

Exploration Life Support Critical Questions for Future Human Space Missions

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Exploration Life Support (ELS) is a current project under NASA's Exploration Systems Mission Directorate. The ELS Project plans, coordinates and implements the development of advanced life support technologies for human exploration missions in space. Recent work has focused on closed loop atmosphere and water systems for long duration missions, including habitats and pressurized rovers. But, what are the critical questions facing life support system developers for these and other future human missions? This paper explores those questions and how progress in the development of ELS technologies can help answer them. The ELS Project includes the following Elements: Atmosphere Revitalization Systems, Water Recovery Systems, Waste Management Systems, Habitation Engineering, Systems Integration, Modeling and Analysis, and Validation and Testing, which includes the Sub-Elements Flight Experiments and Integrated Testing. Systems engineering analysis by ELS seeks to optimize overall mission architectures by considering all the internal and external interfaces of the life support system and the potential for reduction or reuse of commodities. In particular, various sources and sinks of water and oxygen are considered along with the implications on loop closure and the resulting launch mass requirements. Systems analysis will be validated through the data gathered from integrated testing, which will demonstrate the interfaces of a closed loop life support system. By applying a systematic process for defining, sorting and answering critical life support questions, the ELS project is preparing for a variety of future human space missions.

I. Introduction

THE Exploration Life Support (ELS) Project's goals are to develop and mature a suite of Environmental Control and Life Support System (ECLSS) technology options for use on human space missions, including spacecraft, planetary habitats and planetary mobility systems. These technology options fill gaps or provide substantial improvements over the state-of-the-art systems such as those currently flying aboard the International Space Station (ISS) and Space Shuttle. Since space exploration missions are so challenging, mass, power, and volume requirements must be reduced from Shuttle and ISS technologies. ELS is achieving these goals through an organization of four Functional Elements: Atmosphere Revitalization Systems (ARS), Water Recovery Systems (WRS), Waste Management Systems (WMS), and Habitation Engineering, and two Cross-Cutting Elements: Systems Integration, Modeling and Analysis (SIMA) and Validation and Testing, which includes the Sub-Elements Flight Experiments and Integrated Testing. ELS is spread across five NASA field Centers: Johnson Space Center (JSC), Ames Research Center (ARC), Marshall Space Flight Center (MSFC), Kennedy Space Center (KSC), and Glenn Research Center (GRC), as shown in Fig. 1. For long duration missions, technologies which aid in the closure of the atmosphere and water loops with increased reliability are essential, as well as techniques to minimize or deal with waste (Jones/Ewert, McQuillan et al. etc?). Systems engineering analysis is conducted to optimize the overall

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architecture by considering all the interfaces with the life support system and the potential for reduction or reuse of resources. Integrated testing is performed to validate the interfaces, provide data for model validation, and increase the technology readiness level (TRL) of subsystems and systems^{1,2}.

Full closure of the atmosphere and water loops is essential to long duration human exploration missions beyond low Earth orbit due to the high costs of bringing all the required supplies from Earth. The challenge for the ELS Project is to develop an integrated, regenerable, closed-loop life support system while making it efficient, safe and reliable with reduced requirements (mass, power, heat rejection, volume, crew time, consumables). To achieve this closed system, there are many critical questions that need to be answered. So ELS has embarked on a campaign to gather all critical questions that principal investigators of technologies have determined are necessary to answer to ensure their subsystem or system will be successful. This is a ground-up approach that will ensure all the critical questions are captured and that each integrated test that is performed has one or more specific purposes. These critical questions will be assessed as part of the process described below; resulting in validated integrated testing needs for closed loop life support technology development.

