

NextSTEP Appendix A Modular ECLSS Effort Lessons Learned

James Clawson¹

Stellar Solutions, Inc., Palo Alto, CA, 94306

Daniel Barta²

National Aeronautics and Space Administration Johnson Space Center, Houston, TX, 77058

Walter Schneider³, David Howard⁴

National Aeronautics and Space Administration Marshall Spaceflight Center, Huntsville, AL, 35812

and

Marlon Cox⁵

National Aeronautic and Space Administration Headquarters, Washington D.C., 20546

The first appendix under NextSTEP-2 solicitation, Appendix A, focused on developing deep space habitation concepts, engineering design and development, and risk reduction efforts leading to a habitation capability in cislunar space. Collins Aerospace, formerly UTC Aerospace Systems (UTAS), was awarded a Phase 1 and a subsequent Phase 2 contract to “develop concepts that group ECLS systems into logical modules maximizing the use of common components and the development of unique methods and design concepts that support in-flight maintenance and repair for future exploration systems.” This effort developed and matured a modular palletization concept to enable standard rack interfaces, post-launch outfitting, and decoupling of structural supports that withstand launch environments from those needed for lower on-orbit loads. Collins also assessed numerous architecture trades, including the use of condensing and noncondensing heat exchangers, the ability of modular units to accommodate various habitat volumes and thermal loading, and the most appropriate order and timing of delivery of regenerative ECLSS hardware to orbital habitats. Collins additionally developed software approaches for distributed/modular command, control, and communication systems and innovative Bayesian fault detection and isolation techniques. Finally, the effort explored advanced maintainability and supportability concepts including the definition of maintenance units (MUs) in place of the traditional Orbital Replacement Units (ORUs), increasing parts commonality to reduce the number and type of spare parts, the use of augmented reality to guide crews during maintenance and repair procedures, and how crews would prepare for and recover from long durations of habitat dormancy. Now that the NextSTEP Modular ECLSS effort has come to a close, it’s important to summarize the work accomplished under this effort and identify the lessons learned and where they can be leveraged to improve NASA’s broader program of ECLSS technology development and demonstration and ultimately how they can increase the performance of future surface and orbital habitats.

¹ Technical Advisor, NASA Exploration Systems Development Mission Directorate, 300E St SW, Washington, DC 20546, Mail Code.

² Life Support Systems Technical Assistant, Life Support Systems Branch, 2101 NASA Parkway, Mail Code EC3

³ Project Manager, Exploration Capabilities Life Support Systems, 4200 Rideout Rd SW, Huntsville, AL 35812 Mail Code HP30.

⁴ Aerospace Engineer, ECLSS Development Branch, MSFC, Huntsville, AL 35812, Mail Code ES62.

⁵ ECLSS Technology Manager, Exploration Capabilities, 300E ST SW Washington DC 20546, BF000.

Nomenclature

<i>AR</i>	=	Augmented Reality
<i>ARS</i>	=	Atmosphere Revitalization System
<i>BAA</i>	=	Broad Agency Announcement
<i>BPA</i>	=	Brine Processing Apparatus
<i>CAC</i>	=	Condensing Air Cooling
<i>CDRA</i>	=	Carbon Dioxide Removal Assembly
<i>DFMR</i>	=	Design For Minimum Risk
<i>ECLS(S)</i>	=	Environmental Control and Life Support (System)
<i>FDIR</i>	=	Fault Detection, Isolation, and Recovery
<i>GUI</i>	=	Graphical User Interface
<i>HEPA</i>	=	High Efficiency Particulate Absorption Filter
<i>IHMS</i>	=	Intelligent Health Monitoring System
<i>IMCA</i>	=	Integrated Modular Control Architecture
<i>ISS</i>	=	International Space Station
<i>LEO</i>	=	Low Earth Orbit
<i>MU</i>	=	Maintenance Units
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NextSTEP</i>	=	Next Space Technologies for Exploration Partnerships
<i>OGA</i>	=	Oxygen Generation Assembly
<i>ORU</i>	=	Orbital Replacement Unit
<i>SAM</i>	=	Spacecraft Air Monitor
<i>TCCS</i>	=	Trace Contaminant Control Subsystem
<i>TMS</i>	=	Thermal Management System
<i>THC</i>	=	Temperature/Humidity Control
<i>UPA</i>	=	Urine Processing Apparatus
<i>UWMS</i>	=	Universal Waste Management System
<i>WP</i>	=	Water Processor

I. Introduction

NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) effort was a public-private partnership aimed at advancing deep space exploration habitation capabilities. The program was launched in 2015 to leverage available industry existing or planned capabilities in Low Earth Orbit (LEO) to help define feasible potential habitation architecture concepts that address NASA's objectives for deep space missions. NASA awarded four habitation concept study contracts through the NextSTEP BAA under three areas; Transportation, Habitation, and Operations & Environment.¹ One contract was awarded to Hamilton Sundstrand Space Systems International, Inc. (now Collins Aerospace) to "Develop concepts that group ECLS systems into logical modules maximizing the use of common components and the development of unique methods and design concepts that support in-flight maintenance and repair for [...] future exploration systems." The effort arose from the notion of a universal environmental control and life support system (ECLSS) that is adaptable to multiple exploration platforms and missions embodying the key characteristics of Evolvability, Resiliency, Modularity, Affordability, and Intelligence. The scope of the effort involved studying various topics such as identifying driving requirements, outlining baseline NextSTEP technologies, developing initial safety considerations, developing a modularized pallet concept, grouping subsystems together, and performing an in-flight maintenance study.

The work continued under the NextSTEP-2 program in 2017 with the goal of further developing the ECLSS technology. While continuing to mature the concepts addressed in Phase 1, the Phase 2 effort included developing an Integrated Control Architecture, defining ECLSS Standards and Habitat Interface, exploring the use of intelligent systems, developing of a functional Air Revitalization System Prototype, studying methods for in-flight maintenance, and more. Finally, an extension to Phase 2 continued the development of the functional Atmosphere Revitalization System (ARS) pallet to include a full capacity Thermal Amine Scrubber and refinement of the pallet design to decouple the structure required to withstand launch loads from the structure required on-orbit along with smaller tasks.

The NextSTEP Modular ECLSS effort came to a close in 2022. It was a significant step forward in the development of deep space exploration capabilities. The lessons learned contribute to NASA's progress towards its goal of enabling long-duration human missions in deep space.

II. Safety and Reliability

An early focus of the NextSTEP Modular ECLSS effort was the implication of deep space exploration on ECLSS functional hazard mitigation approaches. Deep space exploration has more severe requirements for mitigating functional hazard risks than ISS operations due to longer mission duration, volume and weight restrictions, communications delays, and lack of re-supply from Earth. The philosophy for deep space exploration safety and reliability has two parts: safety and reliability. The safety part aims to identify and mitigate hazards that may cause loss of critical life sustaining functions in the ECLSS. The reliability part focuses on planned maintenance and increased system reliability to ensure safe and highly reliable operation and reduce the number of items and the corresponding mass that must be taken on the mission. Hazards are mitigated based on the criticality of the function and the design of the equipment. Catastrophic hazards, which result in loss of the vehicle or crew life, require two fault tolerance unless mitigated by Design For Minimum Risk (DFMR) that focuses on design properties to control safety.²

A. Hazard Timeline

Many traditional fault detection, isolation, and recovery (FDIR) implementations detect faults after they have occurred. Once the fault has occurred the clock is ticking on the time until a hazardous condition occurs. In addition to the traditional corrective action approach, Figure 1 shows notional hazard timelines for two additional scenarios: a predicted or anticipated fault and a planned maintenance activity.³ Depending on the scenario, there are up to five response segments: Fault Detection, Crew Response, Fault Isolation, Fixing the Fault, and System Recovery.

