Lessons Learned from the Development and Implementation of the Atmosphere Resource Recovery and Environmental Monitoring Project

Monsi C. Roman[1], Jay L. Perry[2] and David F. Howard.[3]
NASA/Marshall Space Flight Center, Huntsville, Al 35812

The Advanced Exploration Systems (AES) Program's Atmosphere Resource Recovery and Environmental Monitoring (ARREM) Project have been developing atmosphere revitalization and environmental monitoring subsystem architectures suitable for enabling sustained crewed exploration missions beyond low Earth orbit (LEO). Using the International Space Station state-of-the-art (SOA) as the technical basis, the ARREM Project has contributed to technical advances that improve affordability, reliability, and functional efficiency while reducing dependence on a ground-based logistics resupply model. Functional demonstrations have merged new process technologies and concepts with existing ISS developmental hardware and operate them in a controlled environment simulating various crew metabolic loads. The ARREM Project's strengths include access to a full complement of existing developmental hardware that perform all the core atmosphere revitalization functions, unique testing facilities to evaluate subsystem performance, and a coordinated partnering effort among six NASA field centers and industry partners to provide the innovative expertise necessary to succeed. A project overview is provided and the project management strategies that have enabled a multidiscipinary engineering team to work efficiently across project, NASA field center, and industry boundaries to achieve the project's technical goals are discussed. Lessons learned and best practices relating to the project are presented and discussed.

Nomenclature

AES	=	Advanced Exploration Systems Program
ARREM	=	Atmosphere Resource Recovery and Environmental Monitoring Project
ARS	=	Atmosphere revitalization subsystem
CDRA	=	Carbon Dioxide Removal Assembly
DDT&E	=	Design, development, test, and evaluation
LEO	=	Low Earth Orbit
ECLS	=	Environmental Control and Life Support
EMS	=	Environmental Monitoriong Subsystem
FY	=	Fiscal Year
ISS	=	International Space Station
NPR	=	NASA program requirements
OGA	=	Oxygen Generation Assembly
PMO	=	Program Management Office
PPA	=	Plasma Pyrolysis Assembly
SBIR	=	Small Business Innovative Research Program
SDU	=	Sabatier Development Unit
SOA	=	State-of-the-art
TCC	=	Trace contaminant control
TRL	=	Technology readiness level
VOC	=	Volatile organic compound

[1] Project Manager, Flight Programs and Partnerships Office, ISS Office/FP10.
[2] Lead Aerospace Engineer, Space Systems Department, ECLS System Development Branch/ES62.
[3] Deputy Project Manager, Flight Programs and Partnerships Office, ISS Office/FP10.

I. Introduction

IN U.S. government fiscal year 2012 (FY12) the National Aeronautics and Space Admininstration's (NASA) Human Exploration and Operations Mission Directorate established a technology maturation program for higher maturity technology development. The Advanced Exploration Systems (AES) Program grew from NASA's Exploration Technology Program and associated needs assessments for the Constellation Program.[1] The AES Protram launched over twenty projects at NASA field centers that targeted high-priority capabilities necessary for successful crewed space exploration missions beyond low Earth orbit (LEO).[2] Technical capability areas pursued by the AES Program included environmental control and life support (ECLS), habitation, crew mobility, logistics reduction, and extravehicular activity systems. Priorities of the AES Program included the early integration and testing of prototype system functional demonstration with the purpose of reducing risk and improving exploration mission program affordability by reducing future developmental costs. The following provides a project overview and discusses the project management strategies that have contributed to the project's success. Lessons learned and best practices relating to the project are presented and discussed.

A. Introduction to the Advanced Exploration Systems Program

The projects pursued by the AES Program were short-term, hands-on, and product-focused. The technical maturity target was Technology Readiness Level (TRL) 6 as defined by NPR 7123.1.[3] The NASA AES program's leadership team implemented a lean cross-agency program guided by NPR 7120.5 that streamlined project management.[4] The AES Program's management style changed slightly over the 3-year period of performance in response to NASA's resource challenges and newly-emerging technical needs, but maintained the central goal of providing the NASA civil servant work force the opportunity to rapidly develop prototype systems, demonstrate key capabilities, and validate operational concepts for future human missions beyond Earth orbit. The program management team encouraged flexibility and innovation not only with regard to technology maturation but also project management and implementation to meet the diverse challenges associated with federal government programs. The result was a highly engaged NASA workforce that was encouraged to leverage existing technologies, maximize the use of commercial processes, and use existing facilities.

B. Introduction to the Atmosphere Resource Recovery and Environmental Monitoring Project

The Atmosphere Resource Recovery and Environmental Monitoring (ARREM) Project is one of several projects within the AES Program related to ECLS systems. Primary objectives of the ARREM Project included maturing Atmosphere Revitalization Subsystems (ARS) and Environmental Monitoring Subsystems (EMS) to reduce future flight program design, development, test, and engineering (DDT&E) risks. The ultimate goal was to produce subsystem architectures consisting of International Space Station (ISS)-derived components that lower lifecycle costs and increase functional reliability and capability for future crewed space exploration missions beyond LEO. The ARREM team focused the project on the targeted improvement of state-of-the-art (SOA) physico-chemical systems currently in use aboard the ISS as well as strategically targeted development and infusion of promising ARS and EMS technologies from other NASA programs such as the Small Business Innovation Research (SBIR) program, academia, and commercially available products. The ARREM team worked to develop, demonstrate, and functionally test leading process technology candidates and subsystem architectures to meet or exceeded current requirements.

II. ARREM Project Overview

Highly reliable, closed-loop life support systems are among the capabilities required to enable longer duration crewed space exploration missions according to numerous technology needs assessments and roadmaps.[5-7] Consumables mass savings in addition to lower lifecycle resource demands that such systems offer may offset the mass of the system and its necessary spares, provided that highly reliable operation can be assured. At the same time, for affordability, it is important to minimize destination-specific technology and equipment development costs. For life support systems, this means that there is the need for cross-cutting mission and vehicle platform flexibility and commonality toward the goal of enabling a safe, affordable, and sustainable crewed space exploration program.

