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Life Support and Environmental Monitoring International System Maturation Team Considerations

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Human exploration of the solar system is an ambitious goal. Future human missions to Mars or other planets will require the cooperation of many nations to be feasible. Exploration goals and concepts have been gathered by the International Space Exploration Coordination Group (ISECG) at a very high level, representing the overall goals and strategies of each participating space agency. The Global Exploration Roadmap[1] published by ISECG states that international partnerships are part of what drives the the mission scenarios. It states "Collaborations will be established at all levels (missions, capabilities, technologies), with various levels of interdependency among the partners." To make missions with interdependency successful, technologists and system experts need to share information early, before agencies have made concrete plans and binding agreements.

This paper provides an overview of possible ways of integrating NASA, ESA, and JAXA work into a conceptual roadmap of life support and environmental monitoring capabilities for future exploration missions. Agencies may have immediate plans as well as long term goals or new ideas that are not part of official policy. But relationships between plans and capabilities may influence the strategies for the best ways to achieve partner goals.

Without commitments and an organized program like the International Space Station, requirements for future missions are unclear. Experience from ISS has shown that standards and an early understanding of requirements are an important part of international partnerships. Attempting to integrate systems that were not designed together can create many problems. Several areas have been identified that could be important to discuss and understand early: units of measure, cabin CO_2 levels, and the definition and description of fluids like high purity oxygen, potable water and residual biocide, and crew urine and urine pretreat. Each of the partners is exploring different kinds of technologies. Different specific parameters may important to define or explore possible ranges depending on the system concepts.

Early coordination between technology developers can create new possibilities for collaboration, and provide input to determine what combined options may provide the best overall system architecture.

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Nomenclature

f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate

I. Introduction

MANY nations share the ambition of exploring our solar system and universe beyond low Earth orbit. The Global Exploration Roadmap shows that we share "the driving goal of human exploration of Mars", though we may have different strategies and near term priorities. Robert Cabana, an NASA astronaut who participated in early missions to build the ISS and now serves in leadership positions at NASA, was quoted supporting international partnership as the model that would support future human exploration. He said, "Right now we've got the United States, Japan, Canada, Russia, ESA and all its partners working together as one up there. When we leave planet Earth, we're not going to leave as any one nation, we're going to leave as the people from planet Earth." Life support and related environmental monitoring systems are a critical part of those future human missions. It is logical that all of the international partners are interested in life support and environmental monitoring systems. An International System Maturation Team (ISMT) has been organized for life support and environmental monitoring topics including NASA, ESA, JAXA, and recently added support from Russia through experts from Energia. Through this collaboration, specialists and experts have a pathway to discuss technologies and issues that are important for the success of future missions.

II. Parter Goals and Roadmaps

Many different factors can influence interests, investments, and priorities as nations consider their investments in life support technologies, and their plans for the future. National priorities for science and technology investments, industry capabilities, and strategic planning for future space exploration efforts would all be considered. These priorities are created in many different ways. But the result of the for life support is specific plans for technology development and demonstration of important system capabilities. These important capabililities are labeled as "gaps"[3]. These gaps are the differences between the system that each partner believes is important for future missions and the system that is available with current technology. In an early ISMT meeting, NASA, ESA, and JAXA compared technology plans. By comparing investments, participants in the ISMT found that there was significant agreement and similarity the technology gaps that each partner was addressing. Formal input was not available from Russian participants at the early meeting, but review of publications[4] shows significant similarities in capabilities and investments as well.

Table 1: Technology Investments by Life Support and Environmental Monitoring Function

Life Support & Environmental Monitoring Function	NAXA, ESA, and JAXA Technology Investments
Carbon Dioxide (CO_2) Removal	• NASA Carbon Dioxide Removal Assembly (CDRA) Upgrades & CO_2 removal technologies with new sorbents or methods[3] • ESA Advanced Closed Loop Life Support System (ACLS) CO_2 Concentration System (CCA) with amine beds[5] • JAXA Amine CO_2 Removal absorption beds[6] • Russian Vozdukh System
Trace Contaminant Control	• NASA testing of commercial sorbents and catalysts • JAXA improved activated carbon and catalysts
Particulate Filtration	• NASA regenerable filters and research for lunar and Mars dust
Condensing Heat Exchangers (CHX)	• NASA new concepts without hydrophilic coating, or coating improvement • ESA existing ISS CHXs
Oxygen (O_2) Recovery from CO_2	• NASA Spacecraft Oxygen Recovery Project for >75% Recovery from CO_2 or Methane Decomposition • ESA ACLS CO_2 Reprocessing Subsystem (CRA) Sabatier Reactor