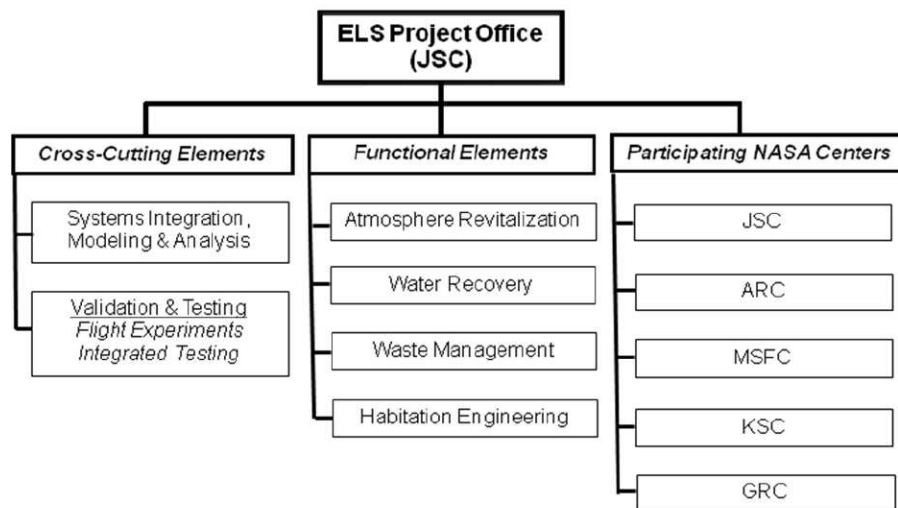


Figure 1. Exploration Life Support Project Organizational Chart

II. Integrated Testing

Integrated testing can be conducted at many levels and is a necessary component of any technology development activity to advance a technology's maturity level. For the purpose of this paper integrated testing is defined as candidate technologies evaluated at subsystem or system levels interfacing with another Element's hardware or challenged by real metabolic loads (i.e. human involvement). Integrated testing allows for demonstration and data collection of technology-to-technology interface compatibility between components, subsystems and systems. End-to-end functionality, including operability and interaction of life support hardware and software, including control algorithms, can be demonstrated. ELS defines a subsystem as a specific technology and defines four systems; atmosphere revitalization, water recovery, waste management, habitation engineering. Together these four systems make up the combined closed loop life support system. Test data is critical to the validation of SIMA Element models used to predict integrated performance of systems. Integrated testing is also useful in identifying weaknesses in technology integration approaches that can assist in down-selections, allowing for more efficient focusing of future technology development resources on hardware with the best characteristics.

Integrated testing also addresses the increasing complexity associated with life support systems as technology development progresses from seemingly simple components to subsystems and systems. One of the objectives of integrated testing is to assist in realizing a robust and reliable design at a multi-functional level. Products from integrated testing include well-characterized functional interfaces at various levels of complexity, suitable for generating design specifications; improved understanding of the effects of component optimization on subsystem and system functional robustness; and improved confidence in the functional robustness of candidate life support system architectures.

The ELS Project manages this effort through the Integrated Testing Element, which is a crosscutting technical area that is utilized when integration between Elements is required or for testing ELS system interfaces with other technology development projects and mission focused programs. This Element encompasses the development of the integrated tests to include development of the validation articles; development or acquisition of special test or validation equipment or procedures; scheduling and staffing facilities; and execution of the tests.

A. Justification

The ELS Technology Develop Project is governed by the NASA Procedural Requirements (NPR) 7120.8 Research and Technology Program and Project Management Requirements document. This document defines Validation and Testing in Appendix K, titled Research and Technology Project Work Breakdown Structure, by stating an Integrated Testing Element “provides for a focus on specific activities to test and validate products of technology development when those activities represent a critical aspect of the overall technology development plan. Not all technology projects require this level of attention on test and validation. Typically, a separate test and validation element will be part of the project that intends to achieve technology readiness level 6/7. The element encompasses the development hardware/software test validation articles; development or acquisition of special test or validation equipment or procedures; scheduling and staffing facilities or ranges; as well as the development and execution of the test or validation plan. Often the full context and content of test and validation may not be known at the beginning of the project and will be developed as required.” The Integrated Testing Element aligns to this guidance by following the process of identifying the critical interfaces that lead to integrated testing requirements.

The NASA Systems Engineering Handbook is another good resource that states the importance of conducting integrated testing by saying “just verifying the component parts (i.e., the individual models) that were used in the integration is not sufficient to assume that the integrated product will work right. The only sure way of knowing if an integrated product is good is to perform verification and validation at each stage.” ELS will address this concept by assessing all the integrated testing needs to determine at what stage of the technology development it is best to start integrating and where it is best to conduct the test.

