECLSS hardware will not be designed for in-flight maintenance, relying on redundancy and limited (~21 day) flight times.

Nascent Commercial Crew Systems such as Dream chaser, CST-100 and Dragon Mk 2, hardware (in development) will be similar to Orion hardware, though less sophisticated. Their ECLSS will also need to be small, light and non-regenerative for cost savings. It will be new and likely have more computer controls than Shuttle hardware and will not have obsolescence issues for years to come, nor will it need the same level of radiation hardening as Orion hardware. It will not be designed for in-flight maintenance, as missions will be measured in hours rather than days or weeks.

COTS hardware has the attraction of not requiring development and having relatively low per unit cost. Some COTS items may have difficulty meeting the power, thermal, computer and crew interfaces required to function in space architecture vehicles and habitats "right out of the box". They may also have a strong tendency to fail in the deep space radiation environment, particularly those components with electronics. COTS hardware needs to be impartially considered for each component where such hardware can be found. The hardware quality will need to be assessed to determine whether the component will meet performance and reliability needs. Another consideration is consistency of builds on hardware that is not subject to the current strict version control of manned spaceflight hardware. Material control issues will have to be addressed to make sure that unacceptable outgassing and other material lessons learned are avoided. If the selected exploration approach is to have a lunar base before a Mars base, then the easier access and rapid emergency return capability associated with the Moon would make the use of more COTS components acceptable. If there are problems, then replacement or repair is more feasible than with a Mars base and emergency return to earth is always the final mitigation. The parts that are proven reliable could then be used on the Mars base to save on the development and recurring costs.

ach of the referenced possible hardware sources has unique advantages and disadvantages for exploration. Exploration hardware will have to be light, compact, robust, reliable, regenerable (wherever possible) and in-flight maintainable. It will have to be designed for deep space radiation environments, and for surface habitats may need a high dust tolerance. Long periods of dormancy after use are quite possible, posing a big challenge for microbially active ECLSS hardware. The combination of these factors drive extended development timetables and associated costs to flight hardware.

One additional consideration in exploration ECLSS is scalability vs modularity. Scalability refers to single multi-crew sized units that can be throttled to the correct crew complement while modularity is single-sized units ganged together to match the number of crew. The advantages of modular ganged systems are that they can be individual units for individual crew needs such as an EMU or coupled together for two crew (e.g. for a rover). However, once ganged together for three, four or more crew (for ascent/descent vehicles or moderate sized habitats) disadvantages such as multiple interface connections are required to support multiple individual systems, making fluid, Electrical Power Systems, and Command and Data Handling architecture more complicated, and redundancy in function (controllers, etc.) is required, The advantages of scalable, single multi-crew units are that a single installation can be tailored to cover a range of crew members and architecture interfaces are simplified. Disadvantages are that different systems (and technologies) would very likely be required for rovers and EMUs as the multi-crew system would be too large and heavy. This also complicates crew training with the need to learn how to operate and maintain multiple systems for the same function. This interesting, yet challenging, topic will be deferred until after the underlying technologies themselves can be chosen and developed, at which point trades can be refined.

For this paper, technologies from ISS, Orion, and some COTS will be examined to identify technology gaps related to EML-2, Lunar and Mars surface Habitats. Our approach for selection of technologies for ECLSS is to start with the systems being used on the ISS and assess the need and associated potential for improvements to life, reliability or weight compared against competing hardware. The results for each ECLS system are described below.

A. Atmosphere Control & Supply (ACS):

Atmosphere Control and Supply is the best developed of the ECLSS subsystems. Its function is to replace lost atmospheric air due to leakage and repressurize the airlock. It is also used to refill any dependent ACS systems such as suits and rovers and provide oxygen purge flow in emergencies. It would be beneficial if the oxygen tanks could be refilled by the oxygen generator to minimize the storage tank size. The selected approach is to use pressurized gas storage with one network using pure oxygen and the other using a mixture of oxygen and nitrogen that is slightly oxygen rich air. This allows us to take advantage of the systems used on all previous manned missions and maintains similarity with the transport and rover vehicles and EVA suits. A nominal cabin pressure of 10.2 psia is assumed for all these future platforms instead of the ISS 14.7 psia approach to reduce the pressure loads on the pressurized cabin bulkhead and reduce leakage and required prebreathing before EVA events. A lower pressure is possible but was not selected because their weight advantages over the 10.2 psia were small and the margin for oxygen concentration control between too low an oxygen concentration for crew support and too high a percentage for fire safety makes a lower pressure less inherently safe. Using a mixture of nitrogen and oxygen as the second gas instead of pure nitrogen does make it more difficult to recover from too high an oxygen concentration in the cabin. Pure nitrogen can dilute an oxygen-rich atmosphere more easily than diluting with a mixture of oxygen and nitrogen. We believe that the cabin's large volume allows more time to detect this oxygen leak failure and prevent it from harming the crew than the failure of supplying a pure nitrogen gas into a pressurized suit that can quickly incapacitate the crew.