An approach to achieve this needed flexibility employs a common core architecture with modularity as the key building block of crewed spacecraft ECLS systems at the lowest functional level possible.[8] Doing so provides tangible non-recurring and recurring cost reduction through minimizing destination-specific DDT&E resource needs and sustaining infrastructures. Deep space exploration mission risk will also be reduced by accumulating operational experience with a finite set of modular, common system components as the exploration framework is incrementally executed.

A. Project Objectives and Goals

The ARREM Project's main objectives are to mature integrated ARS and EMS technologies that build on the ISS SOA to reduce risk, lower lifecycle cost, and validate alternative process design and subsystem architectural concepts for future human missions beyond Earth orbit. These objectives were accomplished while providing maximum opportunities for the NASA workforce to engage in hands-on development projects that will benefit NASA's missions and potentially realize significant spin-off for applications on Earth.

The ARREM Project developed, demonstrated and tested leading process technology candidates and ARS architectures that meet or exceed the ISS SOA functional requirements and fill capability gaps. The technical goal was to significantly improve the efficacy, safety, and reliability over the ISS SOA as the technical platform and basis for comparison. The project accomplished this goal by demonstrating test articles of varying TRLs arranged in candidate integrated architectures within ground-based testing facilities. The best-suited testing, demonstration, and evaluation methods; facilities; and level of integration for each candidate process technology and/or integrated subsystem architecture was based on priorities, availability, needs, and resources.

The specific goals of the ARREM Project were the following:

1) Demonstrate the evolution of the ISS SOA ARS architecture and process design via targeted advancements that benefit ISS operations in LEO and exploration missions beyond LEO.
2) Assess the feasibility of process architectures that offer the greatest potential to maximize process technology and equipment commonality across a variety of mission scenarios and vehicle concepts anticipated under a flexible exploration framework.
3) Advance the process architecture technical maturity level as defined by NPR 7123.1 to the mid-5 range with a goal to reach the mid-6 range.
4) Develop a set of resource recovery capabilities that can be added in modular fashion to a common set of core ARS and EMS equipment to allow mission planners flexibility to extend crewed mission durations without compromising core equipment functionality.
5) Infuse new and/or improved ARS and EMS process technologies into crewed space exploration missions.

The ARREM Project conducted a series of integrated tests and architectural trade assessments encompassing expected exploration mission requirements and constraints to achieve these goals. The actual technical maturity level achieved depended on available resources, funding allocations, budget modifications and shortfalls, changes in customer direction, new requirements, and/or unknown risks.

The ARREM Project's technology development plan was aligned with the findings documented in NASA technology development technology roadmaps.[9-11] Capabilities enabled by the ARREM Project cross multiple deep space exploration destinations and consider platforms that include but are not limited to deep space transportation vehicles, cis-lunar space habitats, surface habitats, surface landers, multi-mission space exploration vehicle platforms, and pressurized surface rovers.

B. Project Content

The individual technology development tasks that comprised the ARREM Project were broad-based and diverse. Yet, each task carried the common goals to identify and mature the most promising process technologies that build from an ISS-derived architecture and physical configuration basis to achieve greater reliability and operational economies as well as ensure that the the natural environments encountered by their host spacecraft can be endured. The ARREM Project's technical approach was developed over several years as a functional method to technology maturation evolved within NASA's research and technology organizations.[12-13] Technical task focal areas were the following:

1) Carbon dioxide removal and management
2) Oxgyen supply and recovery
3) Trace contaminant control
4) Particulate removal and disposal
5) Environmental monitoring

Cross-cutting technical areas included systems analysis, process simulation, and test and evaluation. Figure 1 shows a simplified ARREM Project structure and the project's relationship with the AES Program.

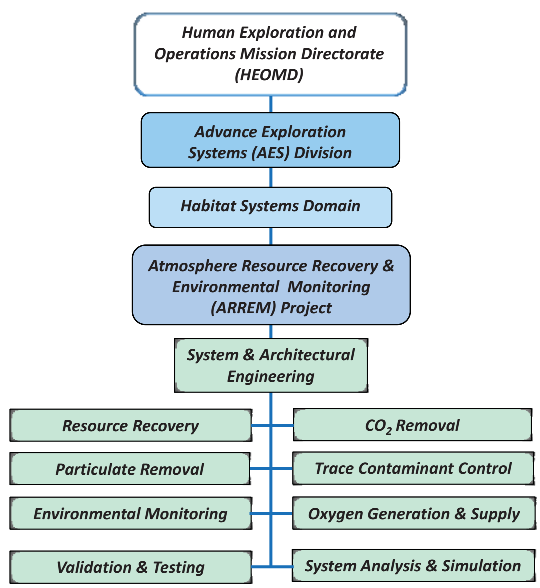

Figure 1. A simplified project structure.

III. Project Accomplishments

The ARREM Project used a functional trade space approach to focus the broad-based technical challenges and guide priorities.[14-15] Consistent with a flexible crewed space exploration strategy, the ARREM Project demonstrated the capability to extend the functional utility of a common set of core ARS and EMS equipment by integrating them with reliable, cost-effective resource recovery capabilities that will allow long-duration human exploration missions to be sustained with minimal dependence on Earth-based logistics support. Testing at progressively complex levels of integration was the primary method used to reach the project's goals.[16] Technical accomplishments toward the project's goals include the following:

1) Developed and tested integrated subsystem architectures and compared performance versus the ISS AR architecture establishing the feasibility of ISS-derived AR for deep space missions.
2) Developed and refined integrated ARS technology testing capabilities that are a national asset.
3) Developed and implemented screening and performance characterization methods for adsorbent media used for bulk and residual drying, CO_2 removal, and trace contaminant control.
4) Assessed bulk and residual drying functional trade space options that found that the ISS Carbon Dioxide Removal Assembly (CDRA) desiccant bed to be the most mass and volume efficient solution as well as indicating that the desiccant bed size can potentially be reduced for exploration class missions to save mass and volume.
5) Advanced technical maturity of the methane Plasma Pyrolysis Assembly (PPA) through 3rd generation and demonstrated integrated operational performance with the Sabatier Development Unit (SDU).
6) Tested trace contaminant control (TCC) component configurations as well as evaluated commercial adsorbent and catalyst product candidates leading to subsystem mass and volume reduction.
7) Improved understanding of trace contaminant propagation through the integrated AR subsystem architecture that provided confidence that there is minimal risk associated with volatile organic compound (VOC) poisoning of CO_2 reduction catalysts.
8) Gained improved insight on CO_2 and bulk/residual drying sorbent mechanical properties and adsorption capacities as well as matured analytical predictive techniques.
9) Demonstrated operational simplifications for the ISS Oxygen Generation Assembly (OGA) that may reduce future mass and volume and address limited life H_2 sensor issues to reduce logistics demand.

Details on numerous technical accomplishments produced by the ARREM Project are contained in the bibliography listed in the appendix.

IV. Lessons Learned

The ARREM Project united a talented labor pool, unique facilities, and a flexible management approach work toward challenging technical objectives and goals. Lessons learned address program and project management, requirements, technical execution, communications, workforce development, and facilities utilization topics.

A. Program management

Clear direction from the AES Program Management Office (PMO) leadership team improved the project's likelihood for success. The project team was allowe the flexibility to customize its management style to follow a "skunkworks"-like management model while staying accountable for delivering technical products within agreed budget and period of performance constraints. Selected lessons learned noted by the ARREM Project team are the following:

1) *Engaged Domain Lead*: The PMO assigned each project a Domain Lead. The Domain Lead participated in all the project meetings and was available for consultation at any time to provide timely guidance and to facilitate two-way communication between the projects and the PMO. The importance of an engaged Domain Lead and the value of effective, timely communication was evident during very challenging budget cuts in FY13. With the Domain Lead's assistance, the project management team was able to minimize the impacts to the project's priorities and workforce by rearranging deliverables in a way that gained ready approval from the AES Program management. This communication helped minimize iteration which saved time and resources plus maintained the delivery of meaningful products.
2) *Streamlined project planning*: The projects were requested to provide the AES PMO a streamlined work plan using guidelines found in the NPR 7120.5. The plan contained objectives, technical approach, cost, and baselined milestones and schedules by which the project's progress could be assessed. The work plan formalized the commitment between the project manager and the AES program manager who both signed the plan. The

AES Objectives	Project Success Criteria
Rapid development and demonstration of prototype systems	• Did the project complete its annual milestones?
Pioneer innovative approaches to improve affordability	• Did the project implement innovative approaches to improve affordability?
Create opportunities for the NASA workforce to gain hands-on experience and learn new skills	• Was most of the work performed in-house by civil servants instead of being outsourced to contractors? • Did people learn new skills?
Multi-disciplinary, highly-collaborative project teams working across organizational lines	• Did the project interact with other AES projects? • Did the project involve multiple NASA centers?
Infuse new technologies and capabilities into exploration missions	• Did the project incorporate new technologies? • Has the project identified a customer or end user (ISS, Orion, SLS)?
Leverage partnerships to amplify investments	• Did the project establish partnerships with external organizations or other NASA programs?
Outreach	• Did the project engage the public through outreach activities?

Figure 2. AES Program success criteria.

flexibility to provide the necessary information in a document that was specific to the project and the PMO's needs was appreciated by the project management team.

3) *Streamlined monthly reporting*: The AES PMO required only the delivery of a monthly report that summarized the project's status and accomplishments. The report's format was a simple chart divided in four quadrants that accommodated the top accomplishments, milestones, issues, and future relevant events. If additional information was needed, it was provided to the Domain Lead to pass to the AES PMO.
4) *Clear project success criteria*: The AES PMO provided a list of success criteria, summarized in Fig. 2, that was clear easy to follow, and concise. Each AES project was aware of the areas that were of interest to the PMO and was given the opportunity to provide information related to these criteria at biannual face-to-face meetings. The success criteria facilitated project progress communication while also providing clear guidance to the project team regarding technical and programmatic areas of most interest to the AES PMO.
5) *Challenging period of performance:* The implementation of relatively short duration projects (3 years) with the understanding that funding was dispersed in one year increments after a successful annual progress review provided the incentive to organize the projects to include long- (3 years) and short-term (a year of less) milestones. This provided an incentive for the team to work to develop technologies across several maturity levels throughout the life of the project as well as to establish interim goals that built toward the project's primary goals.
6) *Biannual project reviews with program management*: The AES PMO had two reviews each year during which each project manager presented their accomplishments to the AES PMO and the other AES project managers. The meetings allowed the teams to network and for the PMO managers to interact with the project managers. This interaction provided the projects with an effective forum to showcase their accomplishments while maintaining accountability and promoting collaboration.
7) *Workforce management*: While the AES projects were initially designed to maximize the use of the NASA civil service workforce and provide hands-on technology development opportunities, in the second and third year of the project it was hard to support and retain the necessary number of civil service employees due to competing needs for the same workforce skills at the NASA field centers as well as project technical scope refinements that reduced the work volume. It was found that after employees new to ECLS system development became proficient with their newly acquired skills while assigned to the ARREM Project, they were not able to continue to support the project because of cuts in resources for labor in the later stages of the project. The result was an overloaded but highly experienced core workforce that was retained and schedule modifications were required to accommodate a smaller workforce. The workforce reduction challenged the project's ability to deliver the promised products. Steady resource allocations for direct labor are necessary for executing the project's original scope.