For the corrective action scenario it may require all five response segments to be completed that can leave little margin prior to the occurrence of a hazardous condition. The margin between completing corrective action and time to hazard can be increased by predicting pending faults, which gives the crew extra response time to address the issue. This scenario provides impetus behind the Intelligent Systems effort under NextSTEP-2 Modular ECLSS

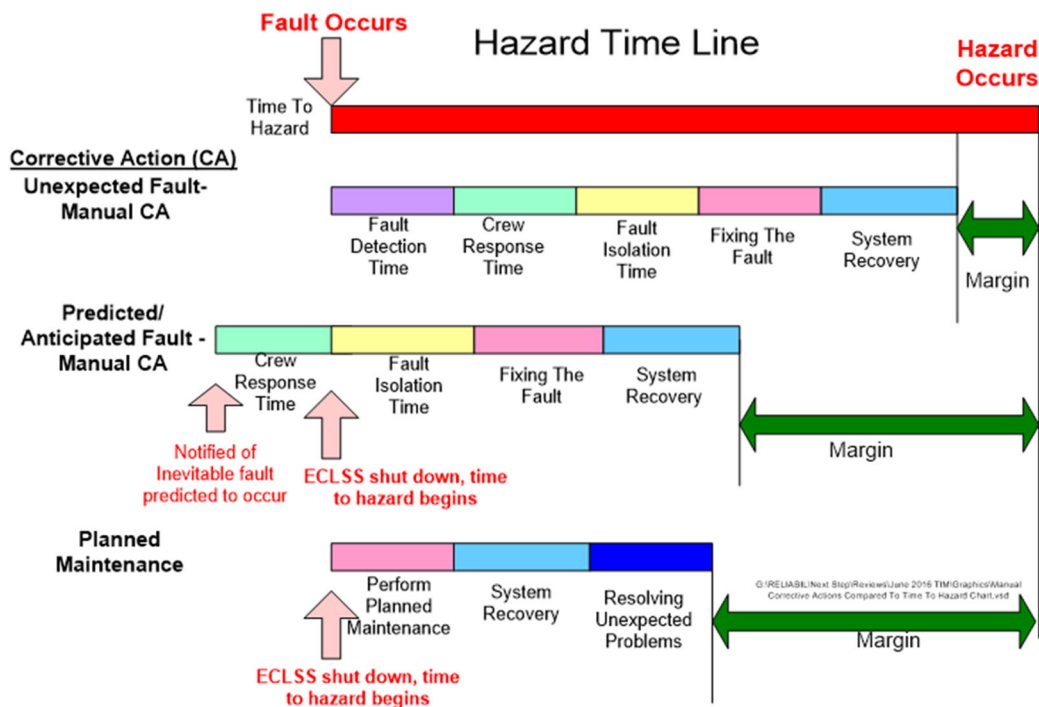


Figure 1. Hazard timeline showing the five response segments that may be applicable depending on the operational scenario.

described in section VII.B.

Planned, or preventative maintenance, is initiated on a schedule or milestone to perform maintenance on components before they wear out. The life sustaining function still has to be temporarily shut off, which creates a time to hazard scenario. However, since there is no fault to address, the Fault Isolation Time and Fixing The Fault do not apply, which increases the margin for time to hazard.

Hazards can be reduced by using built-in redundancy, common components, fault isolation equipment, and repairing components in-flight. While there are several ways that commonality of technologies and components can reduce risks, such as reducing spare hardware and training requirements, it could also create additional risk of common cause failures. The type of redundancy required to mitigating functional hazards depends on the time to hazard. If the time to hazard is shorter than the time required to conduct repairs, then an automatic built-in redundant system is likely needed. If the time to hazard is long, manual corrective action may be used, such as conducting repairs with spare components. The manual corrective action must be performed in a timely fashion and consists of several steps outlined in a timeline that can indicate the margin before the occurrence of a hazard. The time to hazard was estimated for various failures and systems to identify short hazard time requiring redundant built-in ECLS systems. The systems with short hazard times include Condensing Air Cooling (CAC), Trace Contaminant Control Subsystem (TCCS), Carbon Dioxide Removal Assembly (CDRA), Thermal Management System (TMS), and Spacecraft Air Monitor (SAM).

III. Development of a Modularized Pallet

NASA set a requirement for a standard, easily transferable ECLSS for deep space exploration. This approach was driven by the integration needs of vehicles, with a focus on large, integrated ECLSS assemblies that can be installed before launch or assembled on orbit with the aim of improving habitat integration and reducing complexity. In the past, small single-use vehicles used component-by-component packaging, while the ISS used larger integrated module racks. The team developed a Universal Pallet that could be used by multiple exploration habitats for various missions.

A. Universal Pallet

Figure 2 shows the Universal Pallet, which was conceived to be about half the size of ISS racks for ease of translation into habitat and assembly on-board. The Universal Pallet design was constrained to fit through the NASA standard hatch. The cross-sectional shape and length of the pallet was determined via virtual translation and handling considerations, shown in Figure 3. The design includes an opening front panel and pallet pivoting mechanism to facilitate access for in-flight maintenance while preserving high packaging efficiency.

