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Regenerative Life Support Systems for Exploration Habitats: Unique Capabilities and Challenges to Enable Long-Duration-Mission Habitats Beyond Low Earth Orbit

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The Artemis I launch of NASA's Space Launch System and Orion crew vehicle will mark a major milestone in the agency's efforts to return humans to the Moon. Work is underway on the Human Landing System that will carry the next astronauts to the lunar surface, and the lunar orbiting Gateway that will host science and serve as a platform to support sustained human presence on the Moon and ultimately crewed missions to Mars. Two decades of continuous human presence on the International Space Station has provided a wealth of experience operating, upgrading, and demonstrating advanced Regenerative Environmental Control and Life Support Systems (Regen ECLSS). However, habitats that enable sustained lunar surface presence and transit to Mars will encounter many unique conditions and challenges. System characteristics including reliability, maintainability, mass, and power become significantly more critical. Operating environments associated with lower total pressure, low gravity, contingency protocols, and extensive un-crewed and dormant periods impose additional functionality requirements and alter the performance of certain critical systems. Integration and combined operations with other elements such as orbiting outposts, logistics suppliers, and mobility platforms impact capability and interface requirements. Limits on allocated water and oxygen consumable mass influence the need for higher levels of water and oxygen recovery from waste products. Impacts and challenges these unique exploration circumstances impose on the suite of Regen ECLSS systems are explored and discussed herein.

Nomenclature

0-G	=	Zero Gravity
BPA	=	Brine Processor Assembly
ECLSS	=	Environmental Control and Life Support Systems
EVA	=	Extravehicular Activity
HPO2	=	High Pressure Oxygen
ISS	=	International Space Station
NESC	=	NASA Engineering and Safety Center
OGA	=	Oxygen Generation Assembly
psia	=	Pounds per square inch absolute
PR	=	Pressurized Rover
SH	=	Surface Habitat
SOA	=	State of the Art
TH	=	Transit Habitat
UPA	=	Urine Processor Assembly
WPA	=	Water Processor Assembly

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I. Introduction

Humans have been living and working in space for over two decades on the ISS utilizing Regen ECLSS to maintain a livable environment in micro gravity. The ISS ECLSS operating in low Earth orbit has and will continue to serve as an invaluable proving ground and testbed for current SOA and advancing Regen ECLSS technologies to enable and enhance capabilities necessary for exploration. Habitats that enable sustained lunar surface presence and transit to Mars, however, will encounter many unique conditions and challenges not realized on existing platforms. System characteristics including reliability, maintainability, mass, power, and hard limits of logistics resupply become significantly more critical due to the distances from Earth. Operating environments associated with lower total pressure, low gravity, contingency protocols, and extensive un-crewed and dormant periods impose additional functionality requirements and alter the performance of certain critical systems. Both the surface and transit habitats will be required to operate at lower pressures and higher oxygen concentration than seen on the ISS. The surface habitat will be in a reduced gravity environment and will operate at higher oxygen concentrations to limit pre-breathe duration in support of frequent EVA expeditions to explore the lunar surface. The round trip journey to Mars in a transit habitat will last for multiple years, and once departed will not have the opportunity for re-supply.

II. Surface Habitat Regen ECLSS Baseline Operations

The Lunar surface habitat (SH) is a critical surface element to enable NASA's goal of a sustained lunar presence. The SH will support multiple surface missions of four crew for 30 days on the surface at a time, where SH is expected to provide living quarters for two crewmembers throughout the multiple 30 day missions, and to accommodate four crew intermittently while crew from the pressurized rover (PR) perform activities in the SH to include crew rotations between the SH and PR, suit maintenance operations, logistics transfers, and for potential contingency safe haven operations. Nominally, the four crew will work in pairs during the surface stay with two occupying the SH while the alternate pair conducts heavy EVA and traverse activities from the PR. Specific needs, challenges, and concerns of Regen ECLSS in the SH are identified and discussed in the following paragraphs.