8) *Travel*: The travel funding allocated to the ARREM Project was inadequate to support the needs of a team located at five different NASA field centers. Despite this situation, the project succeeded by using alternative communication means. However, the benefits of face-to-face communication were lacking as a result. Travel funding for a project team face-to-face meeting was not available until the last year of the project. The amount of work that was accomplished in that meeting justifies a request for a project team meeting once a year. This funding needs to be in addition to the other travel needs to enable participation at relevant conferences, attending technical interchange meetings, and collaboration with academia, industry, and other federal agencies that may be working in similar technical areas.

B. Project Management

The ARREM Project management team had the opportunity to develop the project proposal and negotiate the technical content with the AES PMO when selected for funding as well as lead the team throughout the life of the project. Selected lessons learned during launching and executing the project are the following:

1) *Roles and responsibilities*: Clear roles and responsibilities for each project team member and organization are very important. After the project began, the ARREM Project team realized the need to stop and spend at least a day to define and understand the roles and responsibilities for each project team member. The project management team enlisted the help of organizational development experts to assist this effort and arranged training to present the subject with the team and promote discussion. The result was very positive; however, it did not go deep enough to clearly define all of the roles and the relationships among the team members due to time limitations. As well, the project office was only able to define the roles and responsibilities from the top down. It was discovered that there there is a need for each organization supporting the project to use the information provided by the project office and work to clearly define their member's roles and responsibilities from the bottom up. This allows each line organization to clarify the relationship between the project and the supporting organization. Taking the time to do this within the first six months of project launch will help increase performance and minimize role confusions that will create tension and unnecessary discussions. This process should be reviewed annually as roles and responsibilities may change over time and lost productivity.
2) *Empowered technical leads*: A senior engineer was assigned to lead the System and Architectural Engineering work breakdown structure (WBS) element. This individual was responsible for defining the technology boundaries and integration requirements for each functional discipline to assure a fully functional ARS architecture. This individual also served as the principal investigator for all the integrated subsystem testing. A separate WBS element was created for each functional discipline depicted in Fig. 1. A principal investigator who was a subject matter expert for the specific function was chosen to lead each WBS element. These individuals were charged with laying out the technical approaches for evolving technologies within their respective functional areas to meet the project's stated goals within the framework of the integrated ARS architecture.
3) *Points-of-contact at each NASA field center:* An individual at each NASA field center was identified to serve as a point-of-contact (POC) responsible for developing resource requirements, providing status charts, communicating issues, and ensuring that task execution at their respective field centers were carried out according to task agreements. The center POCs also served to communicate project special project requests and/or actions to supporting personnel.
4) *Technical task agreements*: Technical task agreements (TTA) were established between each of the supporting NASA field centers and ARREM project management to define their specific scope of work and deliverable milestones. The tasks assigned to each field center, as defined in the TTA, were based on capabilities and expertice available at the particular field center. These tasks were mapped to the project's goals and the WBS leads' technology maturation approach. Each TTA's content was evaluated and approved by the System Architectural Engineer, the project manager, and the corresponding field center POC. The TTAs proved to be valuable guides to ensure activities performed across multiple centers were well defined, aligned with the WBS leads developmental plans, and agreed to by all participating organizations.
5) *Budget management:* For the first two years of the ARREM Project, budget management was performed by a dedicated budget manager assigned to the project. This arrangement made it easy to manage the resources and needs for all the supporting field centers, to maintain control over the funding obligated, and to allow the project manager to spend more time on other project duties. For the third year of the project, budget management was consolidated with all the other AES projects at the field center level. This change made it difficult to maintain control over the project funding; however, the change reduced the direct labor needed in the project office and allowed that funding to pass to the engineering team. It was a challenge to adjust to centralized budget management. The steep learning curve included additional work for a smaller project office. Resource

savings should be considered when deciding if a centralized budget management system will work for multiple projects that need to process numerous procurement actions as well as interface with multiple NASA field centers.

6) *Schedule management:* Detailed integrated schedules were developed and used to manage the multitude of tasks comprising the project's portfolio. The schedule was paramount to efficiently using personnel and facilities and enabling substitutions when delays in one activity created opportunities to accelerate progress of another. The detailed master schedule was flexible and was regularly updated to allow managers to fully understand options and to avoid cascading overall impacts that could delay milestone completion.
7) *System engineering:* A Lead System Engineer (LSE) was assigned to coordinate procurement, personnel, and other resource requirements between engineering and project management organizations. Additionally, the LSE assumed the responsibility for developing detailed schedules to prepare test hardware and outfit test facilities according to requirements specified by the subsystem and architecture WBS leads. The LSE was also responsible for consolidating status information from the various WBS leads and keeping project management updated regarding progress, delays, and technical risks.
8) *Technology investment ratio:* A ratio of new technology investment and SOA refinement (15% to 85%) was established. The ARREM Project, per guidance from the AES PMO, focused the majority of its resources on refining existing technologies to achieve improved performance and reliability. This approach has been refered to as "TRL now". A smaller portion of the project's portfolio was dedicated to developing new technologies that currently reside at lower TRLs. This approach enabled the project to exit the three year period of performance with a recommended integrated subsystem architecture that is feasible for implementation aboard exploration-class vehicles while infusing targeted new technology options that complement the architecture.
9) *Project documentation:* Detailed annual reports were provided by each of the technical WBS leads that described the tasks performed and the accomplishments during the year. A combined effort by project management and engineering organizations will produce a consolidated project final report that will cover all activities and results throughout the project's 3-year period of performance. When the final ARREM Project report is completed, it will be released as a NASA technical publication and will be available through NASA technical publication distribution outlets. The ARREM Project also started the collecting information ECLS system design and testing in the early days of crewed space exploration. The information will be published in a book authored by a team of retired NASA engineers who designed and implemented those systems. The ARREM Project management team strongly supports documenting past, present, and future work on designing ECLS systems as well as capturing lessons learned by NASA retirees before their legacy is lost to time.

