

Exploring Life Support Architectures for Evolution of Deep Space Human Exploration

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Life support system architectures for long-duration space missions are often explored analytically in the human spaceflight community to find optimum solutions for mass, performance, and reliability. But in reality, many other constraints can guide the design when the life support system is examined within the context of an overall vehicle, as well as specific programmatic goals and needs. Between the end of the Constellation Program and the development of the “Evolvable Mars Campaign,” NASA explored a broad range of mission possibilities. Most of these missions will never be implemented, but the lessons learned during these concept development phases may color and guide future analytical studies and eventual life support system architectures. This paper discusses several iterations of design studies from the life support system perspective to examine which requirements and assumptions, programmatic needs, or interfaces drive design. When doing early concept studies, many assumptions have to be made about technology and operations. Data can be pulled from a variety of sources depending on the study needs, including parametric models, historical data, new technologies, and even predictive analysis. In the end, assumptions must be made in the face of uncertainty. Some of these may introduce more risk as to whether the solution for the conceptual design study will still work when designs mature and data become available.

Nomenclature

<i>CCAA</i>	=	Common Cabin Air Assembly
<i>CDRA</i>	=	Carbon Dioxide Removal Assembly
<i>CM</i>	=	crewmember
<i>CO₂</i>	=	carbon dioxide
<i>CRA</i>	=	Carbon Dioxide Radiation Assembly
<i>ECLS</i>	=	Environmental Control and Life Support
<i>ECLSS</i>	=	Environmental Control and Life Support System
<i>EVA</i>	=	extravehicular activity
<i>H₂</i>	=	hydrogen
<i>H₂O</i>	=	water
<i>IMV</i>	=	intermodule ventilation
<i>INCOSE</i>	=	International Council on Systems Engineering
<i>ISS</i>	=	International Space Station
<i>kg</i>	=	kilogram
<i>LEO</i>	=	low Earth orbit
<i>MPCV</i>	=	Multipurpose Crew Vehicle
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>OGA</i>	=	Oxygen Generation Assembly
<i>O₂</i>	=	oxygen
<i>PLSS</i>	=	Portable Life Support System
<i>SOA</i>	=	state-of-the-art
<i>UPA</i>	=	Urine Processor Assembly
<i>WPA</i>	=	Water Processor Assembly

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I. Introduction

OVER the past several years, the National Aeronautics and Space Administration (NASA) has performed many paper studies to evaluate mission concepts for human exploration beyond Earth orbit. Most of these studies are never published, often because some aspect of the mission or architecture is demonstrated to be impossible within current constraints, or it doesn't meet the goals of the effort. Although everyone would like to be part of planning the next mission that will actually fly, quietly figuring out what isn't going to work before making major announcements or investments is an important part of the planning process. These investments are probably better designated as part of the Exploratory Research Stage of International Council on Systems Engineering (INCOSE) project processes, as opposed to true Concept Stage studies.¹ Some studies have found concepts that close within reasonable mass, cost, and schedule, and these concepts can be submitted to influence policy and program development. They are a demonstration of feasibility, but are not necessarily assumed to be the reference concept if NASA does decide to pursue the mission, at least with further concept development.

As subsystem experts, participants can still discover important trends or drivers. Technology development investment may be needed if a subsystem is continuously preventing the mission from closing on mass, power, or some other performance parameter. Subsystem developers may discover, over a course of several studies, that the mission parameters being evaluated do not appear to dramatically change their system, thereby speeding up future analysis. Discovering that the system is similar across a broad mission design space adds confidence to technology development investment plans in the face of uncertain future program decisions.

II. Life Support Systems in Human Exploration Mission Architectures

Developers of human spaceflight systems understand that financially affordable, lightweight, easy to launch, quickly developed, easily operable, and highly reliable are very desirable. Systems that met that description would enable more frequent missions and have a greater impact on scientific discovery. However, these qualities never seem to be simultaneously optimized in a single system. The traditional project management triangle is made of elements of technical performance, cost, and schedule. Technical elements have to be traded off against each other, such as losing performance to save mass. When a design choice can't be explained by a technical point of view, it is usually because it has been constrained by one of the other two elements to make the overall mission or program feasible.