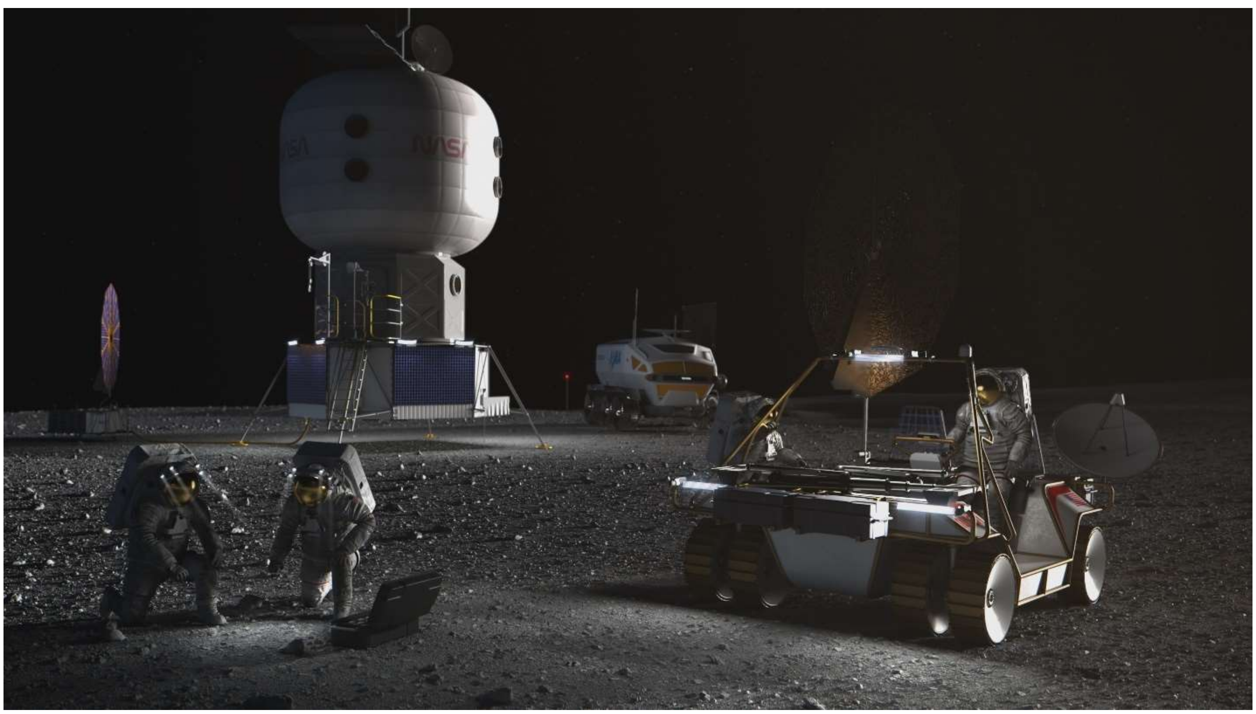

Figure 1: Notional Elements for Extended Lunar Surface Missions, includes conceptual depiction for Lunar Surface Hab, Lunar Terrain Vehicle, and Pressurized Rover.

III. Influencing factors for SH Regen ECLSS Architecture

A. Logistics/Re-Supply Mass

The uniqueness of the lunar surface mission operations and environments pose many distinct challenges that factor into determining the functional architecture needs of Regen ECLSS systems withing the SH. The driving factor that supports Regen ECLSS capabilities within the SH is the logistics mass needed to support each mission. Prior to each crewed mission, logistics will be landed on the lunar surface in near proximity to the SH to provide supplies needed for the upcoming four crew ~30-day mission. At the time of this paper, it is estimated that the allocated mass per logistics lander will be limited to approximately 2,000 kg. This value is not verified or attributed to any specific logistics lander capability but used as a reference for baselining analyses. Without an ability to recover, recycle, and re-use essential life enabling constituents from waste streams to provide consumable oxygen and water for the crew, the total logistics to support four crew for the mission duration will exceed 2,000 kg, the maximum allotted to enable a single logistics lander capability. By incorporating Regen ECLSS systems into the architecture, current analysis indicates the logistics burden can reduced below the 2,000 kg threshold, reducing the number of required logistics landers per mission, or freeing up logistics allocations for other capabilities such as utilization. Consumable oxygen and water estimates based on systems with equivalent recovery capability to the ISS indicate incorporation of an OGA, Water Processor Assembly, Urine Processor Assembly, augmented by a Urine Brine Processor, and high pressure oxygen production and delivery can meet the logistics mass constraint. These systems form the baseline reference Regen ELCSS mission architecture. Evaluation of Regen ECLSS subsystem performance leverages current SOA technology in conjunction with assumed technology advancements where applicable. Estimates for total mission logistics landed mass required to support the four crew / 30-day mission for varying levels of Regen ECLSS loop closure is provided in Figure 2. In additional to basic consumable mass, the logistics estimates include the mass of pressurized carriers and spare/maintenance items for all systems including Regen ECLSS systems for both the PR and the SH.

Table 1: Surface Hab Regen ECLSS Capabilities Baseline

• Water Processor Assembly (WPA) - purifies waste (grey) water and urine distillate.
• Oxygen Generation Assembly (OGA) - produces metabolic oxygen from water, provided directly to Hab atmosphere.
• Urine Processor Assembly (UPA) - produces urine distillate for WPA processing.
• Brine Processor Assembly (BPA) – recovers residual water from UPA brine. (current ISS tech demo technology)
• Carbon Dioxide Removal – removes and vents CO2 from the atmosphere while retaining humidity for condensate collection. (2 candidate systems currently operating as tech demos on ISS)
• High Press Oxygen (HP O_2) – purifies and pressurizes OGA produced Oxygen for tank storage and EVA suit recharge. (technology under development)