C. Requirements and External Guidance

The ARREM Project team actively used requirements and external guidance to assess progress. Two assessment tools that were used are the following:

1) *Figures of merit:* Efforts to evolve existing technologies to improve performance and reliability will ultimately be measured against independently-provided figures of merit (FOMs) defined by the NASA ECLS System Maturation Team (SMT). The FOMs provide performance and reliability goals for functional disciplines to meet beyond what is currently achievable with the recognized ISS SOA ECLS systems. Even though the initial FOM definitions were not established until the beginning of the third year of the ARREM Project, a general idea of the improvement needs were understood by the WBS Leads and preliminary FOMs were established by the System Architectural Engineer and the WBS Leads. As a result, the development and demonstration efforts within the ARREM Project were reasonably aligned with the FOM target goals set forth by the SMT. It is imperative that FOMs are maintained and evolve with NASA's goals to assure development efforts stay aligned with NASA's overall capability goals.
2) *Technology development roadmaps:* Technology development roadmaps provided by the ECLS SMT consist of developmental tasks and related timelines required to achieve exploration-enabling capabilities. Within the roadmap, any ongoing efforts are identified by represented projects, commercial entities, and/or international agencies currently working in those areas. Technology gaps, efforts that are required to meet NASA's technology development objectives but are not being actively persued, are also identified to guide NASA's research and technology development programs. It is imperative that as NASA's priorities evolve, the technology roadmaps are maintained so that projects stay aligned with evolving exploration program needs.

D. Technical

Observations pertaining to technical lessons learned span the role of statistics in design and testing, time allocated for learning within a project, and maintaining consistency for the starting technical basis. Specifics on lessons learned in the technical area are the following:

1) *Role of statistics in bounding the design space:* Emphasis should be given to using a statistical design performance basis to avoid designing and optimizing to average metabolic loads and demands to ensure functional robustness. By designing to average metabolic loads and demands, the equipment ultimately becomes optimized to a 50% confidence interval. Accounting for variance in metabolic loads and demands to set a design point at >95% confidence interval magnitudes will provide for improved functional robustness and potentially improve overall functional reliability. Attaining this result may come at the cost of subsystem component mass. During testing it is highly important to understand test instrumentation errors in an integrated propagation of error context. This provides improved confidence in testing results.
2) *Incorporating reasonable learning periods within the project:* A project with a short period of performance may assume that because the starting basis is mature there is little to be learned. As the ARREM Project progressed, it became apparent that there were technical areas that were originally assumed to be more mature than deeper investigation revealed. Incorporating time between tests to learn from the results and bring flight operational experience into the project is imperative to improving overall functional robustness and reliability. Time set aside for learning also allows the project team to better incorporate lessons learned from the broader community, including commercial industry, as well as what is being learned during project execution. A learning period between each integrated test of at least six months followed by a 6-month test design period is recommended.
3) *Benefits of a mature starting basis as the platform to launch the project:* The ARREM Project was directed to use the ISS architecture as the starting basis rather than completely throwing it out for a “clean sheet” design. This allowed existing developmental equipment from the ISS Program to be rapidly re-purposed and re-configured toward the ARREM Project’s objectives as well as reduced the overall cost of the project. This approach promoted incremental technology development versus revolutionary development and, therefore, allowed for focused innovation at strategic points in the architecture.
4) *Benefits of systems engineering being a mindset of all project participants:* The temptation is to treat system engineering as unique discipline outside of other engineering disciplines. All technical leads were encouraged to have a “big picture” system mindset rather than merely focusing on a function delegated to a single individual or organization. Such a focus is necessary to understand the system in order to develop a functionally robust architecture and process design.
5) *Benefits of analysis being integral to each technical task area:* Rather than delegated to single individuals or an organization, analysis and model development was integral within each task area. The analytical effort was orchestrated by the senior system design engineer and a senior analyst and provided a high degree of flexibility and efficiency while maintaining the fully system-aware mindset across technical tasks. This approach helped to develop an engineering team with knowledge across functional areas and fostered communication between functional areas.
6) *Establishing a sense of urgency:* Although there was a positive programmatic side to the short project period of performance awards, it represented a challenge in the technical side: A 3-year period of performance proved to be very ambitious schedule, that included a yearly integrated testing cycle. The need to provide a tangible product every year to request funding for the following year sometimes presented a heightened degree of difficulty to execute the planned technical content. A project’s period of performance should be suffient to allow the project team to mature as a working unit by achieving a truly “performing” status and afford an appropriate amount of time for learning and applying newly gained knowledge. Conversely, the short period of performance did emphasize a sense of urgency that served to keep the project’s technical scope creep to a minimum.

E. Communications and Collaboration

The distribution of information and collaboration between team members and other groups was very important to the project’s success. Lessons leaned in the areas of communications and collaboration are the following:

1) *Communication within the project*: One ARREM Project management team’s goals was to foster communication during all stages of the project. Communication within the project team was a challenge because the team members were located at multiple NASA field centers. It took a while to find an effective way to communicate important information to all the team members and to understand method each NASA field center preferred disseminating information. The ARREM Project had a monthly general meeting in which all the

project team members participated, in person or virtually, to provide a progress status and to discuss challenges or needs. The project team empowered the task leads to manage communication methods and frequency within their respective task teams, minimizing the need for general weekly meetings. However, the task leads provided a status to the project office weekly. Deciding on meeting frequency can be a challenge and needs to be balanced with the need for the team members to perform their assigned work and other duties.