Participating in these studies to design or optimize a mission as a contributing life support system expert is inherently different from trying to design an optimal life support system. Certain aspects of a life support system (or any other subsystem) are essentially transparent at the vehicle level. Functions must be identified so that the capabilities of the vehicle and mission can be documented, but specific technologies may be interchangeable for performing that function. For example, the choice between an amine-based technology² or zeolite based technology³ for removing carbon dioxide (CO₂) and humidity and venting them overboard has serious repercussions in a detailed life support design. The pressure drop may drive fan performance, the sensitivity to or generation of a trace gas would drive selection of trace contaminant control sorbents, and sensitivity to vacuum quality will drive location and packaging in the vehicle and vacuum vent line dimensions. For an initial vehicle study, however, all that matters is that there is an open-loop technology to control CO₂ and humidity, and approximately what mass, volume, and power should be assumed to operate it. Recommendations for mass growth allowances in these systems are usually on the order of 20% to 30% at the early stage of design.^{4,5} Small variations in subsystem mass do not have a significant impact in determining whether the overall mission is feasible. The goal of the study is to determine whether the entire mission concept is feasible, so the mass of state-of-the-art systems can be used as an upper bound for life support system mass.

One strategy that has been explored is often referred to as "Designing to Cost." In the federal budget environment, it is typically an annual cost that has to be observed, rather than optimizing life cycle cost. This is sometimes referred to as "Pay as You Go." Several types of design may emerge when a life support system is being designed under these constraints. Existing component designs are usually reused if the goal is to fit in near-term cost limits, even if new technologies in development could be lighter or more efficient. The life support system designers may be directed explicitly to try to duplicate existing designs or avoid using new components. The reuse may be in other systems, such as structures. NASA has evaluated several concepts for reusing designs from International Space Station (ISS) pressure vessels (include the permanent modules, nodes, and logistics modules). Volume may become a constraint in those cases. A mission study based on "Design to Schedule" to enable near-term access to a location ends up with similar reuse of existing technology.

Other studies have been designed to look at sensitivity to launch vehicle performance, which is essentially a "Design to Mass" constraint. The life support system may need to be broken into subgroups, or spread across multiple modules launched separately. Although each unit is small, this often drives duplication of items (e.g., ventilation fans).

NASA has a vehicle suitable for short-duration missions already in development—the Orion capsule. These future missions are still trying to accomplish longer-duration missions. They may be trying to have greater capabilities to study an asteroid or demonstrate in-situ resource utilization of an asteroid, or do research on the effects of the space radiation environment beyond low Earth orbit (LEO). Thus, even if the launches are small each time, the vehicle is intended to accumulate a significant number of crew-occupied days during its life, and certainly qualify overall as a long-duration mission according to the conventions that life support system designers have been using to organize technology development efforts.⁶ But if the mass constraint of each launch is small enough, there may not be mass or volume for critical components of the spacecraft bus and the life support system that would have the optimal system closure for the duration and planned exploration activities.⁷ The system needs to be set up in a way such that it is functionally able to sustain human life with very limited mass from the very beginning, but be upgradeable over time to the more sustainable closed-loop design. These concepts often make use of the components of the Orion life support system that are functionally open-loop (not recycling wastes to resources) but are regenerable equipment (reusable and not life limited). The new vehicle would supply of additional consumables to extend the duration of the mission beyond what Orion could support alone. But since the Orion system vents humidity, CO₂, and urine, the closed-loop components have to include alternate technology to remove wastes and new technologies to recycle them. Thus, the break-even time to justify the closed-loop system is not based on the total crew time in the vehicle, but only how much is left after the entire system can be delivered and integrated.

Another type of study conducted is frequently referred to as a “Spartan Mission.” While these mission concepts never have actual program requirements documents, they do have lists of assumptions and try to maintain NASA standards. But when a mission concept doesn’t close, systems engineers try to identify requirements that can be deleted to fit within constraints. Life support system and habitat requirements are designed not just to prevent the crew from dying, but to keep them healthy enough to perform duties during the mission. The typical goal of a “Spartan Study” is to find out whether these requirements are really driving cost and mission performance, or define how small the system could be if they were removed. Another similar question asked for short-duration vehicles is simply “Why isn’t this system as light as Apollo?” Modern requirements have evolved dramatically from the Apollo era, as experience and research have provided more and more knowledge about space medicine and human performance during longer-duration spaceflight missions. New systems cannot simply reuse old designs and meet current requirements.⁸