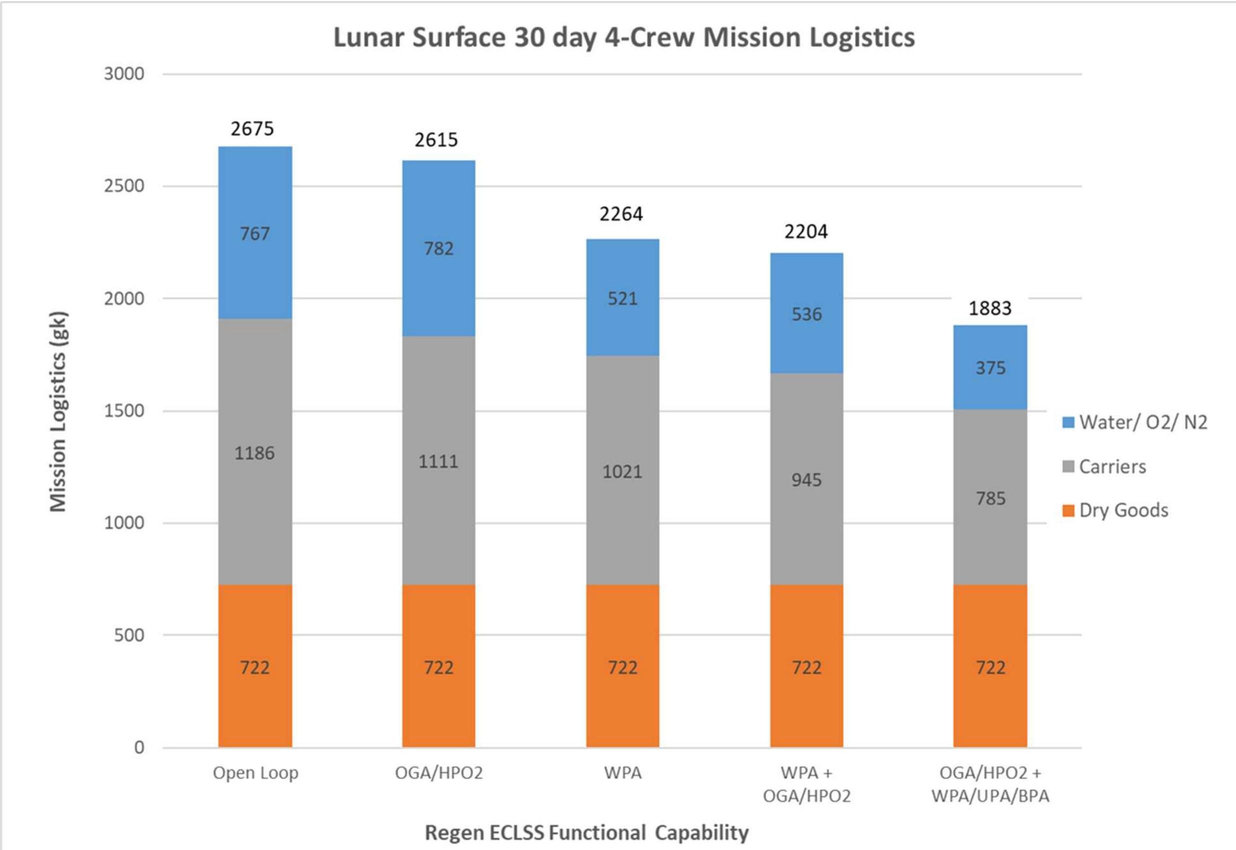

Figure 2: Estimated Mission Logistics vs Regen ECLSS Architecture

While basing the Regen ECLSS functional capabilities on meeting the mission's logistics targets, the impacts and challenges associated with including Regen ECLSS systems in the architecture are considered and discussed in the proceeding sections. A block diagram of the baseline ECLSS functionality for the SH, including the regenerable components is provided in Figure 3. Numbers in parenthesis represent identified functional performance gaps and are not specifically discussed in this document, but discussed at a high level as general challenges.