The Integrated Testing Element coordinates with other projects where there are mutual interfaces. One Project-to-Project Cooperation Agreement (PPCA) that ELS currently has is with the Extra Vehicular Activity (EVA) Project, the In-Situ Resource Utilization (ISRU) Project, and the Advanced Environmental Monitoring and Control (AEMC) Project. The document states that the teams will identify “potential areas for collaboration to address common system interfaces and technical requirements. This collaboration may lead to joint hardware development and system demonstration activities.” Section 2 of the document lists task descriptions including water electrolyzer and fluid system component technology development collaboration, trash processing technology development collaboration, integrated plan development to define concepts and interfaces for an outpost, and integrated testing opportunity definition. The document also refers to an Integrated Plan Task with the objective to identify and define the interfaces (including conditions such as pressures, temperatures, etc.) and operational concepts for distributing consumables between ISRU, ECLS and EVA systems, and the needed quantities. The Integrated Testing Opportunity Task objective, mentioned in the document, is for all projects to discuss their technology development plans and reach an agreement on integrated testing needs that provide value to future systems.

B. Objectives

The objectives of Integrated Testing are to evaluate candidate technologies at subsystem and/or systems levels in a relevant environment, challenged by real metabolic loads and interfaces with other systems as appropriate, demonstrating functional integrated performance at increasing levels of integration complexity. Integrated Testing will achieve the following goals:

- Increase the systems-level technology readiness level, utilizing down-selected matured technologies.
- Validate interfaces between all ELS systems of atmosphere, water, waste and habitation.
- Validate mathematical models that predict the performance of the integrated ELS systems.
- Validate interfaces between external systems from Projects such as In-Situ Resource Utilization (ISRU) and Advanced Extra-Vehicular Activity (EVA).
- Maintain communication with other programs and projects with relevant interfaces to ELS systems.

C. Expected Results

The main products of integrated testing will be test data and reports. The results of integrated testing may lead to updates in mathematical models and further analysis of system interactions.

The current ELS Integrated Testing Element deliverables are:

- A planning document showing all the Elements of the ELS system architecture with all the functional interactions between them.
- An assessment of what interactions need to be tested via an integrated test to ensure the systems will work.
- A prioritized list of the proposed integrated tests to be used for funding decisions.

Future integrated tests are planned to quantify the closure of the atmosphere and water loops identifying and characterizing to the greatest extent possible the key functional interfaces. Once system level hardware has been tested to the appropriate level, systems will be tested together to ensure loop closure is achievable with real habitation interfaces and incorporating waste systems as required. An important part of this testing is with real humans in the loop. Metabolic loads will be simulated or provided directly by human test subjects as deemed technically appropriate and feasible within the constraints of available resources. Testing of integrated atmosphere revitalization, water recovery, waste management, and habitation systems in the context of a complete closed loop life support system in a relevant environment with real human metabolic loads will be conducted as part of the Integrated Testing Element charter to demonstrate a technology readiness level (TRL) 6 system.

The goal of technology maturation to TRL 6 via integrated testing is achieved as hardware with increasing fidelity is evaluated in more and more realistic environments until ultimately a high-fidelity prototype, that adequately addresses all critical scaling issues, is operated in a relevant environment to demonstrate operations under critical environmental conditions with appropriate interfaces. Integrated tests will be scheduled to provide environments and interfaces to demonstrate that potential technology options are mature enough to be adopted by flight projects by the necessary infusion dates.

Opportunities to integrate ECLSS hardware into field tests of demonstration projects and other analog testing opportunities will be considered as they become available. The goal is to have a full systems level test validating all the interfaces required for a closed loop life support system. Some examples of opportunities for collaborative integration are with the Lunar Electric Rover (LER) and Habitat Demonstration Unit (HDU) field tests. The LER development unit, as shown in Fig. 2, is a small pressurized rover that operates with two astronauts for short duration missions with sleeping and sanitary facilities. It is designed to require minimal maintenance and be able to travel thousands of miles during its ten year design life. Astronauts would be able to work in shirtsleeves in the safety of the cabin, and when they need to they could quickly enter and exit their spacesuits through a suit port. One of the objectives of the HDU project is to serve as a platform for integration, tests, and evaluations of technologies. The HDU will be a low to medium fidelity facility demonstrating the 4-port vertical habitat concept, as shown in Fig. 3, with potential capability for operation at analog sites (supporting a 2-4 person crew for 14-30 days). The LER and HDU facilities are particularly good for testing crew interfaces and operational concepts, which are important parts of integrated testing. The potential collaboration opportunities are in the areas of:

- Waste management (waste stabilization, compaction, and water recovery).
- Habitation interfaces (clothing, housekeeping, and dust mitigation strategies).
- Water recovery systems interfaces, evaluation of water requirements.
- Habitat interfaces to ECLSS controls.
- When these projects incorporate higher fidelity environments, then collaboration could exist with:
 - Quiet fan integration.
 - Particulate removal (maybe limited to airlock use at analog sites).
 - A water recovery system could potentially be integrated and operated within the HDU facility.



Figure 2. Lunar Electric Rover.



Figure 3. HDU Analog Concept.

Note that traditionally active Thermal Control Systems (TCS) are included as part of the overall ECLSS, but TCS is not part of the ELS Project. There is currently an independent Thermal Control System Development for Exploration Project that ELS will collaborate with on any potential interfaces and integrated testing opportunities.

III. Critical Questions Flow Diagram

To determine the integrated testing needs, ELS first developed a methodology, as shown in Fig. 4, to determine what testing would be required to meet the goals of the project. The first step was to compile a comprehensive list of critical questions that principal investigators, Element Leads, Center Leads, and Project Management submitted either for a specific technology, Element system or Project level system. The list is now being assessed according to the flow diagram to determine the integrated tests required. The integrated testing needs will be prioritized and then planned accordingly, based on available resources.

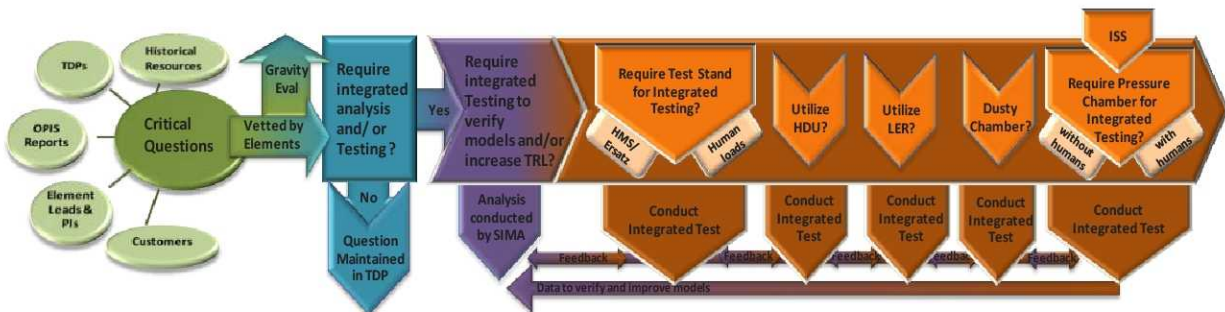


Figure 4. Critical Questions Flow Diagram.

A. Step 1 – Identify and Review Critical Needs

The first step is to identify all the critical questions that need to be answered for ELS technology development to be successful. These questions can be identified from various sources including Technology Development Plans (TDPs), On-Line Project Information System (OPIS) Reports, Element Leads, Principal Investigators, and Customers. ELS requires each Principal Investigator (PI) developing a technology to write and maintain a Technology Development Plan (TDP). The ELS Project Office currently maintains 31 TDPs. The TDP introduces the technology with background information along with the goals and objectives, deliverables, key performance parameters and requirements, justification, progress, current TRL, technical approach/methodology, risks, schedule, and, more importantly, the key research and technology development questions. This section is where the majority of the critical questions are listed, but some PIs also specifically include an integrated test in their long range schedule (See Fig. 5 for an example of these sections in a TDP). The other main source of critical questions is OPIS reports. Each PI of an ELS task is required to complete an annual report detailing their work for the year and post it to their OPIS website Task Page. In 2009, there were 27 OPIS Reports completed. Each OPIS Report is reviewed and approved by the appropriate ELS Element Lead. OPIS Reports detail the general information about the work performed to date and the current state of the technology including hardware specifics and test results. A specific section of the report called system integration, as shown in Fig. 6, is important for identifying critical needs because the author is asked to provide input based on the following guidance:

For each deliverable intended for flight, briefly discuss system integration issues and/or requirements for an operational setting. Consider:

1. What resources does the deliverable produce that other systems may utilize (e.g., waste heat)?
2. What resources may the deliverable be able to utilize from other systems?
3. What interface requirements does the deliverable have (e.g., data, structural support)?