III. A Waypoint Beyond Low Earth Orbit

One type of mission examined was called a “Waypoint,” which was both a physical and metaphorical reference. NASA’s primary goal for near-term human exploration missions is to prove technologies and demonstrate readiness for missions to Mars. Earth-moon libration points were identified as a stable point where research and technology demonstration could be performed. The points also provide stable locations in relationship to the Earth’s moon, which is important to NASA’s international partners who are interested in lunar exploration.⁹ Initial concepts were based on reusing the design of an ISS node, with logistics resupply missions, and eventually delivery of an “Augmentation Module.” The Augmentation Module systems were based on the ISS state-of-the-art (SOA) functions (commonly referred to as “ISS Regen Environmental Control and Life Support System (ECLSS)”). Individual crew visits would be short (30-60 days), but they would be repeated over many years, and grow in duration to 180 days when the augmentation module was delivered. An example overall architecture is shown in Figure 1.

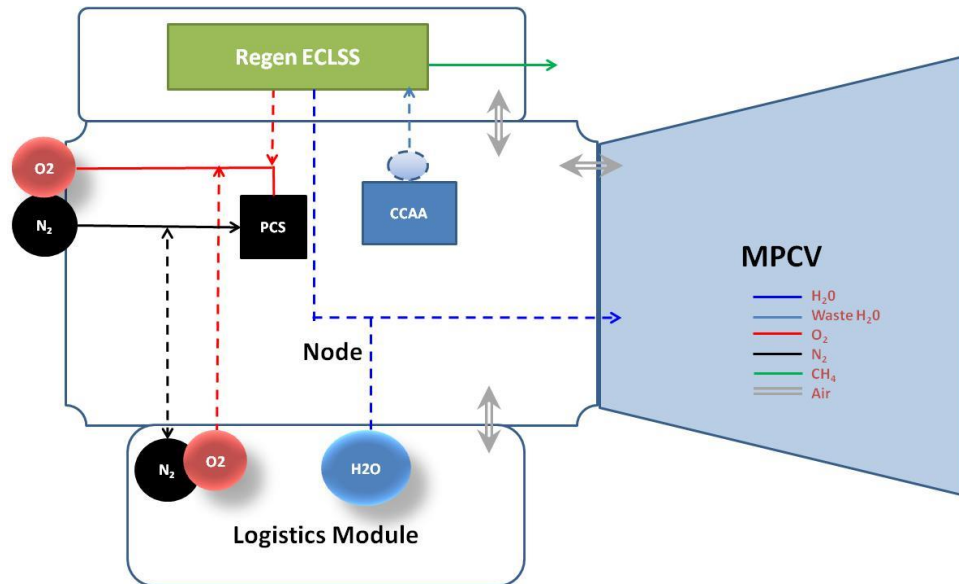


Figure 1. Functional allocation of life support systems and fluid flows for a Waypoint vehicle. (Dotted lines imply drag-through ducts or other temporary lines deployed when vehicles are docked.) Common Cabin Air Exchanger (CCAA) includes a fan and condensing heat exchanger. The Pressure Control System (PCS) includes computer controlled valves.