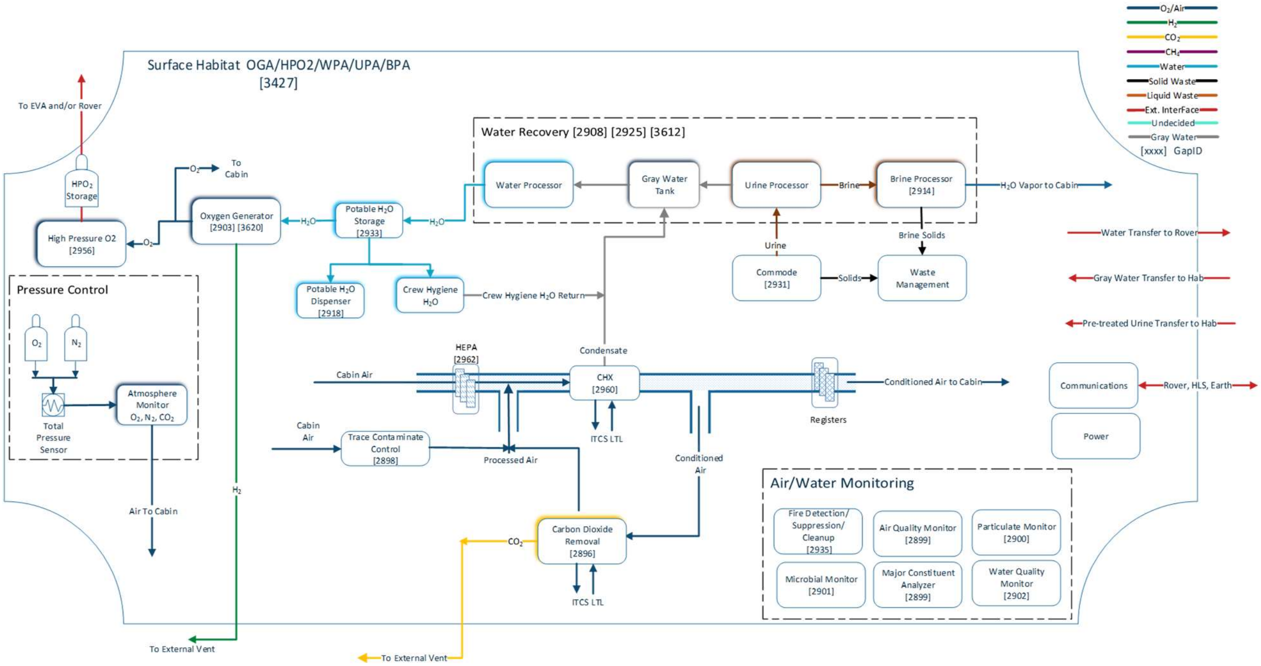

Figure 3: Notional ECLSS Block Diagram for Surface Hab

B. System Mass and Capability Phasing

The total mass of the SH in its landed configuration will be limited, and may prevent including the full suite of baselined Regen ECLS systems upon initial deployment on the lunar surface. With the understanding that the full Regen ECLSS capability is needed to support long-term mission objectives throughout the lunar campaign, an approach to phase in Regen ECLSS capabilities over multiple missions is an option. This approach will require launching, landing, and surface transporting of the the systems separately from the SH. This will also require bringing systems into the Hab, followed by unpacking, outfitting, integrating and activating the systems. This poses challenges such as packaging systems to survive the journey to the Moon, protection from contamination, movement of large heavy systems from a lander into the SH, and system to SH integration for operation. Other aspects to consider include designing to withstand transport outside of a pressurized carrier, sizing to enable movement through hatches and ports, scaring for integration into the hab, planning for increased power and thermal load, and ease of assembly if sub-systems need to be brought up disassembled to account for delivery packaging limits.

Other means to enable Regen ECLSS is to reduce ECLS systems masses. In addition to reducing mass through traditional means such as lighter-weight materials, system scaling, and process optimization, operations on the lunar surface offers the advantage of gravity that is not afforded the SOA systems onboard the ISS. Primarily, the existence of gravity may be employed to eliminate and/or simplify various phase separation functions such as vapor distillation, condensate collection, and various other gas/water separation apparatuses that could result in a significant mass savings over the ISS systems.

C. Processing Waste from Crew in Pressurized Rover

The total mission logistics depicted in Figure 2 for architectures that include water recovery elements is based on combined needs and contributions of both the SH and PR crew. Therefore, to achieve the logistics estimates the PR must be able to accommodate collection, storage, stabilization and transfer of wastewater and urine where applicable for purification into a potable product. This levies additional functionality on the PR and impacts its overall mass and useable volume, but the advantages of reduced consumable supplies and reduced waste disposal are expected to be a net benefit. In addition, a means to efficiently transfer the waste products from the SH to the PR is needed. To minimize crew handling of the waste materials, a method to transfer through connected hoses is desired. This in of itself poses its own challenges as typical fluid stabilization chemicals are caustic and corrosive to many materials.

Figure 4 depicts a notional method for transferring the fluids through umbilical hoses. To minimize exposing mechanical components to the corrosive fluids, a concept of pressurizing the supply tanks with gas is employed. In addition to transfer of waste fluids from the PR to the SH, the concept also allows for bi-directional transfer of fresh water between the elements and the transfer of fresh water from the lander to storage tanks within the PR. After the transfer of waste fluids are complete, the hoses will need to be flushed with fresh water to remove waste residue, demated, and stored. Trades are currently ongoing to compare methods of robotic umbilical mating/demating vs. crew manually performing the connection activities.

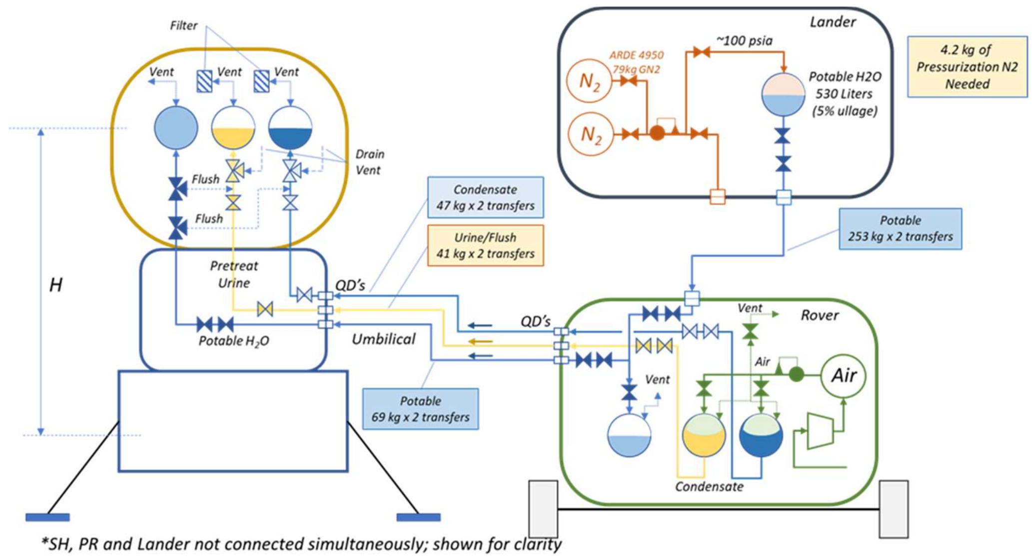

Figure 4: Fluid Transfer Concepts between Lunar Surface Elements.