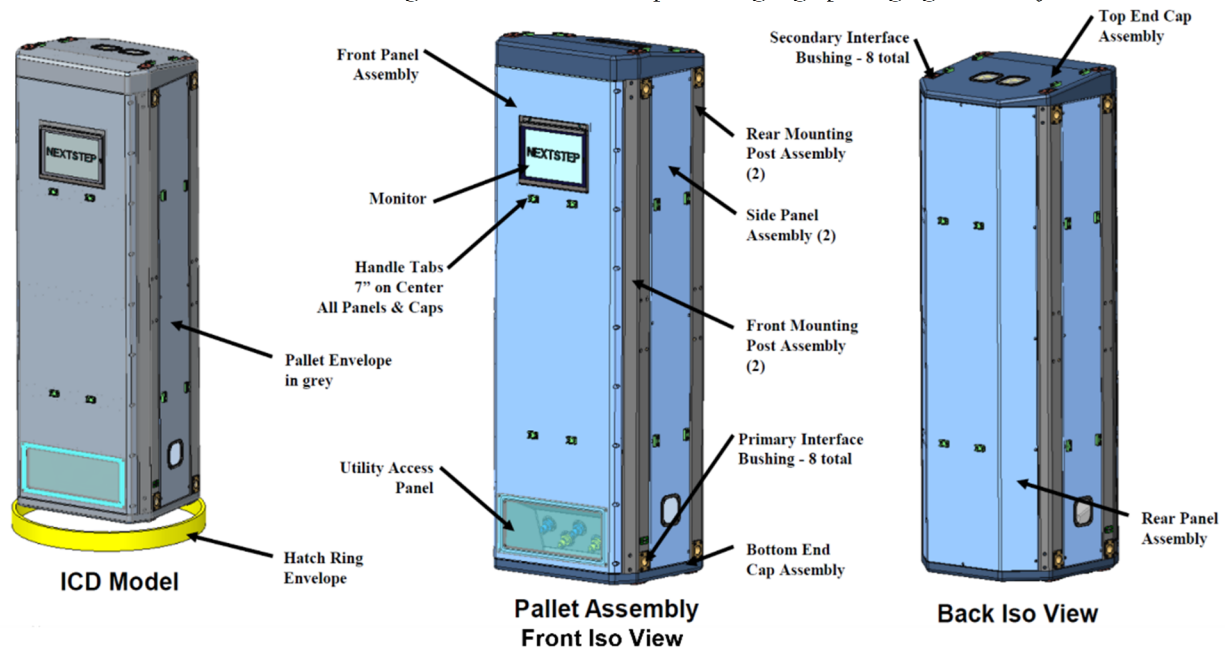


Figure 2. Universal Pallet⁴

The Universal Pallet was designed to withstand 50-g launch loads based on Collins' experience with designing similar hardware for the Orion spacecraft. The frame elements are manufactured from aluminum 6061-T6. The team has developed a lightweight version of the universal pallet for display purposes and a flight-like configuration for a ground test demonstration. Actual flight pallets would likely be fabricated using extruded profiles and machined base and top caps with an estimated mass of 83 kg. The team explored alternative lightweight materials and additive manufacturing methods to optimize volume and reduce mass.

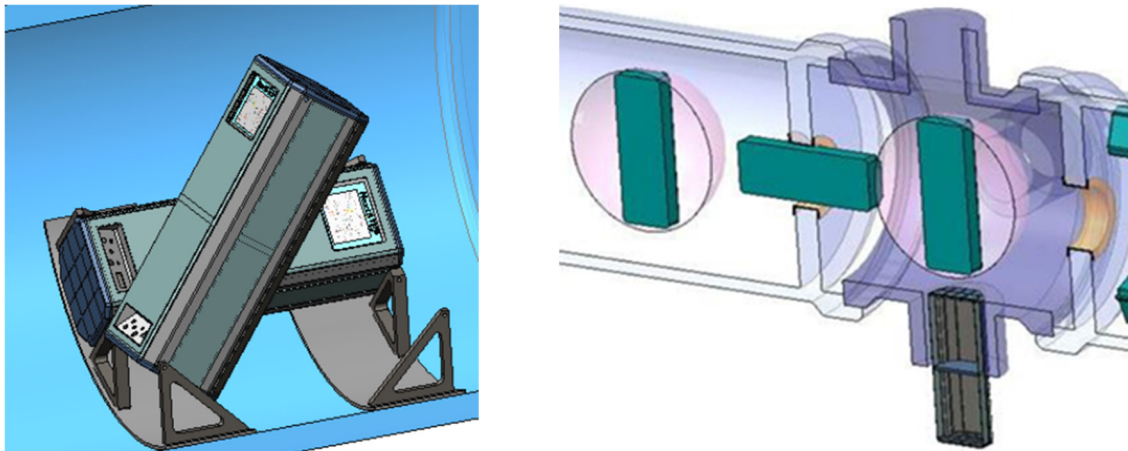


Figure 3. Pallet accessibility and ingress analysis

The Universal Pallet was designed to be used by multiple exploration habitats and has undergone several iterations. Collins shared information on the design with the NextSTEP App A habitat providers to gather feedback on how well the Universal Pallet integrated into different habitat concepts. Some of the feedback from habitat providers included the desire for a shorter and lower mass pallet design. While lower mass is an obvious desire for spacecraft systems, shorter pallets were requested to better package the systems against curved walls or in cylinder endcones. The team also considered the idea of a pallet hinged at the center to fit more closely to the internal curved surfaces, but ultimately did not pursue the concept.

B. Advanced Pallet

The mass of the Universal Pallet was cited as a potential issue that could limit the adoption of a modular ECLSS. NASA requested that Collins explore concepts that would decouple the structure required to withstand launch loads from the structure required to withstand on-orbit loads, which would be considerably smaller. They learned that it was indeed a viable option and the result was called the Advanced Pallet shown in Figure 4.

The Advanced Pallet maximizes modularity with common posts, panels, and endcaps that allow easy scaling of

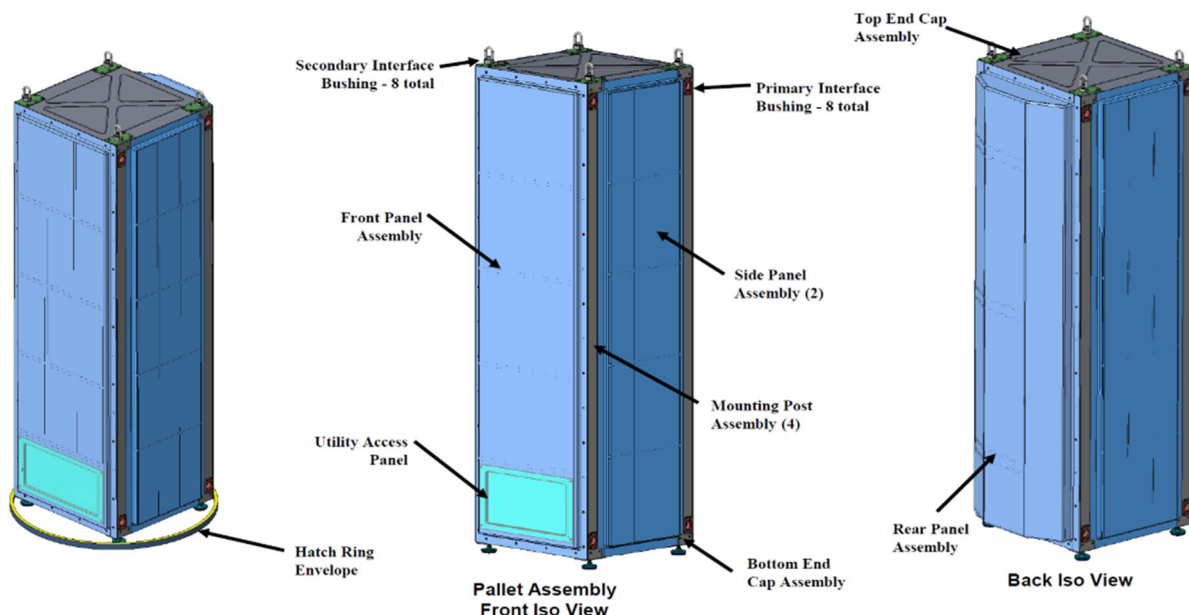


Figure 4. Advanced Pallet⁴

the pallet height with minimal modification to customize it for various habitat layouts. The side panel assemblies consist of an inner lightweight closeout panel and an outer structural panel that stiffens the structure for launch loads, but is removable once on-orbit. The removed panels can either be disposed of or repurposed within the habitat. The panel attachment scheme is identical on all four sides to allow varying configurations of panels, e.g. all four sides could have the ‘bump out’ shown on the rear panel to maximize internal volume while still fitting through a hatch. The pallet is designed to handle hard mounting for launch, but could likely be soft-stowed as well. The basic mass of Advanced Pallet at launch is 39 kg, or ~45 kg with a 15% mass growth allowance, which is ~54% of the mass of the Universal Pallet. The basic mass of the on-orbit configuration is 30.4 kg, or 35 kg with a 15% mass growth allowance, which is ~42% of the mass of the Universal Pallet.