2) *Face-to-face meetings*: The value of face-to-face meetings with a multi-organizational, multi-disciplinary team cannot be underestimated. One of the strengths of the AES projects was the desire to reduce the competition among NASA field centers and foster collaboration. This new way of working together as a true NASA team had a lot of challenges in the beginning. Providing the opportunity to meet and discuss technical issues, share best practices, and simply network helps to build trust. It also facilitates discussion of ideas that could lead to improved outcomes and identify and resolve issues before they become problems. It is recommended that travel allocations for these kind of meetings be set aside at the beginning of a project.
3) *Interaction with other NASA programs and projects*: Interactions with other NASA programs and projects allowed the ARREM Project to maximize the quantity and quality of its products. The collaborations with non-AES projects and programs like the ISS Program, SBIR Program, Synthetic Biology Project, Next Generation Life Support Project, and even projects unrelated to ECLS such as the additive manufacturing project, provided the ARREM Project opportunities to deliver better products. It was clear that these collaborations no only benefited the ARREM Project but also benefited the other projects and as well as provided the opportunity for the NASA workforce to work as a team across field center, project, and technical discipline boundaries.
4) *Collaboration with other groups*: The project team actively pursued collaboration with other government agencies, academia, and industry. In addition, proposals for internal NASA field center discretionary funding and other NASA research solicitations were pursued to enhance the project's portfolio and augment project resource allocation, particulary for low maturity technologies. Collaborative efforts of note include a Space Act Agreement with United Technologies for a CO_2 compressor, a Space Act Agreement with the Department of Energy National Energy Techology Laboratory for dual-use CO_2 sorbents, and work with the National Space Biomedical Research Institute on O_2 concentration.
5) *Outreach*: Project management encouraged all team members to participate in outreach activities whenever possible. The fact that the project did not have an outreach budget was a problem that was mitigated by looking for local opportunities to share the U.S. space exploration vision with the public and explain why developing technologies to enable people to venture far from Earth is important. These opportunities included speaking engagements at schools, NASA-sponsored exhibitions, college-sponsored career fairs, and conferences. The ARREM Project team used graphics created in-house and, when possible, hardware to help explain the exploration technology development challenges associated with ECLS systems and the way NASA scientists and engineers were solving them. Future NASA research and technology programs should consider including a resource allocation for outreach that can be accessed by submitting proposals. Developing a set of outreach "tools" that can be used by several groups at NASA to showcase research and technology efforts and their benefits to society can be highly beneficial in sustaining public support for space exploration programs.

F. Workforce Development
Workforce development was an important part of the ARREM project. Several ways the project worked to develop the workforce included encouraging the senior engineers and ECLS system subject matter experts to work closely with early career engineers, interns, and students. This allowed project team members to collaborate and helped NASA pass corporate knowledge to a new generation of explorers. This is imperative for enabling future exploration missions because a large percentage of the present experienced workforce is eligible to retire within 10 years or less.

The ARREM Project also sponsored overview classes on ECLS system developmental history. The ECLS System 101 class helped educate the new team members about ECLS systems over the past 30 years. The class allowed the new team members to learn the scope of work in the ECLS system technical areas in addition to meet subject matter experts in a wide variety of topics. The class was well received and may be of interest to a broader audience.

G. Facilities Utilization
Early in the ARREM Project's formulation, test facilities and capabilities at all the participating NASA field centers were reviewed before recommending how the work should be divided. Efforts centered on achieving the best

match between the resident expertise, facilities, and the project's needs while avoiding duplication or new facility construction.

Using existing facilities helped the project minimize capital costs and unnecessary duplication of NASA test facilities; however, it is important to understand that the using existing facilities and equipment also means that older test articles and special test support equipment were used which presented a higher risk for failure during a test as well as requiring more frequent maintenance. The test support equipment should be evaluated before the start of each test to undertand the risk of failure during a test and if down time can not be factored in the schedule, the possibility of replacing the at-risk equipment should be seriously considered.

V. Conclusion

In 2012 the AES Program launched several ECLS system dvelopment projects to lay the groundwork for future exploration missions. The ARREM Project was selected to develop the ARS and EMS components and subsystem architectures. The project maximized the use of resources by utilizing existing NASA ground-based facilities, ISS engineering prototypes, available new technology components such as SBIR-produced products, and incorporated the use of analysis and simulation to focus the testing performed. The ARREM Project was supported by six NASA field centers that brought together subject matter experts with over 25 years of experience in the design, development, and testing of spacecraft ECLS systems. These subject matter experts worked hand-in-hand with a team of early-career NASA engineers. The team defined the best-suited testing and functional demonstration methods as well as the level of integration for each candidate process technology and/or integrated system architecture based on priorities, availability, needs, and resources. The ARREM Project team developed and used FOMs to assess the progress towards increasing hardware performance.

The ARREM Project team successfully met all the milestones established with the AES PMO, developed and tested ARS and EMS components and subsystems, worked to fill capability gaps and improve efficiency, safety, and reliability over the ISS SOA. The most important technical product of the project is an ARS architecture and an EMS that can support future exploration missions. A list of lessons learned that may serve as a valuable reference for use by future research and technology development project managers has been developed. One of the most significant lessons learned by the ARREM Project team was the value of empowering the team members by helping them understand the "big picture", providing them a clear vision of how their work fits in that picture, and guiding them via clearly-stated success criteria and expectations. Program management commitment to the success of the project and implementing a skunkworks-like management model allowed the project to tailor its management style to foster innovation and overall success.

Appendix

The following publications document details and technical results from the AES ARREM Project as well as publications that assisted with project formulation and management.

Project Formulation and General Results

J. Perry, J. Knox, K. Parrish, M. Roman, D. Jan, and M. Abney, "Integrated Atmosphere Resource Recovery and Environmental Monitoring Technology Demonstration for Deep Space Exploration," AIAA 2012-3585. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Roman, J. Perry, and D. Jan, "Design, Development, Test, and Evaluation of Atmosphere Revitalization and Environmental Monitoring Systems for Long Duration Missions," AIAA 2012-5120, *AIAA Space and Astronautics Forum and Exposition*, Pasadena, California, 2012.