D. Oxygen Generation for Habitat and EVA

Oxygen generation via water electrolysis is an advantageous strategy for providing metabolic oxygen to the four surface crew members. The amount of metabolic oxygen needed combined with the carrier tank mass required to store the commodity makes it a taxing consumable to deploy on pre-mission logistics landers. With the tank to gas mass approaching a 2:1 ratio, minimizing the amount of oxygen logistics and the resulting storage tanks will provide a substantial delivery mass savings and reduce the number of empty tanks left behind on the lunar surface.

There are multiple challenges associated with using an OGA electrolysis system to meet all the mission oxygen needs. The SOA OGA system is designed to discharge humidity laden produced oxygen directly into the cabin atmosphere at a pressure slightly above the habitat total pressure. To support mission oxygen needs, specifically EVAs and general PR activities, a means to purify and pressurize the product oxygen for tank storage will be required. Development activities are currently ongoing to provide this capability. Processing OGA product oxygen for tank storage requires that the water laden product is dehumidified to meet EVA purity standards, and then compressed and stored in a manner that will enable EVA suit charges and delivery to the PR for oxygen replenishment. This is because the Oxygen used to recharge EVA suits and for transfer to PR is required to be at high pressures above 3,000 psi. Similarly to the water purification scenario, for the generation of Oxygen in the SH to be a valuable function it must transferrable to the PR to support the mobility crew activities as well. Because of the high frequency and duration of planned EVAs originating from both the SH and PR, the inability to process OGA product for high pressure EVA use would render the nominal low-pressure product unhelpful. The total execution of this capability becomes even more challenging when factoring the numerous safety provisions necessary to mitigate flammability concerns associated with materials, rapid temperature/pressure swings, high velocity, and contamination sources could impact ability to implement. In contrast, if the high-pressure oxygen to support EVAs is delivered to the surface via pre-mission logistics, the residual oxygen left in the tanks under 3,000 psi is nearly sufficient to supply all the non-EVA metabolic oxygen to support crew within the PR and SH.

The following Figure 5 represents a notional block diagram schematic to accommodate the generation and transfer of high-pressure oxygen, and also the transfer of gaseous nitrogen between surface elements. As safety and other measures required to execute this capability are identified, the overall complexity and associated mass overhead grows. Connections between the three elements (SH, PR and Lander) are shown for clarity but wouldn't normally be integrated simultaneously.

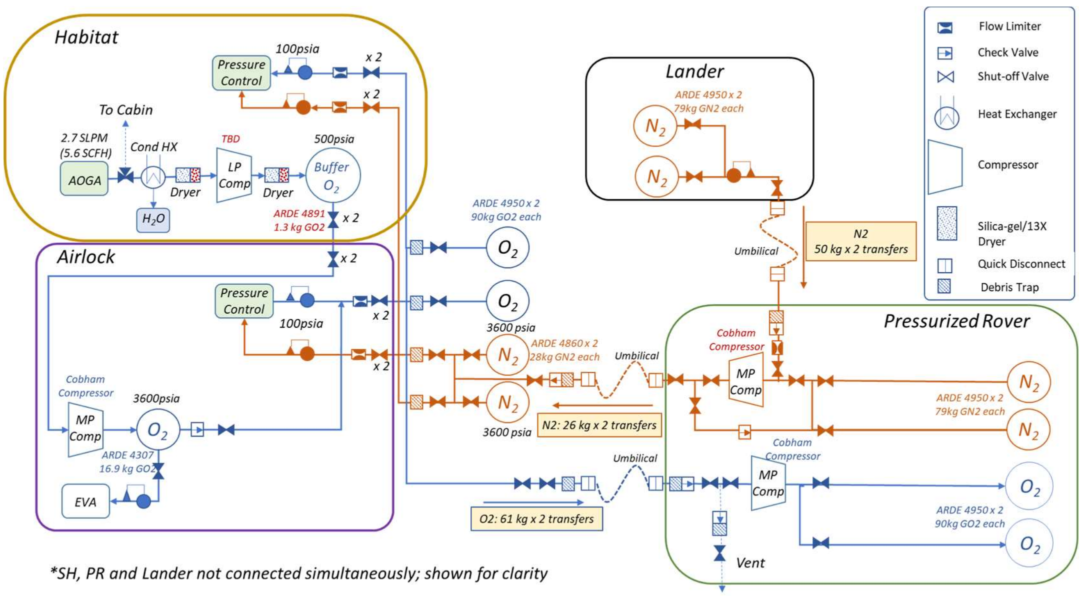

Figure 5: Notional HP O_2 / N_2 Transfer System

E. Long Duration Dormancy

The anticipated mission cadence after the SH element is established on the lunar surface is for one 30-day mission per year with the potential for up to 3 years between missions. With over 90% of the SH's operational life being in an un-crewed status, measures to assure preservation and re-activation of systems are necessary. The Regen ECLSS architecture associated with water processing, delivery, and storage are highly susceptible to contamination, performance degradation and/or damage resulting from biomass growth from exposure to long dormant periods. During the uncrewed periods the habitat must be able to preserve system functionality and operate various subsystems to maintain critical environmental conditions such as temperature, pressure, and cleanliness. Measures to protect systems during this period, such as periodic flush, drain, disinfection, and circulation of fluid systems to prevent formation of biomass is an area of importance and represents operational and functional deviations compared to the current SOA ISS systems. Other considerations for dormancy survival include some level of un-crewed autonomous operations, long-term fluid storage solutions in the relevant environment, long unpowered component shelf-lives, and systems capable of surviving exposure to extreme environmental conditions such as multi-day lunar eclipse. The ability to assess dormancy conditions and validate operations after dormant periods is critical to implementing the baseline Regen ECLSS architecture.