IV. Packaging

With the pallet defined, focus turned to the packaging of the ECLSS functional components. Fourteen subsystems were selected as building blocks for an Exploration ECLSS. The criteria for selection were alignment with NASA's roadmap and a Technology Readiness Level of 6.

A. Functional Groups

As shown in Figure 5, the ECLSS architecture was subdivided into four functional groups: air revitalization (redundant groups A & B with auxiliary temperature/humidity control), water processing, oxygen generation and carbon dioxide reduction, and human waste management with an option for one or more auxiliary temperature/humidity control functional groups. While the number of pallets within a functional group varies, there is generally a controller per functional group with the exception of the already existing universal waste management controller, which could likely be integrated into the human waste management functional group controller in the future. The Collins team organized subsystems into the modular pallets in a way to minimize interfaces, particularly fluid interfaces, and maximize pallet population.

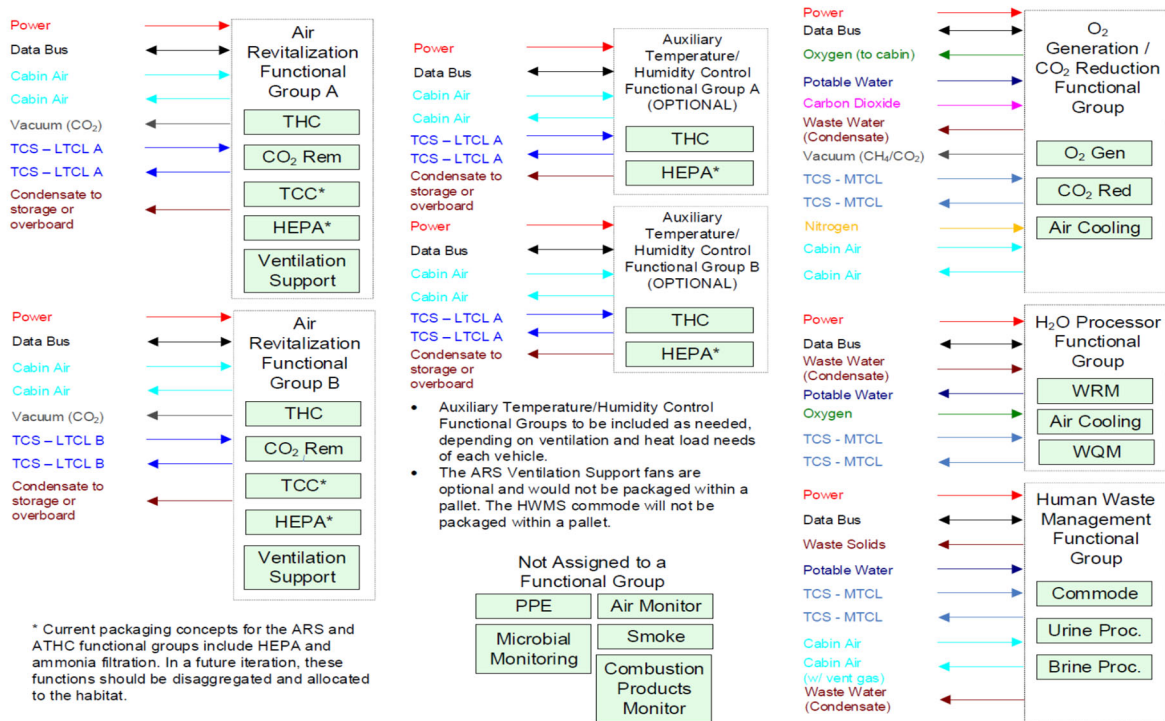


Figure 5. Deep space ECLSS functional groups showing inputs and outputs.

- The atmosphere revitalization functional group includes temperature/humidity control (THC), carbon dioxide removal, trace contaminant control (TCC), high efficiency particulate absorption filter (HEPA), and ventilation support.

- The optional auxiliary temperature/humidity control functional group includes temperature/humidity control and high efficiency particulate absorption filter.
- The oxygen generation and carbon dioxide reduction functional group includes oxygen generation, carbon dioxide reduction, and pallet air cooling.
- The water processing functional group includes water recovery and management, water quality monitor, and pallet air cooling.
- The human waste management functional group includes the commode, urine processing apparatus (UPA), and brine processing apparatus (BPA).

B. ARS Disaggregation and Scaling Study

NextSTEP Appendix A was a multi-track acquisition with system providers developing full habitat concepts while subsystem providers worked to mature components and subsystems that would go inside. NASA facilitated recurring technical interactions between system and subsystem providers, including Collins Aerospace and the Modular ECLSS effort. During these interactions two issues became apparent.⁵

First, the ventilation systems and the geometry envisioned to accommodate them often do not lend themselves well to a centralized circulation subassembly in some habitat concepts. NASA requested a study “to look at the potential for distributing the components included in the ARS functional group in strategic locations as part of the “basic” habitat infrastructure. The study will consider disaggregation strategies that are consistent with an evolution ECLS capabilities toward loop closure via delivering the other functional groups mounted in Pallets, while deploying assemblies required at the beginning of crewed operations.”⁶.

Second, the habitat concepts came in a range of sizes with varying amounts of internal heat loads. While all of the habitats accommodate 4 crew, the larger sizes require higher flow rates to maintain adequate ventilation velocity to prevent stagnation zones that could accumulate higher levels of carbon dioxide. Also, the larger habitats are capable of accommodating more equipment such as scientific instrumentation, etc. Therefore, NASA requested that the study investigate how ARS capability could scale to meet the range of requirements for flow and parasitic heat loads, or the sensible heat load from equipment within the habitat, excluding ECLSS.

The primary lesson learned was that some customization was required for sizing the filtration, ventilation, and temperature/humidity control (ARS Pallet 1 functions) to accommodate different habitat sizes, but carbon dioxide removal (ARS Pallet 2) and trace contaminant control (ARS Pallet 3) are driven by the crew, rather than the vehicle, thus, do not need to be resized for different sized of habitats given the crew complement stays the same. After extensive trades between combinations of condensing and sensible-only heat exchangers, it was recommended to use only condensing heat exchangers configured to process all of the ventilation flow, which maximized heat removal performance. Table IV-1 shows how the different trade study criteria were favored differently among the options. The disaggregated option offered greater customizability with the potential to optimize component mass/volume by offering flexibility in packaging. On the other hand, the palletized options offered better ease of design given the commonality and likely better characterized pressure drop. The outcome of the trade was not decisive, but disaggregation comes with additional design, development, test, and evaluation costs and additional integration and interface control than with the standardized pallets. Disaggregation also increases the potential for longer interconnections to ARS Pallets 2 & 3 that can increase pressure drops requiring more power and may require longer electrical cabling. The lesson taken away from the study is that adapting to the changes in temperature/humidity control needs imposed by habitat size variations is more economical using additional pallets.