Other documents that provide some input are the ELS Monthly Reports and Customer Supplier Agreements (CSAs). The Monthly Report provides the status of all the ELS tasks and a look ahead at the next two months providing a venue for newly discovered questions. The CSA is an annual agreement between ELS and customers outlining the current year plan as well as the long range plan, which includes integrated testing needs. The remaining sources of critical questions are more informal, including Element Monthly teleconferences, technical interchange meetings and direct input from ELS team members and customers. This compiled list of critical questions becomes the database for potential integrated testing needs. So far ELS has identified over 100 critical questions that are maintained in a database, as shown in Fig. 7. Next all these critical questions are vetted by the Functional Elements and Project Office to determine, from a technical standpoint, which questions relate to integration and need to be assessed further. Some needs may refer to issues relating to reduced gravity so they will be forwarded to the cross-cutting Flight Experiments Element for further evaluation.

B. Step 2 – Assess the Critical Needs for Analysis

From this list of vetted critical questions dealing with integration, the SIMA cross-cutting Element will take the lead, assisted by the Functional Elements and Project Office, in assessing the list to determine which questions require some level of integrated analysis or integrated testing to answer. Those questions not requiring any support from the cross-cutting Elements are maintained in the TDP for that particular technology and are expected to be answered within the Functional Element team. Those questions requiring integrated analysis are incorporated into the SIMA TDP and roadmap for future work. Some critical questions may be assessed and determined to not be appropriate for analysis, but may still require integrated testing, so they would still proceed to Step 3.

FY10 Technology Development Plan																													
Direct Osmotic Concentration (DOC)																													
WBS: 439906.04.02.01-03.01.03 [Water Recovery Systems]																													
<p>3.2. Key Research & Technology Development Questions</p> <p>The objective of completing operational testing is to evaluate the systems performance and to identify problems or improvements. The DOC is a new technology and the testing that will occur this year at JSC is the first real operational evaluation of its performance. Initially the objective is to determine mass, power, and volume. Ultimately the objective is to determine the potential of the technology and decide whether to continue development of it.</p> <ul style="list-style-type: none"> What is the power requirement for a long duration mission waste stream? What is the mass required for a long duration mission? What is the volume required for a long duration mission? What is the life of the P/O membrane? What interfaces are required to allow it to work in an architecture? 																													
<p>7. Budget, Schedule and Milestones</p> <table border="1"> <thead> <tr> <th>Milestone</th><th>Milestone Title</th><th>Completion Date</th></tr> </thead> <tbody> <tr> <td>MS# 04.02.XX</td><td>Support JSC Testing</td><td>9/30/10</td></tr> <tr> <td></td><td>Conduct Technology Review</td><td>12/30/10</td></tr> <tr> <td></td><td>Prepare Advanced Development Plan</td><td>2/30/11</td></tr> <tr> <td></td><td>Complete Upgrade from DOC System</td><td>9/30/12</td></tr> <tr> <td></td><td>Deliver System to JSC for integrated testing</td><td>10/30/12</td></tr> <tr> <td></td><td>Support JSC Testing</td><td>9/30/13</td></tr> <tr> <td></td><td>Complete PDR Documentation</td><td>11/30/14</td></tr> <tr> <td></td><td>Support PDR</td><td>TBD</td></tr> </tbody> </table>			Milestone	Milestone Title	Completion Date	MS# 04.02.XX	Support JSC Testing	9/30/10		Conduct Technology Review	12/30/10		Prepare Advanced Development Plan	2/30/11		Complete Upgrade from DOC System	9/30/12		Deliver System to JSC for integrated testing	10/30/12		Support JSC Testing	9/30/13		Complete PDR Documentation	11/30/14		Support PDR	TBD
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Figure 5. Technology Develop Plan Example.