F. Un-crewed/autonomous operations

Prior to crew arrival at the SH, basic conditions and accommodations need to be established by the ECLSS systems. While activation and operation of air systems to establish a habitable atmosphere is relatively trivial at the current technology state, other systems such as water recovery and purification pose new challenges. To maximize water recovery across multiple missions, purifying wastewater during un-crewed periods and associated transition to a dormant state is needed. After the crew departs the SH for HLS, the crew will leave behind unprocessed wastewater and urine that was generated near the mission end. This unprocessed water will consist of waste produced in the SH and a final wastewater transfer from the PR which makes up a significant amount of useable water for the following crew if it can be processed and preserved. Chemical treatment to prevent degradation of waste liquids beyond a recyclable condition is not expected to be achievable for the 1 – 3 year duration between missions. Therefore, this waste will need to be processed into potable water during un-crewed operations shortly after the crew departs and preserved in a purified state for use on a future mission. This will require system automation development to not only perform autonomous system operations, but also the ability for system shutdown that includes transition into its dormant configuration. The addition of this functionality over the current ISS configuration will most likely require additional components that will add mass and complexity and has not been fully characterized to date.

G. Designing for reduced pressure (8.2 - 10.2 psia) and low G environments

Recently a study was performed by the NASA Engineering Safety Center (NESC) to qualitatively assess impacts and incompatibilities associated with operating current ISS SOA systems in a low-pressure high oxygen concentration environment [1]. To significantly reduce oxygen pre-breathe duration, it is desired to operate the SH at a total pressure of 8.2 psia and nominal oxygen concentration of 34% by volume vs. the nominal Earth environment of 14.7 psia and 20% oxygen concentration by volume that is maintained on the ISS. The consensus is that several system processes will need modification to operate in the lower pressure higher oxygen concentration environment, but the modification represent engineering changes and that the overall processes are applicable to the desired SH low pressure high oxygen conditions. The bigger impact surrounds potential material flammability incompatibilities at the lower pressures. Significant material analysis and testing activities are needed to assess suitability for many materials for compatibility with the higher oxygen concentrations.

The existence of 1/6 Earth gravity on the lunar surface is not expected to prevent the use of technologies used in the ISS SOA regen ECLSS systems, as the microgravity systems onboard the ISS also function on the ground. However, the existence of gravity does impose some potential benefits to reducing complexity. Systems that require gas/liquid separation can potentially be simplified by using buoyancy effects. This may allow for the elimination of hardware dedicated to separation and simplify some systems. Additional advantages could be achieved by using natural pressure differentials realized by elevation changes to move liquids and reduce the reliance on mechanical pumps for some operations. Implementing systems to utilize gravitational forces will require system configuration changes and design updates that must be considered.

IV. Influencing factors for Transit Hab Regen ECLSS Architecture

The overall mission profile of the Mars Transit Habitat (TH) calls for the transport of four crew on multiyear round-trip missions to Mars orbit to enable crewed missions to the Martian surface. The TH Regen ECLSS systems are to provide a high level of loop closure such that waste products are recycled to a degree that the balance of available water and oxygen is maintained, assuming water is only added to the balance of available water through metabolism and food ingestion. The TH Regen ECLSS final configuration will support four crewmembers for the mission duration without logistics resupply. This levies high importance not only on the ability to recover and repurpose a high percentage of life enabling molecules, but also requires a comprehensive understanding of the Regen ECLSS reliability to properly predict necessary spares. Well-defined reliability combined with systems designed for maintainability will help assure operation throughout the planned mission duration while minimizing down time. Nominally, the total pressure and oxygen concentrations are planned to operate at ISS conditions of 14.7 psia and 20% oxygen by volume while in transit operations. However, the TH is expected to be deployed, outfitted, and tested at the lunar Gateway (10.2 psia/26% oxygen) such that systems should be capable of operating within both atmospheric conditions. Other operations such as safe haven support, emergency EVAs, and specific contingency operations also factor into the overall architecture.

Figure 6: Notional Depiction of Transit Hab

A. Transit Habitat Regen ECLSS Baseline Architecture

The baseline TH Regen ECLSS results in a high level of loop closure to minimize the amount of consumable water and oxygen stores necessary to complete the mission. Similarities with the ISS operating environment support near direct application of many ISS subsystem technologies for use in the TH. Because of the inability to resupply water and oxygen post departure, even higher levels of recovery are desired. However, it is important to note that the "right" balance of water recovery is more important than maximal recovery. This is because any additional water that is recovered would need to be dumped by the habitat to minimize the impact on the propulsion system that must push the additional mass around the solar system. This is particularly important at arrival and departure burns when assuming hybrid propulsion systems where lower efficiency chemical engines are used therby requiring much more propellant. In addition to the nominal systems onboard the ISS, additional capabilities to include higher levels of Oxygen recovery from CO2, higher levels of water recovery such as from UPA brine and possibly trash are potential considerations. For the baseline architecture, the capability of additional systems to promote oxygen recovery from CO2 at greater than 75%, and additional water recovery from UPA brine are included. The following systems listed in Table 2 are currently assumed for determining baseline vehicle mass and power allocations, and supports estimates for consumables and spares needed to complete the mission.