Table IV-1. Disaggregated ARS trade study results with 1 = poor and 3 = good⁷

Trade Criteria	Options		
	Disaggregated	Palletized, Modular	Palletized, Universal
Customizability (Component Mass/Volume)	3	2	1
Packaging Flexibility	3	1	1
Ease of Design/Deployment	1	2	3
Pallet 2/3 Pressure Drop (Power)	2	3	3
Component Distance (Ducting/Cabling Mass/Volume)	1 – 2*	3	3

*This would depend heavily on implementation and is hard to quantify that this level.

Figure 6 shows the configurations of the ‘modularized’ and ‘universal’ ARS THC pallets. Each of the modularized pallets are essentially a fan, condensing heat exchanger, air temperature control bypass valve, and a muffler. The modularized ARS pallets can be deployed as 1, 2, or 3 pallets depending on the performance level required. The universal ARS consists of one pallet of blowers and one pallet of condensing heat exchangers. The two universal ARS pallets would always be deployed together and can be configured internally to adapt to the performance required. This can result in manifesting too much hardware for smaller habitats, but it could be considered internal redundancy. Table IV-2 shows the recommended configurations of modularized pallets for

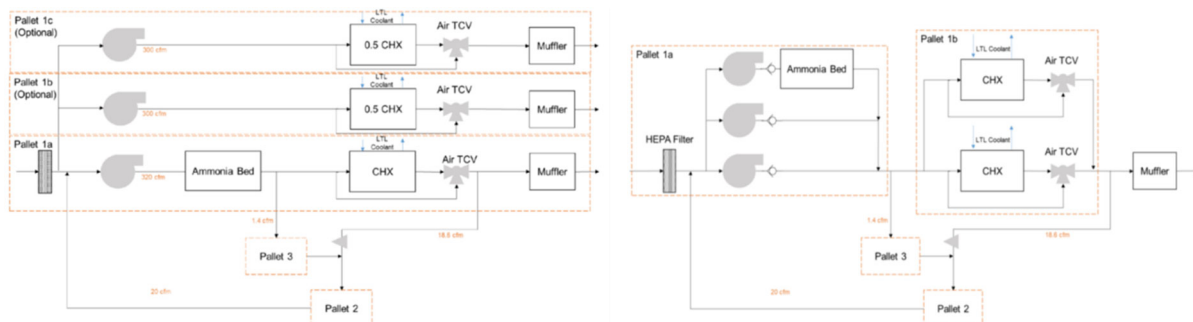


Figure 6 Modularized (left) and Universal (right) ARS temperature and humidity control pallet configurations.⁷

various habitat sizes and parasitic heat loads.

Table IV-2. Recommended configurations of modularized pallets for various habitat sizes and parasitic heat loads.⁷

	Habitat Volume			
	Small (45 m ³)	Medium (125 m ³)	Large (200 m ³)	XL (200 m ³)
Minimum Ventilation Rate	300 CFM	600 CFM	900 CFM	900 CFM
Maximum Parasitic Sensible Heat Load	1 kW	2.5 kW	4 kW	6 kW
Ventilation/THC Pallet Count	1	2	2	3
Disaggregated Ventilation Fan Count	0	0	1	0

V. Evolution from Open-Loop to Closed-Loop

Early incarnations of NASA’s Gateway outpost included a U.S. habitat that was envisioned to support 4 crew members for 30-90 day missions each year for a 15 year campaign. It was assumed to be outfitted at launch with an open-loop ECLSS including an ARS and a UWMS commode, but with the ability to evolve into a regenerative ECLSS once on-orbit. Logistics flights would carry additional hardware and supplies to the Gateway every two years starting in 2024. The impact to cumulative logistics upmass resulting from evolving to a regenerative ECLSS was analyzed. The ultimate recommendation was to launch a Water Processor (WP), Oxygen Generation Assembly (OGA) and Sabatier CO₂ Reduction on the first logistics flight, while the UPA and BPA would be launched on the second logistics flight. The comparison of cumulative logistics upmass between open loop and closed-loop is shown in **Error! Reference source not found.**⁵ The recommended option of launching the regenerative ECLSS in two logistics flights resulted in a mass savings of 53-79%, while an alternate approach of spreading the delivery of regenerative ECLSS over three logistics flights results in a 46-75% mass savings over a 15-year campaign compared to an open-loop ECLSS.

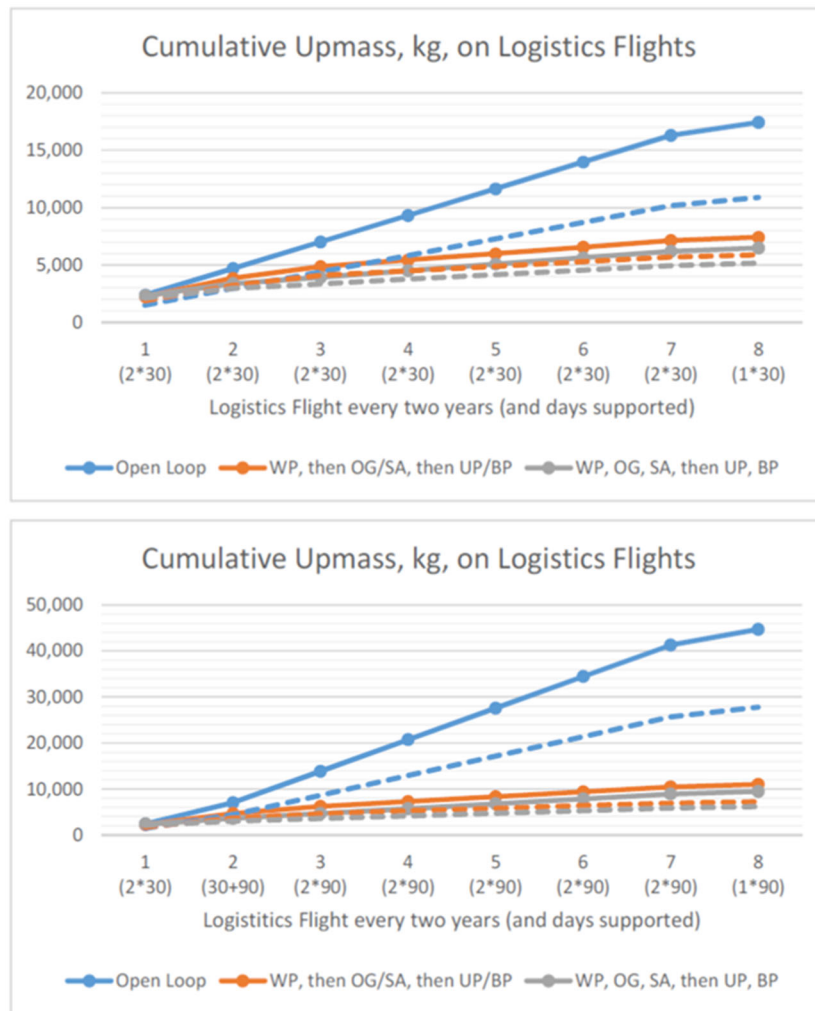


Figure 7. Comparison of cumulative logistics upmass of consumables and equipment between open-loop and closed-loop for fifteen 30-day missions (left) and three 30-day plus twelve 90-day missions (right).