	• JAXA Low Temperature Sabatier Catalyst
Oxygen Generation	• NASA Oxygen Generation Assembly (OGA) Improvements • ESA ACLS Oxygen Generation Subsystem (OGA) • Russian “Elektron”
Urine Processing	• NASA ISS Urine Processor Assembly (UPA) Improvements and Cascade Distilation System (CDS) alternate method • JAXA Integrated Water Recovery Subsystem (JWRS) • Russian SRV-UM for urine distillation
Water Processing	• NASA ISS Water Processor Assembly (WPA) Improvements • JAXA Integrated Water Recovery Subsystem (JWRS) • Russian SRV-KM for condensate and urine distillate, and SOV for purifying water for “Elektron”, and SRV-HG for hygiene water
Brine Processing	• NASA Urine Brine Processing (Primary technology is Ionomer Water Processor[7]) • JAXA Integrated Water Recovery Subsystem (JWRS) manages internally generated brines • JAXA Brine Processing Freeze Drying (for urine brines)
Biocide	• NASA Silver Biocide Development • JAXA Nano-bubble Ozone Development
Urine Pretreatment	• NASA ISS “Alternate” Phosphochromic Preatreat, Low Toxicity “Greentreat” Development • JAXA Low Toxicity, Moderate pH Pretreatment • Russian SPK-UM
Quiet Fans and Acoustics	• NASA Interest in “Quiet Fan” Technology, Limited Development

Additionally, multiple sensors for environmental monitoring are in development for ISS demonstrations by NASA and ESA. For example, the NASA Multi-Purpose Air Monitor (MPAM)[3], Spacecraft Atmsophere Monitor (SAM)[3], and the ANITA-2[8] are all designed to monitor spacecraft atmosphere continuously under nominal conditions, though they have different capabilities, benefits, and challenges.

All of the international communities have plans to demonstrate and test high priority life support systems on board the ISS.

III. Levels of Integration

International collaboration in future missions can be conducted at many different levels of integration. No matter what hardware is provided, all systems are integrated through atmosphere and crewmembers. Spacecraft atmosphere has to be actively mixed in microgravity, and movement between modules is unavoidable. (Of course, in order to not have to repeat systems in every module, airflow is actively created between modules on ISS.) Multiple systems performing the same function, such as CO_2 removal, create dynamics in the atmosphere that impact the performance of those same systems. Recent V-HAB simulations predict the cyclic effects that would occur across the ISS when the Vozdukh, CDRA, and ACLS are operated simultaneously[9]. The input concentration of CO_2 is often an important driver in the performance of CO_2 removal systems[10], and these variations may have dynamic effects downstream, even though the systems themselves are not considered physically integrated.

The most separate systems would be partner nations each contributing modules that were fully outfitted. In the simplest example, the Apollo-Soyuz mission represented two modules fully owned by individual nations. But without coordination of requirements in advance, the 35 kPa (5psia) 100% O_2 atmosphere used by Apollo vehicles and the nitrogen-oxygen mixture at 69 kPa (10 psia) used by Soyuz vehicles were incompatible[11], adding substantial challenges to the operations and required new hardware and systems to successfully create an interface. Ths ISS partnership has been much more successful, and has largely operated with contributed modules. However, as ISS evolves, systems from one partner may be moved into modules provided by another partner. A key example of this is the ESA ACLS demonstration that was originally planned for the ESA provided ISS Columbus module, but which now will be conducted in the ISS Denstiny module[5]. But even with better coordination, incompatible elements have been created. One example is US potable water with iodine residual biocide and Russian potable water with silver residual biocide[3], which cannot be mixed. Another example is the use of two different fire extinguishers originally used on ISS[12], because Russian water fire extinguishers were not compatible with US electronics and power systems.