Table 2: Baselined TH Regen ECLSS systems to support loop closure are largely ISS-derived and include

• Water Processor Assembly (WPA) - purifies waste (grey) water and urine distillate
• Oxygen Generation Assembly (OGA) - produces metabolic oxygen from water, provided directly to Hab atmosphere
• Urine Processor Assembly (UPA) - produces urine distillate for WPA processing.
• Brine Processor Assembly (BPA) – recovers residual water from UPA brine (current ISS tech demo technology)
• *High Press Oxygen (HP O_2) – purifies and pressurizes OGA produced Oxygen for tank storage and EVA suit recharge
• Carbon Dioxide Removal Assembly (CDRA) – removes CO2 from cabin while retaining humidity for condensate collection. System is capable of either venting CO2, or storing it for oxygen recovery.
• Sabatier – produces grey water from OGA and CDRA products (H_2 and CO_2)
• Plasma Pyrolysis Assembly (PPA) O2 Recovery – recovers O2 from metabolic CO2 (PPA is baseslined as a development technology, others technologies are in development and are alternatives to perform this function)

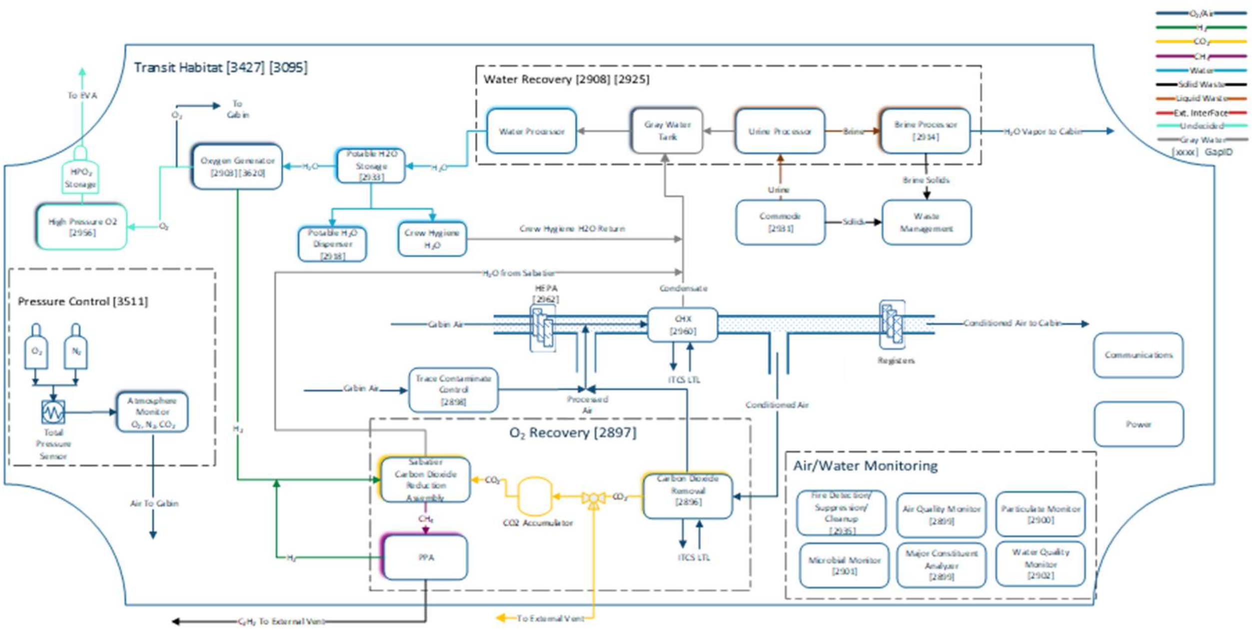

Figure 7: Notional Transit Hab ECLSS Architecture Block Diagram

B. Influence of Reliability Uncertainty and Maintainability on Sparing Mass

Absent the ability for re-supply combined with the total TH mass limitations primarily driven by the in-space propulsion elements ability to push the habitat to/from Mars, it is critical to understand reliability of critical Regen ECLSS systems throughout their operational life to adequately predict the resources needed to support a successful mission to mars and back [2, 3, 4]. Spare part tallies, maintenance downtime, and appropriate contingency resources are all a function of system reliability expectations, and incorrect accounting for necessary repairs could either prevent the architecture from closing or be catastrophic to mission success. Lessons learned from the ISS have shown that predictions of failure modes and the operating life of Regen ECLS systems have been inaccurate in many instances. Fortunately, the ISS benefits from large mass allowances and frequent re-supply opportunities so that major mission impacts from unanticipated failures and system down time is minimal. Such allowances for a transit to Mars are not allotted, so a clear understand of systems life and end of life performance is critical. Operations onboard the ISS have taught us a great deal about failure modes resulting from extended runtimes and operating in the relevant microgravity environment. These lessons have resulted in system upgrades to significantly improve operating life and to better define reliability. However, due to limited number of components being operated at any given time and limited run time on upgraded designs, the reliability uncertainty remains high to date. To reduce reliability uncertainty, a robust ground test campaign represented with actual system components under relevant environmental stresses is needed to compliment in-flight operations in LEO. Such efforts are underway under various NASA activities with plans for future expansion to acquire sufficient reliability data that enables confident sparing need predictions without significant over estimation.