In the initial missions, almost all of the life support systems in the Orion Multipurpose Crew Vehicle (MPCV) would remain operational, but the node module has to provide supplemental capability for several. The Orion service module tanks are not designed to have enough gas or water for the extended mission, thus they are provided by a logistics module. The logistics module would also deliver crew items such as more food, additional fecal collection canisters, and other crew use items. The node also required a pressure control system for maintaining pressure during dormant phases. Spacecraft hatches generally use positive pressure to help provide sealing. If the node pressure were allowed to drop, and the MPCV had to repressurize it by filling the vestibule between the two docked vehicles, there was a possibility that negative pressure could be applied to the node hatch and damage it. Thus, the logistics module was assumed to provide gas to a pressure control system in the node. Redesign of Orion would be required to repressurize its gas storage tanks during a mission. The Orion amine swing bed system removes CO₂ and humidity and vents it to space with small air ullage losses.² The crew is expected to exercise for 30 minutes per person, per day for Orion missions.⁹ The humidity generated from exercise was the sizing case for the amine swing bed system. For longer missions, though, longer exercise periods are expected. The node had to have a condensing heat exchanger to supplement the humidity removal capability of Orion. The reference for the component was the ISS Common Cabin Air Assembly (CCAA). To prepare for integration with the augmentation module systems, the water collected from the heat exchanger could be collected and stored for processing. The Orion air revitalization system includes trace contaminant control based on adsorbents and low-temperature catalytic oxidation of carbon monoxide. In longer missions, the adsorbent capacity could be exceeded and the node system would supply additional capacity. Also, some organics that do not pose health hazards during short missions could accumulate. Since most of the functions are performed in Orion, intermodule ventilation (IMV) between modules is required. The Orion vehicle design does not include an IMV fan. Multiple modules or vehicles that could dock to the node were also being considered. Other studies also examined the possibility that a reusable lander could move between the Waypoint station and the lunar surface. In this case, additional filtration would be needed to help manage the inevitable migration of lunar dust. All IMV functionality was placed on the node to provide commonality in docking hatch design, avoid modifying the Orion design, and minimize the mass of a lunar ascent vehicle, as shown in Figure 2.

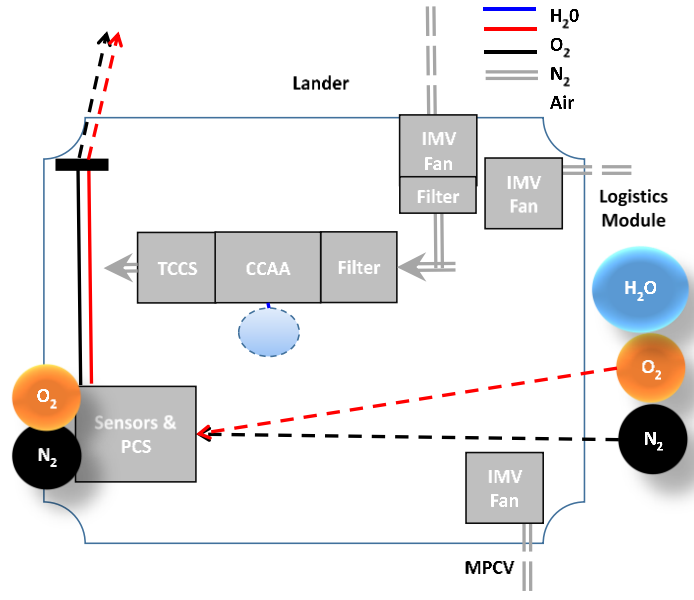


Figure 2. Functional breakdown of life support within the central node of a Waypoint station concept. Intermodule ventilation (IMV) fans provide less airflow than the CCAA fan. The Trace Contaminant Control System (TCCS) contains adsorbents like charcoal and an ambient temperature catalytic reactor.

When the augmentation module systems were proposed, the option of having an additional condensing heat exchanger was included to pick up sensible heat load from new systems, and simplify integration with a water processor.