Other than using the lower cabin atmosphere pressure, the main difference between the ISS and the recommended approach is to use a mixed oxygen/nitrogen gas in place of pure nitrogen. By eliminating the potential risk of exposing the crew to pure nitrogen, overall safely is enhanced. There are other options for oxygen and nitrogen storage. Cryogenic storage, either subcritical or supercritical, can reduce storage mass under certain mission profiles, but bring added complexity of temperature control and minimum boil-off constraints. A Mars base, and possibly a lunar base, could take advantage of "shadows" to make cryogenic storage more favorable but then there would be restrictions to the system's flexibility. If a location can be identified that is permanently protected from the sun's rays and exposed to space, it could naturally keep oxygen and nitrogen at cryogenic temperatures for the mission duration with lighter tankage and minimal insulation. This would place limitations on base locations and make refill from pressurized tanks in the transport vehicles and as a source for the base suits and rovers more difficult.

Orion has baselined pressurized gas storage with separate nitrogen and oxygen systems. The pure oxygen is used to replenish the metabolically consumed gas in the cabin as well as provide flight suit and medical oxygen if needed. Since there is no oxygen generation capability on the Orion, this function is provided by the ASC. Nitrogen is used, in conjunction with the stored oxygen, to repressurize the cabin air either to make up for external leakage or to raise the cabin after a depressurization event. Having pure nitrogen also provides a fire suppressant for unoccupied pressurized volume, but it is not used in habitable areas as the potential of crew suffocation is too much of a concern.

COTS hardware could be used for these systems if appropriate components are located. There is a stronger likelihood that previously developed shutoff valves, sensors and pressure regulators could be used. Since most of these components can work over a wide range of gas flow rates, there may not be any advantage to modularity. The same components can used over a range of subsystem crew size with only different tank sizes (or number of tanks) determining the number of crew it could service and the life of the consumables.

The comparison showed that pressurized gas storage is still superior to cryogenic or chemical storage for these long missions. Thus the recommended approach is similar to existing systems with an evolutionary optimization of using a mixed gas instead of pure nitrogen. High pressure storage is still preferred over cryogenic or chemical storage. The high pressure oxygen tanks can be recharged by the oxygen generation subsystem. The high pressure oxygen generation system needs development, but it should not significantly affect the design of the storage tanks. The TRL for high pressure gas storage and atmospheric composition control is high. There is no substantial difference in technology in going with a mixed gas instead of pure nitrogen, so that the TRL remains at 9. Improvement in tank materials that have been made with composites will be considered to save weight on future missions, but no specific technology development has been identified for manned spacecraft.

B. Temperature, Humidity Control & Air Circulation

A condensing HX (CHX), with or without a non-condensing cabin air cooling HX, with a bellows tank for the collection of condensate is a proven approach for cabin air temperature and humidity control. Using a CHX allows recovery of the cabin humidity for use as potable water which is needed for these long duration missions. Temperature/humidity control is normally provided by coolant temperature control or bypass. The issues have been the generation of particles that contaminate downstream components such as valves and water separators. The system issue is that the condensing HX requires a low temperature coolant supply that can impose a vehicle mass penalty, especially if the CHX is the only component that requires this utility. Even with this potential penalty, the condensing heat exchanger approach still offers overall advantages. It allows the dehumidification of the cabin air with recovery of the condensate for purification in the water processor and reuse by the crew. The condensing heat exchanger also removes water soluble trace contaminants in the air, such as ammonia, for removal in the water processor.