OPIS	
System Integration	
IMPORTANT! - Do not change this bordered section in any way -	
<p>For each deliverable intended for flight, briefly discuss system integration issues and/or requirements for an operational setting. Consider:</p> <ol style="list-style-type: none"> 1. What resources does the deliverable produce that other systems may utilize (e.g., waste heat)? 2. What resources may the deliverable be able to utilize from other systems? 3. What interface requirements does the deliverable have (e.g., data, structural support)? <p>Responding to this request in full detail could require extensive effort. Therefore scope the response according to data availability, deliverable TRL and task level of effort. Low TRL deliverables may have a general response with a modest level of detail, but response extent, detail, and accuracy should increase with TRL. If portions of the request are not applicable, please explain so. You may cross-reference other sections in this report and other documents to avoid repetition. You may upload supplementary information to this report as separate files in OPIS, using the report upload page, but you must cite that information by filename in this report.</p>	
<p>Quality of the water recovered will affect the integration with the Water Recovery System (WRS).</p> <p>Off-gassing and gaseous contaminants released during the waste processing system may be important in deciding the ability to integrate with the Air Recovery System (ARS).</p>	
End of System Integration - Do not change this bordered section in any way -	

Figure 6. OPIS Report Example.

Exploration Life Support (ELS) Integrated Testing Needs Database														
Needs - Critical questions					Gravity Eval	Element/Technology Level	Integrated Analysis	Integrated Testing						
#	Element	Technology	Description	Timeframe				HMS/Ersatz	Human loads	HDU	LER	Dusty Chamber	Chamber	
											w/o humans	w/ humans		
22	All	ECLS Architecture	What are the impacts of process vents on subsystem/assembly equipment sizing and their functional robustness?		No	Maybe - if no impact to other systems then yes	Yes - model to predict impacts on downstream systems	Yes - preliminary testing	Yes - more realistic data	No - not currently a sealed environment	No - not currently a sealed environment	No	Yes - test interfaces and operation scenarios	Yes - validate models
23	All	ECLS Architecture	Will the system deliver any off-nominal compounds (or energy) to its nearest downstream neighbor? Will the back-pressure of downstream components affect this system's performance? How?		Maybe - depends on system	No - definitely involves all elements	Yes - model to predict impacts on downstream systems	Yes - for basic impacts	Yes - needed to get compounds correct	Maybe	Maybe	No	Yes - test overall impacts	Yes - validate models
24	All	ECLS Architecture	Can long duration integrated function be maintained in a closed loop life support system without excessive accumulation of residuals?		No	No - Involves close loop system	Yes - to determine residuals	No	No	No	No	No	No	Yes - long duration testing
25	All	ECLS Architecture	What sensitivities do candidate ECLS processes have for various chemical classes, such as cleaning agents? Are there any chemical classes that should be avoided or banned to prevent functional degradation or loss of function? How will the crew clean food processing equipment, utensils and dinnerware?		No	Maybe - depends on impact to other systems	Maybe - if impact on system	Yes - test compounds in system	Yes - test using cleaning agents	Maybe - field testing	Maybe - field testing	No	No - need humans to use	Maybe - as part of closed loop test
26	All	ECLS Architecture	Given a system design, how do we control its operation so as to optimize its use of resources? What metric do we use to measure the goodness of different resource management strategies?		Maybe - depends on control scheme	No - Involves close loop system	Yes - to optimize controls	No	No	Maybe - field testing	Maybe - field testing	No	Yes - to test interfaces and controls	Yes - operation control test

Figure 7. Critical Questions Database Example.

C. Step 3 – Assess the Critical Needs for Integrated Testing

The SIMA team, working with the Integrated Testing team and Project Office, will determine out of the remaining needs, which ones will require an integrated test to provide data to support, improve or validate the models developed in the analysis work. ELS has a goal of being able to model closed loop life support accurately enough to provide analytical results to multiple customers for decision making in a multitude of mission scenarios. The list of critical questions will also be assessed to determine which require integrated testing to demonstrate the integrated system in order to increase the Technology Readiness Level of a technology.