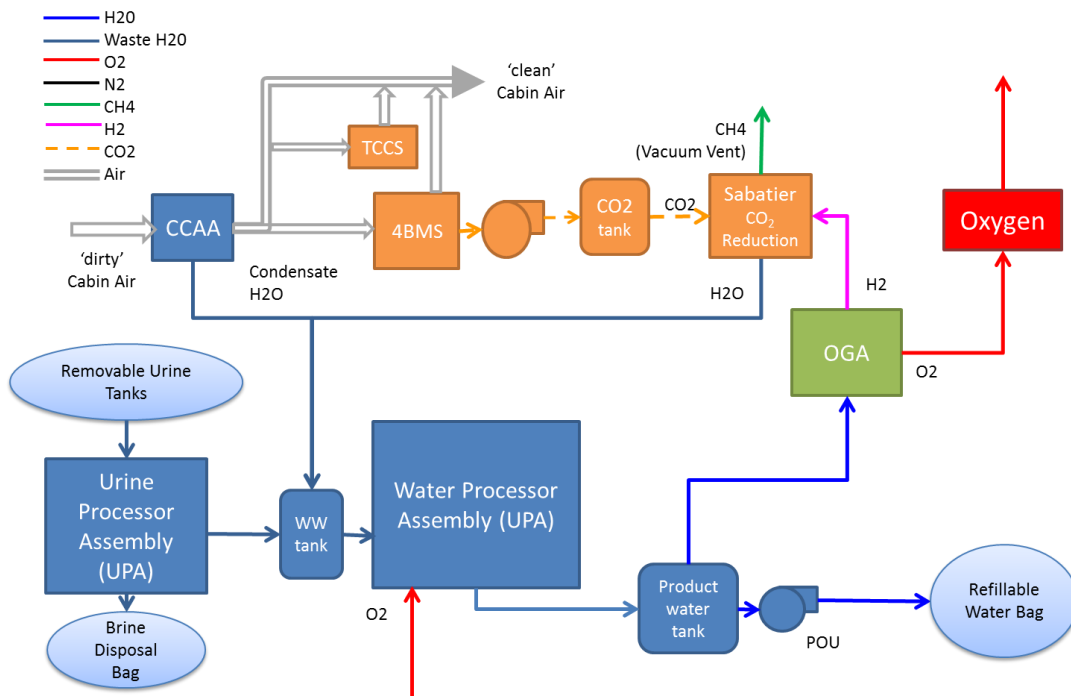


Figure 3. Simplified schematic for a partially closed-loop life support system augmentation module based on ISS systems state of the art. Four Bed Molecular Sieve (4BMS) generically describes the type of technology used in the ISS Carbon Dioxide Removal Assembly (CDRA). The Oxygen Generation Assembly (OGA) is a water electrolysis technology.

A. Functional Architecture Studies for State-of-the-Art Systems

For long missions, stand-alone analysis of life support systems show that consumables and overall levels of system closure drive mass⁷. For missions with minimal extravehicular activity (EVA), a level of system closure similar to the ISS SOA is sufficient, and thus a system functionally similar to the ISS ECLSS was proposed. Adding additional functionality was not part of the design exercise in discussions where cost or schedule dominated concerns. Including all of the state-of-the-art systems in the Augmentation Module resulted in a large total mass. To help the overall design close, the vehicle system engineers wanted to probe whether a different set of components would be a better solution, and asked for more detailed analysis.

The first critical element to be analyzed was explaining the mass balance to determine how much of each consumable was saved by using the ISS SOA closed-loop ECLSS instead of an Orion-like (or actual Orion) open-loop ECLSS. The water and oxygen use rate per crewmember (CM) that was assumed in an early study is shown in Table 1. For an open-loop system, the mass of tanks to deliver the fluids in the logistics vehicles is also important. Water tanks were assumed to use lightweight Russian Rodnik tanks with a bladder in an outer rigid metallic shell with a mass of 35 kgs per 210 kgs of water stored. Gas tanks were assumed to have a mass equal to the mass of gas stored in the tank. (The crew will also generate water through metabolic processes after eating.) A total of 21 kg/CM/day would be required for potable water and oxygen, and the tanks to store them, in an open-loop system. Additional oxygen is required for leakage, and even more for expected ullage volume gas venting for the Orion amine swing bed system. The mass of the savings could be compared to the mass of the equipment assumed to be in the augmentation module shown in Table 2. It is important to note that the equipment in Table 2 was not scaled to new requirements. In this study, it was simply assumed that components would be used as-is, and could support the four-crewmember operations.

Table 1. Assumed Crew Mass Balance for Water and Oxygen Feed, and Liquid and Carbon Dioxide Waste

Input	Rate (2 Significant Figures)	Collected Outputs	Rate (2 Significant Figures)
Drinking water	2.0 kg/CM/d	Perspiration & Respiration Water	1.7 kg kg/CM/d
Food rehydration	0.50 kg/CM/d	Urine	1.4 kg/CM/d
Hygiene water	0.40 kg/CM/d	Hygiene water	0.40 kg/CM/d
Medical Use	0.05 kg/CM/d	(Medical Waste Sealed & Not Recoverable)	
Urinal Flush	0.25 kg/CM/d	Urinal Flush	0.3 kg/CM/d
Oxygen	0.82 kg/CM/d	Carbon Dioxide	1.1 kg/CM/d