Fans will be used to provide the airflow needed for temperature and humidity control as well as provide the cabin ventilation needed to distribute the clean air and provide air velocity for crew comfort. There are many flight-proven fans employed on the ISS including the IMV, AAA and Cabin fans. All use 120 Vdc motors with either fixed or variable speed designs. Other fans are being developed for the Orion and commercial vehicles that will also be considered. The THC traditionally provides the air particulate control function. HEPA filters, sometimes used in conjunction with coarser filters, provide this function. HEPA filter can remove the airborne particles generated by the crew and equipment in the cabin and control airborne microbe levels to help maintain crew health.

Lunar or Mars dust control will have to be considered for this subsystem as entrained particles would make the operation of the THC more difficult. The assumption for this paper is that the majority of dust control will be handled by the airlock function with only a small filtration penalty imposed on the ECLSS. A combination of HEPA and courser air filters will be used to remove crew and cabin equipment generated particulate loads and to remove any lunar or Mars dust that avoids control in the airlock, but relying on the bulk of the dust removal in the THC is not practical for the base design. The dust can permanently damage many base systems and once it contaminates something, it is very difficult to remove. Therefore, relying on the THC to be the prime controller of environmental dust is not realistic. It must be prevented from entering the base and not just removed once introduced.

Orion uses a solid amine pressure swing device that removes the cabin CO_2 and water vapor and dumps it overboard. Since the active mission phase of the Orion is so short, recovering the water vapor or the CO_2 does not trade well against the additional hardware required. However, this does not apply for the longer crew missions of the subject bases and platforms, where recovery of the condensate for reuse by the crew trades very favorably. Orion uses two THC loops. One is a low flow, high pressure drop loop that provides the air flow for the CO_2 and humidity control, air monitoring and trace contaminant control. A second loop provides a high flow rate for air temperature and particulate control. This high flow loop has the vehicle's HEPA filter to provide at least 20 cfm of filtered air flow rate per crewmember. It has redundant high flow, low pressure drop fans. A third fan is used to provide ventilation of the cabin post landing. The electrical power system on Orion is 120 Vdc. All three fan designs will be assessed for applicability to the future platform applications.

The use of COTS parts will have to be considered for the commode. The separation of condensate from the air in micro-gravity is typically done by the use of a rotary separator. These designs use a motorized, rotating drum to centrifugally separate the liquid from the air with a fixed pitot that collects the liquid and pumps to the storage tank. The lunar and Mars base designs could take advantage of gravity to eliminate the complexity of a rotating separator making more earth-like gravity assist approaches more feasible. The pumping function to transport the condensate to a pressured tank would have to be handled by a small pump as there is not expected to be enough of a height within a base to take advantage of gravity feed, but it would trade favorably against a separator. The storage tanks could also take advantage of gravity to eliminate the need for a bellows tank. Even though many common ground water tanks use bellows or diaphragms to separate the water from the pressurant to prevent loss of pressurant in the water, active pressure control of the water storage tank by the mixed oxygen/nitrogen gas would maintain pressure and degassing in the cabin of this small amount of gas would help make up for leakage and metabolic oxygen consumption. The transport vehicles would still need a rotary separator and bellows or diaphragm tanks. Once on the surface, the gravity assisted separators could be used.

COTS fans will also be evaluated for use. There are many high quality fans that have been developed that could be modified to meet EEE part requirements or qualified as is. First, the power bus voltage for the three applications will have to be selected. ISS and Orion use 120 Vdc. Having a d.c. power supply to the fans greatly limits the availability of COTS fans that could be used as is. Most commercial fans use a.c. or different d.c. voltage levels. In addition, most commercial d.c. fans are not fixed speed. Their speed varies with pressure drop and supply voltage. This causes them to normally operate at higher flow rates than needed to insure that they meet the minimum requirements at worst case conditions. This causes an increased power draw over the life of the mission. There are spaceflight quality fans being developed for commercial vehicles that could bridge this gap between the conventional spaceflight man-rated fans and the true COTS ones.

The technology improvement needed is in the hydrophilic and anti-microbial coating within the condensing heat exchanger. Making it more durable will improve its life and prevent contamination of downstream components. This effort incorporates advances in coating technologies as well as lessons learned from previous ISS and shuttle experience. Coating technology is currently being advanced by UTAS, but knowing that a different formulation is expected to be used on these future manned missions, it is still at a TRL 7. Fan TRL, in general, is high. If the platforms use 120 Vdc power, then there are several motor and motor controller designs that are flight proven.

Other supply voltages would have to be assessed to see if comparable ones are being developed for commercial vehicles.