D. Step 4 – Assess the Integrated Testing Needs

Finally, the down-selected list of integrated testing needs will be assessed to determine what type of integrated test will best answer the critical question and which tests are required to increase the TRL of technologies. The options available to answer integration questions range from a laboratory test bed to a reduced pressure human-rated chamber to a test on the ISS. Laboratory test beds will be utilized for basic integration tests. These tests will most likely use a Human Metabolic Simulator (HMS) and ersatz solutions to simulate human loads. A HMS produces the metabolic output of human respiratory systems including carbon dioxide and moisture. A separate system is used to inject trace contaminants if that type of load is required for the relevant environment of the test. Ersatz solutions mimic the chemical and physical properties of human urine and humidity condensate from living spaces, as well as hygiene wastewater.

When the fidelity of these tests needs to be increased to ensure more relevant environment data, human inputs to the test could include crew evaluations and actual human generated waste streams. Crew evaluations involve getting the astronaut office to send representatives to review the usability and feasibility of a design and technology operational scenario, which may result in feedback that has a big impact on the technology development plan. Human generated waste streams include collected urine, humidity condensate (collected from test subjects exercising in a closed chamber), hygiene waste water (collected from test subjects taking showers, washing hands, shaving, and brushing teeth), and, in the future, laundry waste water. Specific test beds that could be used to answer a specific question include dusty chambers, the HDU and the LER which can provide some aspects of relevant environments, such as volume and operational scenarios. Chambers capable of sealing the atmosphere and going to reduced pressures (which are expected for human exploration missions) will be utilized for more complex integration tests requiring relevant environments with and without humans in the loop. After conducting tests, the data will be delivered to SIMA for model verification and improvement. It is important to note that SIMA will be involved in the planning of the tests as well so that specific data can be requested that will help specifically with model development and validation. Integration is an iterative process between analysis, integrated testing and hardware developers. Any integrated testing that is determined to be conducted on ISS will be sent to the Flight Experiments Element for execution.

IV. Critical Question Example Assessments

The critical questions presented here are examples showing the assessment process each question will be subject to in order for ELS to determine future integrated testing needs. Starting with Step 1, a critical question taken from the OPIS Report for a waste management technology to recover water from waste states:

“Can the off-gassing and gaseous contaminants released during the waste processing system cycle be vented directly to the cabin environment or is it required and able to be processed by the trace contaminant control system (TCCS) of the atmosphere revitalization system?”

To complete Step 1 the question would be vetted by the Element leads. Assuming the question is supported by the leads this question does not appear to have any microgravity issues and therefore would not require any microgravity sensitivity evaluation by the Flight Experiments Element. Next is to assess if the question requires integrated analysis or testing to complete Step 2. If through performance testing conducted within the WMS Element it is determined that the process vent gas is safe to dump into a cabin environment then no further assessment would be required and that question would remain at the technology level. It will be important to note any aggregate effects of multiple vent gases being dumped into a cabin environment in a closed loop life support system. If the vent gas is not safe to dump into the cabin then the question would involve two ELS Elements and would need to be addressed by the Integrated Testing Element. Step 3 is the assessment for integrated analysis and one could be performed to assess the impacts on the TCCS based on input stream models and TCCS performance models. In order to validate those models an integrated test would need to be executed with a test stand incorporating the waste processing hardware and the TCCS hardware, which addresses Step 4. The input stream would use both simulated human waste for preliminary data for verification of the interface and real human waste to provide data to validate the models.

Another critical question from historical resources dealing with Habitation Engineering for a laundry technology states:

“Can a down-selected laundry system (minimal to full) be successfully integrated into a habitat and WRS?”

This question may require microgravity evaluation depending on the mission and type of system employed. If it uses water in a microgravity setting, then it would certainly be required. This technology would need to be integrated into a water recovery architecture because it would greatly increase the quantity of wastewater. It also involves a crew interface and therefore would require the Integrated Testing Element to be involved. An integrated analysis could be conducted with closed loop life support system water models to address sizing and other system

impacts. Those models would need to be validated by testing using laundry ersatz solutions and then real human laundry wastewater. The integrated test would eventually need to incorporate the WRS architecture in a closed loop for interface verification, crew acceptance and to determine the full impact on the water architecture.