J. Perry, M. Abney, K. Frederick, Z. Greenwood, M. Kayatin, R. Newton, K. Parrish, K. Takada, L. Miller, J. Scott, and C. Stanley, "Functional Performance of an Enabling Atmosphere Revitalization Subsystem Architecture for Deep Space Exploration Missions," AIAA 2013-3421, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

Carbon Dioxide Removal and Management

C. Junaedi, S. Roychoudhury, D. Howard, J. Perry, and J. Knox, "Microlith-based Structured Sorbent for Carbon Dioxide, Humidity, and Trace Contaminant Control in Manned Space Habitats," AIAA 2011-5215, *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

L. Miller and J. Knox, "Development and Testing of a Sorbent-based Atmosphere Revitalization System 2010/2011," AIAA 2011-5217. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Perry, J. Knox, D. Howard, S. Roychoudhury, and C. Junaedi, "Performance Evaluation of Engineered Structured Sorbents for Atmosphere Revitalization Systems on board Crewed Space Vehicles and Habitats," AIAA 2011-5218. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Knox, R. Gostowski, D. Watson, and J. Hogan, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems," AIAA 2012-3642, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, K. Kittredge, R. Coker, R. Cummings, and C. Gomez, "Developments in Atmosphere Revitalization Modeling and Simulation," AIAA 2012-3584, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Hogan, B. Luna, L. Mulloth, M. Varghese, B. Koss, G. Palmer, P. Linggi, J. Melton, and Z. Lu, "The Low-Power CO_2 Removal and Compression System: Design Advances and Development Status," AIAA 2012-3587 *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, R. Gostowski, D. Watson, J. Hogan, E. King, and J. Thomas, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems," AIAA 2012-3642 *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

J. Knox, H. Gauto, R. Gostowski, D. Trinh, D. Watson, J. Hogan, J. Thomas, and E. King, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2012-2013," AIAA 2013-3422. *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Coker, J. Knox, R. Cummings, C. Gomez, and C. Evans, "Additional Developments in Atmosphere Revitalization Modeling and Simulation," AIAA-2013-3455. *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

"Simulation Helps Improve Atmosphere Revitalization Systems for Manned Spacecraft," COMSOL User Story, 2014.

R. Coker, J. Knox, H. Gauto, and C. Gomez, "Full System Modeling and Validation of the Carbon Dioxide Removal Assembly," ICES-2014-168, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

D. Jan, J. Hogan, B. Koss, G. Palmer, T.J. Richardson, P. Linggi, and J. Knox, "Performance of Silica Gel in the Role of Risidual Air Drying," ICES-2014-243, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Hogan, D. Jan, G. Palmer, T.J. Richardson, P. Linggi, and Z. Lu, "Development and Testing of a Two-Stage Air Drying System for Spacecraft Cabin CO_2 Removal Systems," ICES-2014-220, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

J. Knox, H. Gauto, R. Gastowski, D. Watson, J. Thomas, L. Miller, R. Coker, and C. Stanley, "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2013-2014," ICES-2014-160, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Oxygen Supply and Recovery

C. Junaedi, K. Hawley, S. Roychoudhury, M. Abney, and J. Perry, "Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction," AIAA-2011-5033. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

J. Mansell and M. Abney, "Influence of Oxygenated Compounds on Reaction Products in a Microwave Plasma Methane Pyrolysis Assembly for Post-Processing of Sabatier Methane," AIAA 2011-5035. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

M. Abney and L. Miller, " Evaluation of Sorbents for Acetylene Separation in Atmosphere Revitalization Loop Closure," AIAA 2011-5057. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

E. Schmitt, T. Norman, R. Roy, B. Murach, and K. Ogle, "Development of High-Pressure Cathode Feed Water Electrolysis Cell Stacks for Microgravity Environments," AIAA 2011-5058. *AIAA 41st International Conference on Environmental Systems*, Portland, Oregon, 2011.

C. Junaedi, K. Hawley, D. Walsh, S. Roychoudhury, S. Busby, M. Abney, J. Perry, and J. Knox, "Compact, Lightweight Adsorber and Sabatier Reactor for CO_2 Capture and Reduction for Consumable and Propellant Production," AIAA 2012-3482. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

R. Wheeler, N. Hadley, R Dahl, M. Abney, Z. Greenwood, L. Miller, and A. Medlen, "Advanced PPA Reactor and Process Development," AIAA 2012-3553. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Swickrath and M. Anderson, "The Development of Models for Carbon Dioxide Reduction Technologies for Spacecraft Air Revitalization," AIAA 2012-3586. *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Abney, L. Miller, Z. Greenwood, M. Iannantuono, and K. Jones, "Methane Post-Processor Development to Increase Oxygen Recovery beyond State-of-the-Art Carbon Dioxide Reduction Technology," AIAA 2013-3513, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

T. Nalette, P. Yu, J. Perry, and M. Abney, "Investigation of the Potential Impact of Trace Contaminants on the Performance of the Sabatier Catalyst," AIAA 2013-3528, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Wheeler, N. Hadley, S. Wambolt, and M. Abney, "Third Generation Advanced PPA Development," ICES-2014-34, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Trace Contaminant Control

J.L. Perry, M.W. Pruitt, R.M. Wheeler, and O. Monje, "Atmosphere Resource Recovery and Environmental Monitoring Trace Contaminant Control Through FY 2012," NASA/TM-2013-217496, NASA, 2013.