C. Fire Detection and Suppression

Fire Detection and Suppression (FDS) systems on human-rated space vehicles start out with the concept that materials are tested and chosen to be non- and/or self-extinguishing to start with, making FDS a complete back-up that should never have to be used. Because the idea of a fire in a space vehicle is so daunting and the crew has no escape, vehicles are outfitted with detection and suppression systems anyway.

ISS smoke detectors utilize LASER Diode technology. An initial concern with this technology was possible high frequency of false alarms due to device sensitivity, or lack of alerting the crew because it was not sensitive enough to be effective. While these systems have worked out very well, the state of the art of electronics at the time resulted in relatively large units (about the size of a lunch pail with the thermos sticking out one side.) Copies of these devices would work well anywhere, however smaller would be better.

ISS employs carbon dioxide and fine water mist (under development)[5] extinguishers for fire suppression. Halon systems have been deemed incompatible with crews that cannot vacate the vehicle within a short time, so many COTS devices are removed from the trade space. Fire suppression in surface habitats could take advantage of gravity to employ chemical-based systems with particulates that can be cleaned up after the event.

Orion plans to utilize particle detectors and IR cameras. These will no doubt be the latest SOA devices and will be flight certified under the Orion program.

Orion plans to use the same fine water mist extinguishers planned for deployment to ISS.

COTS smoke detectors (such as home units that run on 9V batteries or existing aircraft units) might be a good fit, particularly for partial gravity environments like Lunar and Mars Habitats where they can be ceiling mounted like in one's home on earth. They would be inexpensive if useable in their unaltered state. New wireless devices are coming onto the market that allow for easy integration into a home (or in this case space habitat).

Given the above considerations, we conclude that COTS devices have come of age and warrant testing on ISS as a prelude to taking out of earth orbit.

D. Waste Management (WM)

The waste management system starts with the commode and includes how the human waste is treated, stored and pre-processed. As with most of the ECLSS technologies, no revolutionary approach is needed as the current ISS and shuttle designs are close to optimal for these long duration missions. Urine will be collected using an air stream. It will be separated from the air and pretreated before joining other waste waters in the water processor. The approach to collecting urine has evolved from the early days of human spaceflight to current development units. The human interface can still be improved, but the basic approach has years of use on the ISS. As with the THC, lunar and Mars bases could take advantage of gravity to help collect the urine and feces, separate the urine from the air and store the waste. This would mean using a different design from the micro-gravity versions being developed today or modifying the design to have micro-gravity and low gravity assisted modes of operation.

The urine pretreat will depend upon the water processing approach and the duration of its storage. For all three missions, some of the urine will need to be stored for long periods of time. Even though most of the urine will be processed in a relatively short amount of time, there will be residual urine in the urine storage tanks and transport lines that will probably not be thoroughly cleaned during the life of the system. This puts a larger demand on the urine pretreat to stabilize the urine so that it doesn't negatively affect the life of the components.

Solid waste management will have to incorporate the advantages of the previous designs into a lower weight device. The Russian ISS, the shuttle orbiter and the extended duration orbiter commodes have been tested and assessed by many crew members. The human interface, ease of use, and on-orbit and ground processing and cleaning have been studied and improvements recommended. Crew members have generally preferred the Russian seat over the other designs and their restraint approach is also preferred. The EDO use of canisters with individual bags and lids is preferred for storage of the collected solid waste. It provides clean handling of the waste product and a secure method of storage with odor control. Long term stability of the stored waste should be assessed to verify that it will be effective over the life of these long space missions. The baseline approach is to store the vented canisters in the cabin atmosphere with charcoal filters used to control odors. This venting should eventually dry out the stored waste helping to stabilize it for longer term storage needs. This approach compare favorably to alternate methods of storing and stabilizing the solid waste such as active dehydration, due to the loss of water, or sealed storage which would have to handle the unavoidable pressure build up due to outgassing. All these features are being incorporated into the Universal Waste Management System (UWMS) being developed by NASA and UTAS.[6]

This selected option is the result of evolutionary improvements over previous designs that maintain relatively high TRL levels over an unproven overall approach.

Water and food could be used to protect the crew from deep space radiation as water is an effective barrier to the radiation that is dangerous to human beings. Carrying additional quantities of water and wet food, beyond what is needed for a closed loop system, to replace other shielding materials and protect crew would significantly change the ECLSS trade space. This paper assumes that other methods will be used to protect the crew and ECLSS will not be required to carry extra water or use waste products to provide this function.