The next level of integration is between subsystems. This occurs on ISS as well, when urine collected in a Russian commode is processed in the NASA Urine Processor Assembly (UPA), or condensate is transferred between US and Russian modules to balance water resources[13]. Even if it was not intentionally designed to function this way, these operations effectively create system to system integration between the US Common Cabon Air Assembly (CCAA) and the Russian Elektron, and between the Russian toilet and the UPA. Looking at the list of technologies in development in Table 1, it's clear that many possible system to system integrations could be created. Some systems are preintegrated, such as the ESA ACLS performing CO_2 collection, Sabatier reactions, and oxygen generation in one unit, or the JWRS design to process urine to potable water in an integrated process without an additional downstream system. More examination will be required to see if the system can be operated with a substation of a partner technology in one location. Systems may be able to be used in different roles when integrated, such as replacing the Water Processor Assembly (WPA) downstream of the NASA UPA with the JWRS. This would be a different set of requirements, and the JWRS would likely be overdesigned for the task. This might add a benefit of robustness. Evaluation of new requirements and trade studies would have to be conducted to see if the JWRS is an efficient replacement option. Russian and NASA designs both appear to separate urine processing from downstream processing of the water recovered from the urine and condensate. These systems might be very compatible as system to system integrations.

The lowest level of integration would be component to component within a function. Many of the partners have or are developing Sabatier reactors. Adding a new Sabatier catalyst into a system design from another partner could be feasible. This method of integration requires shared development responsibility, and is probably the most difficult to execute. If partners are able to be open about development processes, there may be opportunities where a proven component from another system could solve a problem. One strategy may be to identify unctions that are repeated in many systems. Sharing reliable phase separators, efficient fans, robust pumps, and lightweight storage containers could help all partner systems, and improve sparing and commonality in an eventual flight mission.

In any of these integration strategies, items like quick-disconnects, hoses and pumps to transfer fluids, or storage containers also become component to component integration between partners. Designing them early for the broadest set of requirements will simplify operations in the future.

IV. Requirements and Standards

The functions required to sustain human life are likely to remain similar across many future missions. Technology development can (and should) begin before future programs officially exist. However, this creates a challenge. Detailed performance requirements can drive the selection of technologies for future investment. The ISMT is beginning to develop informal standards and requirements relevant to life support and environmental monitoring systems. These are intended to improve collaboration, and avoid awkward integration challenges in future vehicles. The initial work focused on identifying the most important topics for standards. Later work may be able to look deeper into interface requirements between systems or components. Different details matter depending on the technology, such as CO_2 sorbents that may be more or less sensitive to the presence of water[14]. Sharing these topics helps predict future integration issues that should be discussed. The standards described below are expected to be an evolving list.

A. Units of Measure

Units of measure are a classic integration problem in engineering systems. Official NASA policy[15] requires use of the International System of Units (SI Units) unless exceptions are granted by the NASA Chief Engineer. SI units are already used by most international partners. Units may not matter as much as the technology development stage, where drawings and physical integration aren't happening yet. But it is an important part of improving collaboration between teams. Spoken language is already a challenge in many international partnerships. Minimizing the need to convert units during a technical conversation

B. Fluid Quick Discconnects

Quick Disconnects (QDs) are the most basic interface between technologies and supporting equipment or storage volumes. Multiple types of QDs are used on the ISS, from different international providers. Standardizing connections would simplify integration of demonstration units on the ISS, as well as prepare for future missions. Future work in this area should include a comparison of requirements and specifications for each type used to see if there are underlying reasons driving their differences. Existing spaceflight hardware and other designs from industry should be assessed. New designs may need to be considered if none of the units meet all the necessary requirements.