ELS customers and other technology development projects can influence or dictate some critical questions about ELS technology efforts such as:

“What is the quality of water received from ISRU?” and “What is the best method to make it potable?”

These questions are not related to microgravity, so no assessment would be required. Since the question involves another project the Integrated Testing Element would be required. An integrated analysis could be conducted to predict the impacts to the water system and the model could be validated with test data using a test stand with ISRU hardware and WRS hardware.

For the ARS, some other important questions that have been identified are:

“What is the propagation and/or fate of trace chemical contaminants through a closed ECLS system, such as a distiller venting non-condensable volatiles or waste processes creating organics?”

What is the proper trace contaminant load and performance model to drive the design and operation of the trace contaminant control system?

How does the quiet fan design impact the cabin ventilation design and prime mover (fan) design to benefit the ARS acoustic characteristics?”

For the WRS, some important issues are:

“What are the long term effects of corrosive pretreatment on the WRS system?”

How does wastewater composition (pre-treat, surfactants, etc.) impact processing?

Is it economical/practical to integrate brine and solid waste processing systems?”

When assessed, these first two critical questions were determined to remain with the WRS Element, while the third was found to be an integrated question.

For the WMS, some questions being addressed are:

“Can the waste product (bricks) from the heat melt compactor be used for radiation protection on habitats?”

Must human waste be sterilized for planetary missions?

What about vented gases?

What are the costs of sterilization, stabilization, or just storage?

Can we meet planetary protection standards? At what cost? Given the costs and benefits, what is the right requirement?”

For Habitation Engineering, questions include:

“Can solar light piping be integrated into a habitat or vehicle to provide natural light?”

Can a prototype collapsible/reconfigurable stowage system be successfully integrated into a vehicle habitat?

Does the type of clothing material have an impact on the WMS if processing the waste?

How does the occurrence of a solar particle event (lasting up to 10 days) affect the design and operational scenario of a habitat for a Mars transit vehicle?

How will the crew clean food processing equipment, utensils and dinnerware?”

Many critical questions affect all Elements of ELS. These include:

“What are the efficiencies possible with waste heat availability in an integrated system?”

What sensors are required to provide environmental data, monitor performance and provide inputs to control systems?

What are the requirements for AEMC?

What level of redundancy is acceptable? Should redundancy include systems that offer alternative processing or pathways? Are there operational advantages to having redundancy besides the robustness to failures?

How do we design for reliability on a mission? Rather than designing for low failure rate, shouldn't we plan for maintenance, repair, and replacement? How do we design life support systems to handle off-nominal or failure scenarios?

Can we look at reasonable "worst case" scenarios to identify effects on system design?

Can long duration integrated function be maintained in a closed loop life support system without excessive accumulation of residuals? What sensitivities do candidate ECLS processes have for various chemical classes, such as cleaning agents?

Are there any chemical classes that should be avoided or banned to prevent functional degradation or loss of function?

How does growing a small amount of food (salad machine) affect the air, water, and other systems?”

A final critical question for the closed loop life support system that will be discussed here is:

“How do we design life support systems to handle variability?”

Crew loads will vary. We must think about the dynamics of input-output relationships for the crew, especially in high-mobility mission scenarios? As some crew members go EVA or leave their habitat to spend a few days in a pressurized rover, their metabolic loads move to new locations. If their waste products are to be collected and processed, this complicates a closed loop ECLSS architecture. This is not a gravity dependent issue per se, but it needs to be addressed at the Integrated Testing Element level. Different operational scenarios can be modeled for an entire system, but the models will need to be validated using an integrated closed loop life support system test with real human metabolic loads.

V. Conclusion

A method has been presented to gather, assess and answer questions that are critical to successful development of life support systems for future human space missions. This method, which is being utilized by NASA's Exploration Life Support Project, involves careful evaluation of gravity sensitivity, the role on integrated analysis and separation of issues into those that can be resolved within ECLSS Elements and those which require integrated testing across systems (e.g. obtaining water from solid waste). By using the flowchart presented here to help answer the critical technology development questions for an exploration ECLSS, the ELS Project is helping to ensure that NASA can carry out a variety of human space missions beyond low Earth orbit.

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