Orion had baselined a new commode that uses a single fan to provide the air flow for the urine collection, solid waste collection and the wet trash. It uses a rotary separator to remove the urine from the entrained air stream and pump it into a storage tank. It uses the ISS "string of pearls" urine pretreat approach. The urine is stored in a bellows tank until emptied on the ground. Solid waste is stored in canisters. It is manually compacted to save storage volume. This design may be replaced with the Universal Waste Management (UWMS) described below[7].

The UWMS is recommended over the Russian ISS, the Shuttle or the extended duration orbiter commodes as it takes the best features, astronaut feedback and lessons learned of each design and creates a better functioning and lighter weight option. Although currently at TRL 3, there is currently development in work to advance this design. Urine pretreat will also have to be developed to integrate with the selected urine/water processor technology. There are development activities in progress and others being considered by NASA. In 2013, UTAS built and delivered a prototype version of the UWMS to NASA for evaluation and ground testing. In 2014, the key technology development component, the dual fan separator, is being developed by UTAS. This device combines the commode fan, the urine collection fan and the urine/air separator into one device to reduce cost and power and simplify the commode operation. NASA is also considering a flight experiment version for assessment on the ISS, advancing the selected UWMS to TRL 9.

E. Atmosphere Revitalization (AR)

AR is a complex but important branch of ECLS. Not really having much in the way of terrestrial commercial applications to draw on, and historically being big, heavy and power hungry systems, these must be carefully considered as we move forward.

1. Carbon Dioxide Removal

ISS Carbon dioxide removal has been with use of a regenerative 4-Bed molecular sieve (USOS CDRA), and backup disposable LiOH canisters for short term emergency repairs. Regenerative Silver Metal Oxide (METOX) and LiOH systems are used on EMUs and recently a development test solid amine swing-bed system for Orion has been demonstrated on ISS.

All systems to-date have had some success, but the primary system (CDRA) continues to have reliability issues. Additionally, the requirements for crew CO_2 exposure limits is expected to change from 5.3 mm Hg 24-hr time average to approximately 1-2 mm Hg 24-hr time average, a significant challenge for the current technology, and a requirement expected to be levied on exploration crew systems.[8] Developing more reliable systems along with lower exposure levels is paramount to successfully supporting crews in deep space habitats. There are no known COTS CO_2 removal devices available to review.

Orion carbon dioxide removal is the above mentioned solid amine system. It has a dual role to also control cabin humidity, and does this by virtue of the solid amine absorbent material, which takes both CO_2 and humidity out of the cabin air in the same pass and vents it overboard (known as CAMRAS or CO_2 And Moisture Removal Assembly) Current Orion ppCO_2 requirements are 4 mm Hg 24 hr time averaged exposure, but as stated this will likely change, driving the Orion program to re-evaluate its choice system.[9]

Given the above considerations, and the need to reclaim as much water as possible to minimize logistic resupply, we conclude that both the ISS CDRA and the Orion CAMRAS systems need to be considered. While there are potentially new Zeolite materials to improve CO_2 removal performance for CDRA, CAMRAS could be outfitted with water-save feature that makes it competitive with CDRA and the device with the lowest mass and highest capacity at the lowest CO_2 partial pressure is the device to take with you.

2. Carbon Dioxide Reduction

ISS Carbon dioxide reduction has been achieved with the delivery of the Sabatier reactor. It takes the carbon dioxide from CDRA and the hydrogen from OGA and makes water and methane (~ 50% water recovery). Integration challenges currently hamper water production efforts.

Orion has no plans for carbon dioxide reduction due to the short duration mission requirements (21 days x 4 crew). Sufficient water can be carried from launch to provide the crew needs and the carbon dioxide is vented overboard.

There are no known COTS CO_2 reduction devices available to review.

Given the above considerations and that no other CO_2 reduction technologies have been tested in space, and the need to reclaim as much water as possible to minimize logistic resupply, we conclude that the ISS Sabatier system is the only candidate and therefore efforts to improve its integration with either CDRA or CAMRAS systems be considered along with efforts to reduce weight and volume.