A. Assessment of Dormancy

A critical capability of a deep space ECLSS is surviving long durations untended. A primary concern for expected dormant periods is microbial growth, particularly in wetted portions of the system⁸. The impact of dormancy on waste management and water processing systems has been reviewed and a procedure to enter stable dormancy has been proposed.^{9,10} NASA requested Collins review the proposed procedure, develop details of implementation, address possible failures during dormancy, assess logistics mass impacts, and generate alternate concepts. The procedure was thoroughly reviewed and minor changes proposed along with alternate concepts. The resulting logistics mass assessment identified an impact of 32 kg for an entire campaign in addition to 121 kg of consumables required for each dormancy cycle (i.e. mission).¹¹ This mass must be considered when contemplating manifesting the functional groups involved. Additionally, the crew time involved in recommissioning the system and the risk that recommissioning would be unsuccessful must be considered.

VI. Maintainability

The deep-space Environmental Control and Life Support Systems (ECLSS) face the challenge of maintaining continuous service for up to three years during Earth-independent operation, as there will be no routine logistics flights to resupply spares. Maintainability refers to how easily and quickly a crew can fix a failed system in space and involves removing, repairing or replacing, and recommissioning the system. Crews will need to fix problems in-flight without real-time support from mission control, and the limitations of resources and communications pose a threat to mission success. Therefore, deep-space systems need to be designed with maintainability in mind,

addressing factors such as modularity, commonality, simplicity, and tools to enable crews to quickly and easily restore operational status to a failed system in a self-sufficient manner.

A. Commonality

Commonality is a crucial architectural feature that can enhance the feasibility and safety of a mission while also increasing its practicality. By maximizing commonality, it becomes possible to interchange components and sub-components both within and between systems, which can aid in carrying out timely repairs and offering contingency measures to address problems encountered during the mission. Furthermore, utilizing common components can reduce the number of spares required for the mission, leading to a reduction in launch mass and associated costs.

Two classes of components were investigated for commonality potential, sensors and solenoid valves. The current suite of regenerative ECLSS functional groups were found to have 23 unique solenoid valves between 2-way normally open, 2-way normally closed, and 3-way valves. While it was found to be infeasible to replace all of the instances with a single valve design, Collins realized it was possible to design a common electrical coil assembly. The use of a common coil assembly would add mass to components given that a single coil would not be optimized for a specific application, but it would likely be offset by the mass savings in reducing the number and types of spares across the system.

A further analysis of the existing suite of ECLSS equipment identified 24 unique pressure sensors and 13 unique temperature sensors. Again, it was found to be infeasible to significantly reduce the number of unique sensors given with existing technologies. However, as part of the exploration of new technologies, Collins identified an optical sensor technology that has broad applications including both temperature and pressure sensing. They found it was conceivable to reduce the number of sensors to one pressure and one temperature sensor with optical technology.

While this study indicated that it is technically feasible to achieve significant commonality within the current suite of ECLSS, standardization would be a challenge given the number and variety of organizations involved with providing these systems. Unfortunately, there is currently little incentive for the industrial base to organically establish standard parts let alone for an individual contributor to expend the resources to adopt standard components on their own. NASA would have to play a significant role by either establishing requirements for commonality during system acquisition or fund focused efforts to redesign existing systems to incorporate standardized components.

B. Component Remove and Replacement

It was realized that the Orbital Replacement Unit (ORU) approach used for ISS did not lend itself well to on-orbit maintenance. Further, modifying existing ORUs to substantially increase on-orbit maintainability did not appear feasible. NASA requested Collins to explore approaches to improving on-orbit maintainability of ECLS systems. Collins initially focused on an approach to remove and replace individual components directly from the system. The team ideated over 40 different interface solutions that would allow easy removal and replacement of components. The solutions were assessed against an exhaustive list of design requirements and weighted criteria and concluded that using quick-disconnect features for easy leak-proof removal and replacement of components actually resulted in reduced reliability, increased weight, volume, cost, and complexity, and lowered the technology readiness level of the components. Further, it became apparent that it is reasonably acceptable for many fluids (e.g. Water, Nitrogen, and Oxygen) to leak during removal and replacement; leak-proof approaches are only needed when working with hazardous fluids. In the end, the team realized that maintainability must be considered at all levels of the design, not just modular component interfaces.

C. Maintenance Unit Method

The study shifted away from component remove and replace to a system-level approach dubbed the "Maintenance Unit Method" after concluding that maintainability must be considered at all levels of the design and not just at modular component interfaces alone. The design team identified Maintenance Units (MUs) that are aggregations of components designed for easy removal from the overall system and repaired by fixing or replacing smaller subcomponent¹². As an aggregation of components, MUs are not unlike ORUs except that they are intended to be fixed while on-orbit instead of being returned to Earth. The boundary definition for MUs were influenced by factors such as simplicity, safety of removal, working fluids disrupted, acceptance testing of repaired items, accessibility, and types of failure modes.

Collins derived a list of design principles for defining MUs, which were then applied to the redesign of the NextSTEP ECLSS OGA and Sabatier pallets¹². Although not quantitative, there was an observed qualitative increase in mass and volume, which was expected. However, the impact was not as much as the component remove

and replace approach. Figure 8 shows that the MU design principles embody the design for maintainability guidance in the NASA-STD-3001¹³. Therefore, the effort provides additional validation for the design for maintainability guidance in NASA-STD-3001 as well as demonstrate the application of these principles to real-world systems.

NextSTEP App A MU Design Principles		NASA-STD-3001 Vol 2 Rev C									
		9.7.1.1 Design for Maintenance	9.7.2.1 Maintenance Time	9.7.2.2 Captive Fasteners	9.7.2.3 Minimum Number of Fasteners	9.7.3.1 Maintenance Variety of Fasteners - Item	9.7.3.2 Check and Service Point Accessibility	9.7.3.3 Maintenance Accommodation	9.7.3.4 Visual Access for Maintenance	9.7.3.5 Tool Clearance	
DFMR products in back of pallet	X				X	X	X				
Serviceable Items in front of pallet and forward facing	X					X	X	X			
Minimize fastener variation to limit required tooling			X								
Use captive fasteners and seals			X								
Avoid using boxes or covers when possible to improve accessibility	X				X	X	X				
MU tray / rack mounting provisions	X		X			X					
Maximize component commonality				X							
Provide test points					X						

Figure 8. Cross reference of the Collins' derived Maintenance Unit design principles with NASA-STD-3001 section 9.7 Design for Maintainability.