C. Atmosphere: Partial Pressure of CO_2

The ISS is actively trying to reduce CO_2 levels below the original design points. Medical research is continuing to set new, lower partial pressure levels as requirements for future missions. Without formal requirements, technology development engineers have looked for a consensus on a level that can be used to design initial prototypes. <Note to reviewers – this meeting is scheduled for spring, and an actual recommended level will be updated for the final version.>

D. Atmosphere: Stored O_2 Purity and Pressure

Oxygen purity is important for safe crew atmosphere, but spacesuits and medical use drive new requirements. Any diluent gases in the oxygen cannot cause hazards for human health. The NASA next generation spacesuit for exploration is expected to require oxygen at least 99.5% pure, and at pressures greater than 21000 kPa (3000 psia) to refill tanks in the Portable Life Support System (PLSS). Diluents such as Argon do not pose a threat to human health at low concentrations, but may be undesirable because they build up over time in the cabin or spacesuit atmosphere, or are difficult to separate.

E. Atmosphere: Spacecraft Cabin Total Pressure and O_2 Concentration

The Exploration Atmospheres Working Group[16] explored the risks and benefits of spacecraft atmosphere setpoints with reduced total pressure and increased oxygen concentration, with recommendations in 2006, and an update in 2010. Follow on work recommended small changes to the lowest pressure atmosphere, settling on a 56.5 kPa (8.2 psia) at 34% O_2 instead of 55.1 kPa (8 psia) at 32% O_2 atmosphere[17]. Most long duration missions with closed-loop life support systems will still be conducted at Earth-normal type atmospheres of 101 kPa (14.7 psia) and 21% O2. But if life support developers want to operate short duration vehicles with lots of extravechicular activity (EVA), some of the components and technologies should be prepared for the lower pressure, higher oxygen atmosphere. These conditions are also likely to impact habitat outfitting with softgoods and textiles because of flammability risk. They will also determine which items need to have direct coldplate cooling, and which can be air cooled based on heat transfer reductions in the lower pressure atmosphere.

F. Atmosphere: Trace Contaminant Levels and Generation Rates

Understanding atmospheric trace contaminant gases is important for design of removal hardware, like adsorbents and catalysts, but also for sensors and other hardware. The Spacecraft Maximum Allowable Concentrations (SMACs) for Airborne Contaminants[18] are current requirements that are expected to apply to future missions as well. But the SMAC may or may not be the right level to use when designing hardware. When challenging a system for robustness or possible failures, exposure to contaminants at SMAC levels or higher would likely be appropriate. When designing a system to remove trace contaminants, a much lower level should be assumed as the input concentration because the SMAC is not intended to be the nominal cabin level. A generation rate model is also required to design life support system hardware. The simplified model published by Perry in 2009 is the current leading explanation of design methods, assumptions, and load models for trace contaminant control systems.

G. Water: Potable Water and Residual Biocide

Standards for potable water quality can vary across nations and communities, and spacecraft requirements are often very different than terrestrial requirements. Program requirements for water sometimes include requirements for humans and requirements designed to protect hardware. The Human Integration Design Handbook[20] gives an overview of concerns about potable water quality for humans. Limits set by toxicological concerns are documented in Spacecraft Water Exposure Guidelines (SWEGs)[21]. Some systems are known to have sensitivities to particular contaminants. These may require a special standard, or at least engineers need to know the worst case water that could be fed to the system to design protections. For example, both US and Russian systems that generated oxygen from water electrolysis must carefully control the water fed to the unit and include extra treatment steps.

Residual biocides are chemicals added the water to control microbial growth. For years, NASA has used iodine as a biocide, but had to remove it before crew consumption. Russia has used silver on the ISS. NASA intends to transition to a silver biocide for future spacecraft. But even with a common biocide in the future, the concentration and limits need to be defined. A minimum concentration is needed for microbial control, and at least one standard in use on ISS is for 0.1 mg/L as the minimum level[22]. NASA SWEGs set the limit of silver in drinking water at a maximum of 0.4 mg/L for 1000 day long term exposure[21].

Additionally, some definitions of potable water may have included the addition of minerals for taste[22].