3. Trace Contaminant Control

Short term transit vehicles (including the Shuttle Orbiter) historically have relied on charcoal beds that can be replaced between flights. The ISS uses a very large charcoal canister for high molecular weight contaminants and a high temperature catalytic oxidizer for low molecular weight trace contaminants. The Charcoal bed is huge and is replaced every 5 years. The RS uses much smaller charcoal canisters that are regenerable.

Orion plans to use a smaller but non-regenerative charcoal bed and an ambient temperature catalytic oxidizer.

There are myriad COTS charcoal beds for use in everything from cars to homes, but very little in the way of complete systems as on earth it is far easier to ventilate and exchange air with the outside world than scrub trace contaminants out of a facility.

Given the above considerations, and the need to minimize logistic resupply, we conclude that a combination of system features be combined for deep space use. An ISS system with a much smaller & regenerative charcoal bed seems like the optimum choice, but it must be developed.

4. Major Constituent Monitoring

Short term transit vehicles (including the Shuttle Orbiter) historically have used chemical oxygen and CO_2 sensors that would be changed out between flights.

ISS, with a much longer operating life requirement and devices expected to generate hydrogen and methane, went to mass spectrometer technology, known as the MCA (Major Constituent Analyzer) which allowed for direct nitrogen measurement as well. This feature has come in handy for spotting leaks in the ISS vehicle as total pressure, CO_2, oxygen and humidity partial pressure are too dynamic to use for trending for leaks. Also, over time it has been found that high accuracy, particularly with respect to oxygen and carbon dioxide monitoring is essential for atmosphere constituent control operations.

Orion plans a next-gen mass spectrometer based on the ISS MCA, known as MPAM (Multi-Platform Air Monitor. While not sampling all the MCA constituents, the weight power and volume are expected to be significantly less than the MCA is today, making it very attractive for exploration.

COTS devices used to be limited to Draeger tubes and the like, but now similar to FDS equipment, they are coming of age and rate serious consideration. For the cost of shipping normal space flight hardware from one place to another one could purchase a lightweight, portable complete GC-QMS device. Unfortunately these COTS devices typically do not monitor for major atmospheric constituents and would have to be modified. Another challenge will be integrating one into the vehicle or habitat in a way that allows remote monitoring and/or automated computer responses to detected problems, something MCA and MPAM already do.

Given the above considerations we conclude that the MPAM is the optimum choice for exploration and anticipate its development for Orion.

5. Trace Gas Monitoring

Short term transit vehicles do not typically monitor trace gasses because they do not have time to build up during flight. Trace gas monitoring will become very important as we leave low earth orbit because mission durations will necessitate monitoring for crew health and the ability to return atmospheric grab samples will become non-existent.

ISS uses grab sample bottles returned to earth for analysis. There have been one or two near-real time monitor DTOs on ISS, but as of this writing there is no ECLS system trace gas monitor on-board.

Orion has no need for trace gas monitoring due to the short mission timelines (21 days). Reliance on the charcoal bed and ATCO system is sufficient.

F. Water Recovery & Management (WRM)

WRM is another complex but important branch of ECLS. While Mir was the first space station to employ technology for this purpose, ISS has gone much farther and is the integrated systems champion today.

ISS hardware can be generally characterized as big, heavy and power hungry systems. However, water recovery is hugely important for deep space due to the logistics savings and these systems must be carefully considered as we move forward.

ISS has the only water processing systems used to date, the USOS WPA & RS SRVK. The USOS version is a multi-filtration bed system with a high temperature catalytic reactor. It is effective but very large and heavy to consider for exploration.[10]

Orion has no need for water processing due to the short mission timelines (21 days). Tanks of fresh water are filled pre-launch and humidity condensate is vented overboard with the carbon dioxide.

COTS analogs abound on earth (i.e. city potable water and sewage systems), however they don't readily adapt to microgravity, flight weight space vehicle hardware. The technologies are similar and are where the ISS systems were derived from originally.

Given the above considerations we conclude that the ISS based water processor must be evolutionarily improved to meet the weight, volume and reliability needs of deep space.

G. Urine Processing

ISS has the only urine processor flown to date is the ISS UPA. Due to the challenges of microgravity distillation it is necessarily a rotary distillation unit. It is effective but very large and heavy to consider for exploration.

Orion has no need for urine processing due to the short mission timelines (21 days).Tanks of fresh water are filled pre-launch and provide for crew needs while collected urine is vented overboard.

COTS distillation devices are surprisingly simple and effective when gravity can be utilized. Given gravity fields exist on the moon and Mars these terrestrial devices bear a close look.