D. Augmented Reality Demonstration

The length of deep-space missions, especially those to Mars, will prohibit detailed training on every possible activity prior to a mission and will pose difficulties in retention of information learned. In addition crews may not have access to real-time support from mission control when a maintenance or repair task needs to be performed. To ensure crew safety and productivity, efficient methods to provide in-flight training or support to tasks without ground support will be required. Augmented reality (AR) shows promise to improve efficiency of maintenance operations of a deep-space ECLSS¹².

Collins developed a demonstration of in-flight maintenance to replace a failing pressure sensor on the OGA cell stack using AR. In the demonstration, the graphical user interface (GUI) of the Integrated ECLSS Command Center which houses control systems for each ECLSS subsystem, alerts a crewmember that a pressure sensor is beginning to drift. The GUI walks the crewmember through a troubleshooting procedure to aid in isolating the cause to a specific pressure transducer). Then using an augmented reality headset, the crewmember follows a virtual checklist to perform the repair/replacement task. Features of the AR include repositionable procedural steps in the visual field and “floating” hardware indicators that aid the crewmember rapidly identify the parts they need to interface with for the current step of the procedure.

Figure 9 depicts a the crew member’s view while installing the cell stack removed from the OGA on to a workbench platform to perform repair/replacement of one of its pressure transducers. Orange circles indicate what fasteners need to be tightened to secure the maintenance unit to the workbench. Procedural steps are barely visible at



Figure 9. Augmented reality view while installing OGA cell stack on a workbench to perform repair/replacement of a pressure transducer

the top of the picture, mostly cut off from view, having been repositioned by the user. The previous, current and next procedural steps are displayed in the AR view.

VII. Control Systems

A significant part of a deep space ECLSS is its control system. Five different architectures were traded, including Centralized, Integrated Modular, Hierarchical, Hybrid, and Decentralized. The evaluation criteria included Complexity, Repairability, Robustness, Development, Flexibility and Form Factor.¹⁴ Both Hierarchical and Integrated Modular architectures scored high, but additional consideration of the communication topology and the necessary software architecture led to a selection of the Integrated Modular Control Architecture (IMCA).

A. Integrated Modular Control Architecture

The Integrated Modular Control Architecture is based on a publish and subscribe system allowing the universal ECLSS to behave as an Internet of Things with independence and redundancy that provides a more resilient system than the current Federated System used on ISS. The core of the system is a triple-redundant network that can communicate with any computational node in the system, including the physical deployment of communication lines. The control functions are deployed in a hierarchical fashion, with a Command Center interacting with the crew, ground, and habitat. The functional Group Controllers contain the detailed control logic for each ECLSS functional group.

Figure 10 shows the Integrated ECLSS Controller Demonstrator that was developed using commercial off-the-shelf parts and consists of four components: hardware-based demonstrator, model-based demonstrator, software/control-logic development Command Center, and three independent local area networks. The hardware-based demonstrator implements the communication infrastructure between sensors/actuators and the rest of the system, while the model-based demonstrator implements communication infrastructure between pallets. The Command Center is used to develop, download, and deploy models and controller software, as well as network and middleware monitoring, GUI development, telemetry, failure injection, and response logging. Four demonstrations were conducted to test the system, including nominal operation, network failure detection, hardware failure response, and Command Center disconnection.



Figure 10. Control system hardware/ software demonstrator

The IMCA effort also demonstrated the use of common software deployed to each functional group, which is then customized by a configuration file specific to that functional group. This approach maximizes code reuse that lowers development and test costs by minimizes the number unique lines of code. It also improves resiliency by allowing peer functional group controllers to respond to the failure of another by spawning a second controller instance configured to the failed controller specification. As long as the network communication remains intact, the peer controller can take over until the failure of the primary can be addressed. One potential drawback is that extensive commonality introduces susceptibility to latent flaws or common cause failures. However, the anticipated savings in the development of the primary software enables the development of dissimilar, independently coded backup software.

B. Intelligent Systems

Section II.A highlighted the beneficial increase in margin to a hazardous condition if a fault condition can be anticipated or predicted in advance. Intelligent systems are a key enabler to predicting and isolating faults at the component level. There are several types of intelligent systems that vary widely in their application specialty. Various types of intelligent systems were traded and the scoring indicating Bayesian Network (Bayes Nets) as the highest rated in the trade followed by Random Forest.¹⁵

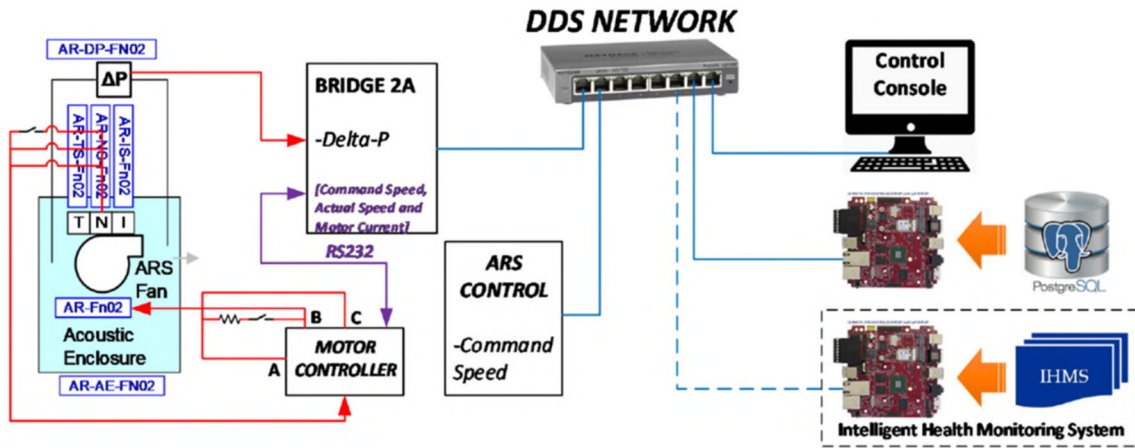


Figure 11. Intelligent systems test schematic

A Bayes Net-based intelligent health monitoring system (IHMS) was created as a proof-of-concept, which included a network middleware and ARS database as shown in the schematic in Figure 11. The IHMS was tested on an ARS fan motor and demonstrated its ability to detect and discriminate between two similar fault types. The results of the tests were analyzed using a 5-fold cross-validation of the Bayes Net model, and the results showed that the IHMS has the potential to aid in fault isolation and component health monitoring.

VIII. Conclusion

The NextSTEP App A Modular ECLSS effort investigated many aspects of ECLS systems important to long duration human spaceflight. The Modular ECLSS effort was initiated with the goal of achieving ECLS systems embodying the key characteristics of Evolvability, Resiliency, Modularity, Affordability, and Intelligence. These characteristics provide a gauge against which the body of work can be compared.

One definition for evolvability is to develop gradually, especially from a simple to a more complex form¹⁶. The Universal and Advanced Pallets contribute to evolvability in two key ways. First, palletization offers the flexibility to integrate systems after launch, which can address the evolution of a habitat's ECLSS from open- to closed-loop. Second, the use of standard rack interfaces allows swapping out of the existing systems with new improved technology. Together with the integrated modular control architecture this essentially enables a plug and play capability to reconfigure the pallets over time.