Table 2. Simple Augmentation Module Master Equipment ListSubsystem/Function

	State of the Art or Other Hardware as Reference Point	Assumed Mass (kg)
Pressure Control	ISS Oxygen Generation Assembly (OGA)	426
Pressure Control	Oxygen Compressor to Supply EVA (Prototype)	18
Pressure Control	Orion Pressure Equalization System	12
Pressure Control	Oxygen Lines (Estimate)	11
Water Management	ISS Urine Processor Assembly (UPA)	527
Water Management	ISS Water Processor Assembly (WPA)	846
Water Management	Potable Water Stowage & Transfer Bags	15
Water Management	Temporary Urine and Brine Storage Bags (for UPA brine)	15
Air Revitalization	ISS Common Cabin Air Assembly (Condensing)	105
Air Revitalization	ISS Trace Contaminant Control	12
Air Revitalization	ISS Carbon Dioxide Removal Assembly (CDRA)	173
Air Revitalization	ISS Carbon Dioxide Reduction Assembly (CRA/Sabatier)	187
Air Revitalization	Air Revitalization Ducting	20
Air Revitalization	Intermodule Ventilation Fan	5
Air Revitalization	Intermodule Ventilation Ducting	1
Air Revitalization	Trace Contaminant Control	61
Fire Detection & Suppression	Smoke Detector	3
Fire Detection & Suppression	Portable Fire Extinguisher	5

In cases with reduced recycling, some of the closed-loop components could be deleted and replaced with stored consumables in tanks. None of the functions (e.g., CO₂ removal) would need to be replaced because they could be performed by their open-loop equivalent in Orion.

To proceed with this analysis, the team has to be clear about the order in which closed-loop systems can be deleted. Essentially, all closed-loop life support system components make dirty water, except for the WPA. Thus, the WPA must always be present. The UPA (which was assumed to recover 85% of the urine and flush water, based on a compatible urine pretreat formulation), could be removed, leaving the WPA to process only condensate. However, the WPA cannot process condensate unless the CCAA is working to remove it and the CDRA is available to remove CO₂ without collecting water, unlike the Orion system, which vents water (H₂O) and CO₂ overboard. The Sabatier reactor, which converts CO₂ and hydrogen (H₂) into methane and H₂O, cannot operate unless an electrolysis-based OGA is present to make H₂ as a by-product of its process. With those rules understood and assumptions of four crewmembers and no scaling of hardware size, a breakeven analysis was done for each case. If the mission provided more days than that after delivery, the investment was justified. If all of the ECLSS hardware in the augmentation module was compared to the 21 kg/day resupply rate, 116 days would be sufficient total duration of the mission to justify the investment. (This is longer than the typical duration discussed to justify closed-loop life support, but the system includes oversized ISS components used as-is in this case for the four-crewmember study case.) Additional mass for integration and ducting was also deleted when closed-loop components were removed.

Table 3. Resupply Required if Closed-Loop Life Support Functions are Deleted

Case Name	Savings	Fluid Deficit	Resupply with Tanks	Breakeven (days)
No CRA	200 kgs	1.34 kg/d H ₂ O	1.56 kg/d to supply H ₂ O	128 days
No CRA, No OGA	625 kgs	3.39 kg/d O ₂	6.78 kg/d to supply O ₂	92 days
No CRA, No OGA, No UPA	1150 kgs	2.52 kg/d H ₂ O 3.39 kg/d O ₂	2.96 kg/d to supply H ₂ O 6.78 kg/d to supply O ₂	118 days
No UPA	500 kgs	4.44 kg/d H ₂ O	5.20 kg/d to supply H ₂ O	96 days
No Sabatier, No UPA	725 kgs	6.34 kg/d H ₂ O	7.42 kg/d to supply H ₂ O	97 days

As shown in Table 3, time to justify adding back the “savings” mass that could be achieved for removing closed loop components from reduced system concepts is under 180 days. The total occupied duration of the vehicle in the proposed study was measured in multiple years, so adding closed-loop life support at least to the ISS SOA level is justified.