Given the above considerations we conclude that to meet the weight, volume and reliability needs of deep space surface habitats COTS distillation systems should be applied, however they will not work for an EML-2 facility. For that tanked re-supply of potable water should be considered as the UPA is too big and heavy and would not be expected to scale well to smaller crews.

V. Conclusions and Recommendations

ECLS systems for spaceflight have always pushed the boundaries of technology and required the corresponding high investment costs. Additional investments for human space exploration are needed as current ECLS systems are not ready to meet the requirements of human travel to the moon and beyond. To minimize the cost of ECLS development, careful and efficient technology investment choices are needed within a defined framework of mission destinations to create a technology roadmap. This roadmap will help assure that ECLS technologies support multiple destinations and will minimize the overall number of required technologies and systems.

While ECLS technology for spaceflight has shown a trend toward system loop closure and loop closure does offer significant mass savings by reducing consumables, system cost increases rapidly with degree of system loop closure. This implies that full ECLS loop closure is not the most cost efficient option for near-term exploration missions. We conclude that a moderate degree of ECLS system loop closure, similar to the ISS today, is most desirable when balancing among consumables mass penalties, system complexity and total system cost. We also note the diminishing return of ECLS system loop closure when compared to the potential need to carry additional water as radiation shielding.

Two important factors were considered for this evaluation but ultimately not included in selections: dissimilar redundancy and scalability versus modularity. Dissimilar redundancy provides additional mission assurance by avoiding common failure modes but adds additional cost, mass and complexity. However, determination of dissimilar redundancy requirements will involve policy setting beyond ECLSS and are outside the boundaries of the technological review context of this study. We also considered scalability versus modularity. While there are obviously valuable comparisons to be made in scalability versus modularity, we determined that these trades are best made after basic technology selection rather than before due to the quite different design implications of the various technologies.

Mission architecture and destinations are important in determining technologies in which to invest and when. However, the technologies indicated by this study are broadly applicable to most missions being evaluated. As long as technology development is started in a timely manner, the top technology targets can be flexibly matured in a capability-driven framework throughout the architecture, while also providing benefit to ISS and commercial spaceflight. The earlier these technologies are matured, the greater the flexibility in the overall architecture.

While the ECLS technologies in use today on ISS are more mature, alternate technologies could have distinct advantages in reduced power, reduced mass, less complexity and greater reliability. For most of the selected ECLSS technologies, the change from the ISS/shuttle systems is evolutionary and not revolutionary. This will allow the vehicle to take advantage of the reliability born from years of operation including improvements made to the original designs with relatively small changes to reduce weight and improve its operating life. What is learned from the emphasis of COTS parts on the commercial space ventures will be applied to these long duration missions where prudent. Several COTS systems were found to warrant consideration.

The recommended technologies are ISS-baseline with the exception of the following:

- ACS Storage Form - Mixed Gas & Separate O2
- ACS Oxygen Generation - PEM (high DP)
- FDS – COTS
- WM Collection – Rotary Canister/UWMS
- WM Storage & Processing – Urine Pretreat, Passive Store with Filter Carbon
- ARS Carbon Dioxide Removal - CDRA/CAMRAS
- TCCS - Low Volatile Contaminants - Regenerable Packed Bed
- TCCS - Volatile Contaminants - Enhanced Catalyst HTCO
- WRM Water Processing - COTS Distillation (surface only), Multi-filtration Bed, High Temperature Catalytic Reactor

Most of these technology selections are evolved from currently operating ECLS systems rather than completely new technology development. This takes advantage of the known characteristics and operations data while improving making improvements to mass, cost and reliability.

The authors believe near-term investments in ECLS technology should focus on enabling as many destinations as possible while remaining within fiscal constraints, as investments in ECLS technologies can be leveraged to enable a variety of mission types. This implies the development of a logical mission architecture that includes lunar orbit and surface proving grounds and a corresponding technology roadmap to inform the technological investment decisions to get to Mars. These decisions must be assessed against affordability targets and will benefit from the inclusion of COTS hardware and already developed technologies to the maximum extent possible. ECLS systems are a basic requirement for all human spaceflight regardless of future destinations. Given the very different requirements of operations in the potential destinations, careful choices in ECLS technology development are necessary to provide ECLS systems that can support the mission requirements while remaining within fiscal constraints.

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