Long duration missions involve limited communication, limited ability for ground support, and limited to no resupply requiring resiliency in many respects. Therefore, many of the Modular ECLSS tasks were conceived with the express goal of improving resiliency. For example, the hazard timeline analysis highlighted the beneficial

increase in the margin to a hazardous condition if a fault condition can be anticipate or predicted in advance. Research into intelligent systems showed that Bayesian network-based intelligent systems can potentially predict and isolate pending faults at the component level prior to the occurrence of a fault condition. The ability of the common software approach in the IMCA provides extra levels of controller redundancy to improve resiliency.

The investigation into designing systems for in-flight maintenance identified several practical approaches to increasing resiliency. An important lesson learned was that designing for component-level removal and replacement resulted in increased weight, volume, complexity, and cost. A better solution was to aggregate several components into Maintenance Units that limited the interface disruption within the pallet. This approach balanced the benefits of modularity against the weight and complexity of applying interface controls to every component. MUs are similar to ORUs, but are generally smaller aggregations of components that can be repaired at a workbench while in flight. When maintenance is required, it is important to complete the repairs in a timely manner to prevent the occurrence of pending hazardous conditions. Collins developed and demonstrated an augmented reality application that efficiently guided crewmembers through the repair, which improved timeliness of repairs with reduced reliance on prior knowledge or training.

Modularity provides flexibility or adaptability to multiple habitat platforms and contributes to the other characteristics of evolvability, resiliency, and affordability. The Universal and Advanced pallets enable easy installation of ECLSS in diverse platforms. In particular, the Advanced pallet is in itself a modular assembly that makes it easy to adjust length or incorporate alternate external panels. Also, increased modularity/commonality has the potential of reducing spares. Finally, the integrated modular control architecture and common software approach improves independence and redundancy for a more adaptable architecture.

Several of the Modular ECLSS tasks contributed to a more affordable system. Palletization enables the integration of ECLSS functional groups in parallel to habitat assembly, which promotes affordability by reducing production schedules and cost. Leveraging more commonality reduces the number of unique parts in the system that can lower acquisition costs and reduces the number of spares that can lower logistics cost. Logistics savings can ripple through the entire spacecraft by reducing the mass and volume allocations for spares. Finally, the adaptability to multiple habitat platforms afforded by modularity eliminates redundant design, development, test and evaluation costs of unique systems for every habitat platform.

Intelligent systems can be an enabler of long duration spaceflight by offloading the crew from monitoring onboard systems that would traditionally be accomplished by ground controllers. The integrated modular control architecture demonstrated during this effort allows the ECLS systems to behave as an Internet of Things with independence and redundancy that provides a more resilient system than the current Federated Systems. The commonality of controller hardware and software components combined with the networked architecture allows a controller from one functional group to temporarily take over the controller tasks of another functional group should a failure occur, which provides crews with extra margin to address the issue. Likewise, the Bayesian Net intelligent health monitoring system proof-of-concept demonstrated the ability to predict and isolate pending faults, which also provides crews extra time to balance workloads while avoiding hazardous conditions.

In summary, all of the work under the NextSTEP Modular ECLSS program have contributed to the realization of an ECLS system embodying the key characteristics envisioned for a long duration habitat. Going forward, the lessons learned from this effort can inform the redesign of existing systems or development of new systems. For example, whether or not the specific pallet designed under this effort is adopted, the benefit of consistent interface for habitat system and utilization hardware is undeniable and actually a lesson relearned from the International Space Station. The Maintenance Unit principles will augment existing maintainability recommendations to guide more maintainable designs going forward. Finally, this NextSTEP effort has shown that modular ECLSS systems are not only feasible, but are desirable in many ways.

References

¹NASA (2016), *Next Space Technologies for Exploration Partnerships -2 (NextSTEP-2) Appendix A: Habitat Systems*, BAA NNH2CQ001K, Washington, D.C.

²Wetherholt, J., Heimann T. J., "Design For Minimum Risk", Proc. Fourth IAASS Conference 'Making Safety Matter', 19–21 May 2010 (ESA SP-680, September 2010), Huntsville, Alabama, USA

³Stapleton, T. J., Heldmann, M., Schneider, S., O'Neill, J., Samplatsky, D., White, K. Corallo, R. (2016), "Environmental Control and Life Support for Deep Space Travel (ICES-2016-450)," in *46th International Conference on Environmental Systems 10-14 July 2016*, Vienna, Austria.

⁴Collins Aerospace (2021), *TIM 6 NASA/Collins NextSTEP Phase 2X*, Windsor Locks, CT.

-
- ⁵Collins Aerospace (2020), *Con-ops of the ECLSS Evolution*, NSTEP-2018-021 NNH15CN27C, Windsor Locks, CT.
- ⁶NASA (2016), *NextSTEP 2 Appendix A Modular ECLSS Phase 2X Statement of work*.
- ⁷Collins Aerospace (2020), "Air Revitalization System (ARS) Disaggregation Study (NSTEP-2020-004 NNH15CN27C)," Collins Aerospace, Windsor Locks, CT.
- ⁸O'Hara, W. J., M. J. Sargusingh (2019), "Challenges of Mars Mission Phase Transitions on Spacecraft Environmental Control and Life Support Systems (ICES-2018-124)," in *48th International Conference on Environmental Systems (8-12 July 2018)*, Albuquerque, NM.
- ⁹Carter, D. L., Tabb D., Anderson K. M. (2016), "Water Recovery System Architecture and Operational (ICES-2016-043)," in *47th International Conference on Environmental Systems (17 – 20 July 2017)*, Charleston, SC.
- ¹⁰Carter, D. L. (2018), "Dormancy Assessment for Advanced Exploration Systems Memorandum for Record," NASA MSFC, Huntsville, AL.
- ¹¹Collins Aerospace (2019), "Impacts of Dormancy on ECLSS (NSTEP-2019-023)," Collins Aerospace, Windsor Locks, CT.
- ¹²Rohrig, J. A., O'Neill, J., Stapleton, T. J. (2019), "In-Flight Maintenance Design Philosophy for Gateway and Deep-Space Life Support Systems (ICES-2019-305)," in *49th International Conference on Environmental Systems 7-11 July 2019*, Boston, Massachusetts.
- ¹³ NASA (2018), *NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health*, NASA-STD-3001, Volume 2, Revision C, Approved 4/8/2022
- ¹⁴Stapleton, T., Heldmann, M., Torres, M., O'Neill J., Scott-Parry, T., Corallo R., White K., Schneider S. (2017), "Environmental Control and Life Support System Developed for Deep Space Travel (ICES-2017-44)," in *47th International Conference on Environmental Systems 16-20 July 2017*, Charleston, South Carolina.
- ¹⁵Stapleton, T., Heldmann, M., Torres, M., Bowers, J., Corallo, R. (2018), "Environmental Control and Life Support for Deep Space (ICES-2018-343)," in *48th International Conference on Environmental Systems 8-12 July 2018*, Albuquerque, New Mexico.
- ¹⁶ Oxford Learner's Dictionary (2023, May 10), Definition of Evolvable. <https://www.oxfordlearnersdictionaries.com/definition/english/evolve>