In concert with improving system reliability and reducing reliability uncertainty, packaging of systems to enable lower-level component maintenance is needed to enable operations over the mission duration while minimizing spare part mass. Current ISS systems typically have large Orbital Replacement Units (ORUs) that are replaced in entirety when a component within that ORU fails. Challenges to re-design system layout are needed to accommodate a directed approach to lower-level maintenance and associated component level spares. Other approaches such as repairable vs. replaceable items could also significantly reduce the sparing mass but pose new challenges for maintenance level activities that should be weighed when incorporating design concepts. While simpler systems may offer a more robust design for repair and replace, the mission profile requires the use of more complex recovery systems to close the mission architecture.

C. Advanced Oxygen Recovery

The current TH baseline Regen ECLSS assumes the ability to recover oxygen from CO_2 beyond the existing ISS SOA system. The current SOA is a Sabatier reactor, which is theoretically capable of recovering approximately 50% of the oxygen held in metabolically produced CO_2. Because the Sabatier system relies on hydrogen produced by the OGA electrolysis system, and the Sabatier produces methane (CH_4) as a waste product, there is only enough available hydrogen to react with 50% of metabolically generated CO_2. The baseline TH system used for estimating the total water amount that needs to be packed in the TH for use in the mission includes a Plasma Pyrolysis Assembly (PPA) that recovers enough hydrogen from the methane product to increase oxygen recovery from CO_2 to an approximate theoretical 75% and offers a substantial reduction in the amount of water that needs to be carried. The PPA is being held as a baseline for resource estimating purposes, other technologies such as Bosch among others are also being explored under NASA managed technology development efforts. A cross technology challenge associated with high levels of oxygen recovery from carbon dioxide is how to manage the production of carbon. In general, recovery methods beyond the SOA Sabatier produce carbon that tends to build up and foul or otherwise disrupt the process. Techniques to manage this condition are being persued, but such concepts and are yet to be fully demonstrated that would enable continuous reliable operations. Additionally, analysis suggests that efforts to improve oxygen recovery needs to be combined with lower food hydration, otherwise the savings will be cancelled by excess water introduced into the overall balance as food is consumed and its overall effect on tranporation as discussed earlier.

D. Post Dormancy Operations

While not as mission critical as with the SH, the ability to survive prolonged dormancy periods is needed for the TH. The TH is not expected to experience significant dormant periods during its actual mission to Mars and back. It will experience pre-mission dormancy periods during build up and check out phases while docked to Gateway. Because the TH system can be manually put into its dormant state, measures by the crew to drain, dry, flush, and inspect the system prior to crew leaving will need to be developed and verified. While critical to maintaining the systems between crewed periods at Gateway, the crew will not be reliant on the Regen ECLS systems while docked at the lunar outpost during pre-mission outfitting and testing. This will afford opportunities to perform system verification and maintenance that enables recovery from dormancy caused system degradation during mission shakedown testing prior to departing on Mars missions. Design and operational considerations to minimize significant impacts to systems during dormant periods are needed and impacts and recovery expectation should be well defined and implemented into the Regen ECLSS architecture.

E. 10.2 PSIA compatibility

Nominally, the TH hab will operate at 14.7 psia during its transit to and from Mars, and systems should be optimized for this condition. While docked to the Lunar Gateway as a visiting vehicle, systems may need to operate with the TH in an open hatch configuration at Gateway's nominal operating pressure of 10.2 psia and 26% Oxygen by volume. At the lower Gateway pressure, it is anticipated that some systems within ECLSS will perform less efficiently than when at their designed pressure. This is acceptable because Gateway ECLSS is able to support the crew in this configuration, and operations of the TH ECLSS would be considered supplemental. The TH ECLSS systems should still have the ability to safely operate at 10.2 psia total pressure harming the TH systems or posing an increased. As covered in the SH section for low pressure operations, provisions to assure material compatibility for operating at the higher oxygen content, including material flammability assessments are needed to support designs for many of the TH systems including Regen ECLSS [1].

V. Conclusion

Habitats that support sustained human presence on the lunar surface and multi-year transits to and from Mars must adhere to logistics and consumable mass limitations that rely on Regen ELCSS. Many of the necessary functional capabilities needed to enable these missions have a long history of successful operations in low Earth orbit on the International Space Station. These systems, along with planned upgrades and ongoing development activities, comprise the foundation for predicting the overall habitat mass and mission logistics needs. While versions of the Regen ECLS systems onboard the ISS are proven, matured, regularly upgraded, and considered the current SOA, modifications and augmentation with additional capabilities are necessary to enable the exploration habitats of the future. System capability challenges outlined in this paper represent some of the needed functional augmentations identified to date, many of which are currently being addressed by various technology development activities. While this paper focused on the Regen ECLS systems, many additional capability needs exists across the entire ECLSS architecture. Ongoing and future efforts to enable these capabilities have been identified throughout the ECLSS community and are paramount to enable these missions. Other challenges such as integration of Regen ECLSS with other functions such as waste and trash management, water distribution, airlocks, EVAs, and resource sharing between systems and elements are also needed and will be explored in more detail in the near future.

VI. Acknowledgments

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