H. Wastewater: Urine and Urine Pretreatment Chemicals

Human urine is highly variable based on individual human characteristics, diet, hydration levels, and other factors. NASA has had on-orbit failures of the ISS UPA based on the concentration of calcium in the urine and the sulfuric acid used in the urine pretreatment[23]. The concentration was higher than expected and tested by the engineering community, but not officially outside of a healthy range. After considering several options, the engineering community has responded by developing a new formulation for the pretreatment chemical used in the ISS US commode[24]. (Though the design of the commode is the same as the ISS Russian commode, ownership and control are negotiated differently.) Many other pretreatment fomrulations have been used in the past or proposed as alternates. Requirements for the urine pretreatment chemicals, and testing methods are also important to discuss to compare options.

In related developments, NASA flight surgeons and water experts[25] have been studying relationships between urine calcium and bone loss. Crewmembers are being encouraged to increase water consumption. These studies also detect variation in urine from crewmembers. While nationality is not a biological description, the operations, instructions for drinking water, and primary diet may vary based on the nationality of the crewmember. The ions that caused problems in NASA's distillation based UPA may not be an issue for the JWRS since it is not distillation based. But some other contaminant may prove to be a challenge. Future conversations will include documentation of the current range of expectations for crewmember urine. But development testing of new water systems should also work to identify the species or contaminants that could cuase problems. These problem species may not be measured regularly in crew urine, and data gathering would need to begin to create design requirements.

I. Sensor Requirements

A diverse set of monitoring and sensor technologies has been used on the ISS and is in development at various agencies. Discussing sensors is complex because it is hard to easily categorize the requirements set. Sensors may be divided by whether they take samples from air, water, or surfaces. But some sensors can process multiple kinds of samples. They may be characterized as measuring physical, chemical, or biological parameters. Additionally, previous spacecraft requirements are not necessarily matched to the parameters actually measured by state of the art sensors. This is especially true in biological sensors, where DNA based technology has dramatically changed the field. The process of organizing requirements and matching them to sensor performance needs will be long and complex. But it should involve international partner collaborations from the beginning. This will ensure that technology development is coordinated to meet the high priority needs, and tested in a way that is useful to all the future stakeholders.

J. Crew Metabolic Rate

Human metabolism can vary depending on size, gender, activity level, and other individual differences. The HIDH[20] documents oxygen consumption, carbon dioxide production, and respiration and perspiration water that can be considered requirements for future life support systems. However, the exercise profile included is based on assumptions for the Orion spacecraft. Longer duration missions are likely to have longer exercise periods to maintain crew health. The impacts of those exercise changes are not yet fully understood. These requirements probably do not determine whether different life support technologies are feasible for future missions. But they will determine the size and performance requirements. Understanding whether systems are truly built to the same requirements will be important when comparing and selecting between technologies from partner nations.

K. Biological Systems

Many plant growth experiments have been and will be conducted on the ISS. Investment and interest in biological systems may receive less of a focus at NASA than at other agencies, and these systems are not always considered part of the life support system. However, even a small "pick and eat" plant growth system will have impacts on the life support system. Ethylene is a classic example of a contaminant that can damage plant growth at levels that do not harm human health. Also, plant transpiration of water from roots to release through the leaves will significantly increase the amount of condensate that has to be collected, and thus the amount of various kinds of wastewater to be processed. And plants that are exposed to the bulk cabin atmosphere will remove CO_2 and generate O_2. Even if only a small system is considered, the presence or absence of plant growth changes requirements on the life support system.

V. Future Topics

Technologies are relatively easy to discuss as individual topics. But the architecture of the life support system is also a key area that needs to be discussed for good collaboration. ISS has taught us that sharing standards is important. But dissimilar redundancy, such as multiple CO2 removal systems, has proven to be very important to ISS success as well. Strategies for build-up and integration of systems over time will be important to the implementation of ISS demos and to the design of early vehicles in cislunar space.

VI. Conclusion

Collaboration through the ISMT is just beginning, but has already had an impact on technology development processes. Stories and explanations of failures and lessons learned on urine processors has led to conversations about how challenging early tests may prevent unexpected failures in the future. Discussion of atmosphere requirements with international partners has helped elevate the need to clarify and share information even with internal NASA stakeholders. And discussions of sensor requirements for a mission where there is no sample return avaialble is contributing to conversations on sample frequency and cost for existing operations.

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