B. Logistics Consumables

Along with examining oxygen (O₂) and H₂O supply, life support engineers participating in these studies also validated assumptions on crew consumables against sources like the Orion Master Equipment List (MEL), the understanding of system managers, or the accumulated knowledge in the Life Support Baseline Values and Assumptions Document. Unsurprisingly, food stowage is a major driver for logistics resupply mass. Discussion with food experts on the team revealed several key assumptions. Bulk food stowage (i.e., a carton of a food that could be opened and closed repeatedly to save packaging mass) was considered untenable because crewmembers are instructed to throw away food that has been opened but not consumed within a short period of hours. Technologies to resterilize food during the mission might improve that. Fecal canisters based on proposed Orion adoption of the Universal Waste Management System take up a surprising amount of volume in logistics resupply vehicles since they are not stackable and are not flexible. Future waste processing efforts for resources must also address the disposable fecal collection canister model adopted by both NASA and Russian engineers, to date. Individually, each canister seems small, and not in need of optimization. At the vehicle level, the impacts show that new options are needed.

IV. Enhancing Asteroid Exploration

Another type of mission examined in several study iterations were visits to asteroids by human crews. Several concept studies were published before looking at human missions to asteroids. The Plymouth Rock mission concept, for example, assumed that the crew spent a long duration in space and visited an asteroid in its natural orbit.¹⁰ More recent NASA studies, however, have focused on mission concepts where the asteroid is brought closer to Earth in a stable orbit around the moon.¹¹ This makes the duration of a crew visit much closer to the Orion design requirement duration. In these studies, the most important impact to the life support system overall is the addition of EVA. Orion is designed to support crewmembers in suits during launch and entry phases of the mission. Life support is provided by recirculated atmosphere via umbilical connections from the central vehicle life support. Concepts for exploring a

very large asteroid, however, would require umbilicals with lengths so long they are untenable. To move farther from the vehicle would require either open-loop O₂ purge (expensive consumable use rate) or a tremendously powerful fan. Additionally, long thick umbilicals would inhibit crew movement.

As a result, a portable life support system (PLSS) worn on the suit was deemed to be necessary. Interfaces to support the PLSS, however, are not provided in the current Orion design. Additionally, the Orion is not designed to support multiple nominal repressurizations if it is used to support crewmember science activities that require EVA at an asteroid. Studies have examined multiple ways to include these. The first group of options examine adding a node-like volume for the Orion to dock to with built-in EVA interfaces and act as an airlock (though a large volume airlock). The second option is removing mass from Orion by reducing the number of crewmembers, and adding tanks of gas to repressurize the PLSS and the cabin.

V. Small Open-Loop Vehicles

Once a study team has determined that PLSS-based EVA is necessary, and is examining an additional volume for the Orion capsule docking, questions arise about how much additional performance can be expected from adding that volume, while minimizing system mass. Cases that want to use a volume as an ascent module for a lander or as an airlock suitable for “camp-out” before EVA while separated from Orion find that additional functions are required. The new module has to have an air revitalization system with functions nearly equivalent to Orion. Architecture teams have often thought that mass, power, and volume savings can be made if the PLSS could be used instead of full vehicle ECLSS. The PLSS scrubs CO₂, provides O₂, cools the body, circulates air, and performs many of the same functions as a vehicle ECLSS. However, when one studies the PLSS design, it becomes clear that the PLSSs are made for a specific mission and set of contingencies for an EVA. A trade study was conducted in 2009 for the Lunar Electric Rover to determine whether the PLSS could be used as the vehicle Environment Control and Life Support (ECLS). The trade revealed the use of the PLSS required modifications of the PLSS plumbing, addition of hardware for failures, operations of PLSS hardware for duration outside of its designed specification, and the addition of fans, CO₂ removal, regulators, and valves to augment the PLSS. This study did determine that portions of the PLSS could be considered to save mass for the vehicle ECLS. For instance, the PLSS CO₂ removal system could support the CO₂ removal for the crew in a vehicle volume, but additional studies would be needed to determine whether the subsystem design including the plumbing and manifold would save mass, power, and volume when compared with the vehicle sized CO₂ removal system.

VI. Conclusion

For the actual implementation of spaceflight ECLSS systems, multiple lessons-learned databases, conferences papers, and late nights in Mission Control have demonstrated that “the devil is in the details” when looking for the key to success. However, those details do not necessarily impact the major architecture questions that mission and vehicle designers are evaluating in the early stages of evaluating mission feasibility. Participation by ECLSS experts in multiple vehicle concept studies resulted in essentially the same answers, in many cases. But participating in studies such as these can reveal the key drivers for life support systems; e.g., break-even durations and level of system closure.

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