O. Monje and S. Nolek, "Solar Simulator Testbed: Demonstration of a Solar Photocatalytic Oxidation System," AIAA 2012-3426, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

L. Levine, J. Coutts, P. Hintze, and C. Clausen, "Review of Transforming TiO_2 into a Visible-Light-Responsive Catalyst for Water and Air Purification," AIAA 2012-3629, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

O. Monje and O. Melendez, "Low Temperature Catalyst for NH_3 Removal," AIAA 2013-3423, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

O. Monje, J. Surma, M. Johnsey, and O. Melendez, "Evaluating the Adsorptive Capacities of Chemosorb 1000 and Chemsorb 1525, ICES-2014-282, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Particulate Removal and Disposal

J. Agui and R. Vijayakumar, "Development of an Indexing Media Filtration System for Long Duration Space Missions," AIAA 2013-3486, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

M. Meyer, "ISS Ambient Air Quality: Updated Inventory of Known Aerosol Sources," ICES-2014-199, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

R. Green, R. Vijaykumar, and J. Agui, "Development of Test Protocols for International Space Station Particulate Filters," ICES-2014-216, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Environmental Monitoring

M. Darrach, A. Chutjian, B. Bornstein, V. Carkanian, V. Hoemmerle, J. Hofman, D. Karmon, J. Kenny, R. Kidd, J. MacAskill, S. Madzunkov, N. Toomarian, and R. Shaefer, "Trace Chemical and Major Constituent Measurements of the International Space Station Atmosphere by the Vehicle Cabin Atmosphere Monitor," AIAA 2012-3432, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

D. Jan and R. Newton, "Environmental Monitoring as Part of Life Support: Preparing for Deep Space Missions," AIAA 2012-3433, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

B. Bae, J. Kim, J. Yeom, Q. Chen, and M. Shannon, "Development of a Portable Gas Analyzer Using a Micro-Gas Chromatograph/Flame Ionization Detector for NASA's Environmental Missions," AIAA 2012-3435, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

M. Homer, A. Shevade, and R. Huerta, "Rapid Analysis, Self-Calibrating Array for Air Monitoring," AIAA 2012-3457, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.

O. Monje, S. Volling, J. Cornish, and K. Rojdev, "Dynamic Sampling of Cabin VOCs during the Mission Operations test of the Deep Space Habitat," AIAA 2013-3312, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

M. Homer, A. Shevade, J. Fonollosa, and R. Huerta, "Faster Array Training and Rapid Analysis for A Sensor Array Intended for an Event Monitor in Air," AIAA 2013-3451

J. Li, A. Hannon, Y. Lu, B. Kim, and E. Contes-de Jesus, "A Phone Sensor for Trace Chemical Detection," AIAA 2013-3452, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

S. Madzunkov, J. Simcic, R. Kidd, M. Darrach, and B. Bae, "Recent Developments in Gas Chromatograms and Mass Spectrometers for Crewed and Robotic Space Missions," AIAA 2013-3453, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

R. Briggs, C. Frez, S. Forouhar, R. May, and G. Ruff, "Portable 4.6 μm Laser Absorption Spectrometer for Carbon Monoxide Monitoring and Fire Detection," AIAA 2013-3474, *AIAA 43rd International Conference on Environmental Systems*, Vail, Colorado, 2013.

J. MacAskill and E. Tsikata, "Recent Advances in Water Analysis with Gas Chromatograph Mass Spectrometers," ICES-2014-316, *44th International Conference on Environmental Systems*, Tucson, Arizona, 2014.

Acknowledgments

The authors thank Mr. Scott Jones for his scheduling and project documentation expertise and Ms. Melanie Holloway for her budget management acumen. The authors thank the AES Program management team and Domain Lead Barry Epstein for their programmatic guidance. And, finally, special thanks to the ARREM Project team and the Jacobs Engineering team at the Marshall Space Flight Center for their professionalism and superb technical know how.

References

[1]Moore, C.L. and Peri, F., "The Exploration Technology Development Program," AIAA 2007-136, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2007.

[2]NASA Advanced Exploration Systems, http://www.nasa.gov/directorates/heo/aes/.

[3]NASA Systems Engineering Processes and Requirements, NPR 7123.1B, April 18, 2013, pp. 100-102.

[4]NASA Space Flight Program and Project Management Handbook and the Standing Review Board Handbook, NPR 7120.5E, August 14, 2012.

[5]Hurlbert, K., Bagdigian, B., Carroll, C., Jeevarajan, A., Kliss, M., and Singh, B., Human Health, Life Support and Habitation Systems—Technology Area 06, National Aeronautics and Space Administration, April 2012.

[6]Metcalf, J., Peterson, L., Carrasquillo, R., and Bagdigian, R., "NASA Environmental Control and Life Support Integrated Roadmap Development, AIAA-2012-3444, *AIAA 42nd International Conference on Environmental Systems*, San Diego, California, 2012.
[7]Voyages—Charting the Course for Sustainable Human Space Exploration, NP-2011-06-395-LaRC, 2011.
[8]Mulloth, L.M., Perry, J.L., and LeVan, D., "Integrated System Design for Air Revitalization in Next Generation Crewed Spacecraft," SAE 2004-01-2373, ICES 2004.
[9]Drake, B.G., "Human Exploration of Mars Design Reference Architecture 5.0," NASA/SP-2009-566, July 2009.
[10]Drake, B.G. and Watts, K.D., Human Exploration of Mars Design Reference Architecture 5.0, Addendum #2, NASA/SP-2009-566-ADD2, March 2014.
[11]"NASA Exploration Destinations, Goals, and International Collaboration," Conference Report (House Report 112-284) accompanying the FY 2012 Consolidated and Further Continuing Appropriations Act (P.L. 112-55), August 2012.
[12]Perry, J.L., Carrasquillo, R.L., and Harris, D.W., "Atmosphere Revitalization Technology Development for Crewed Space Exploration," AIAA 2006-140, 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, Nevada.
[13]Perry, J.L. and Howard, D.F., "Spacecraft Life Support System Process Technology Maturation using Stage Gate Methodology," SAE 2007-01-3045, ICES 2007.
[14]Perry, J.L., Bagdigian, R.M., and Carrasquillo, R.L., "Trade Spaces in Crewed Spacecraft Atmosphere Revitalization System Development," AIAA 2010-6061, 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.
[15]Perry, J.L., Abney, M.B., Knox, J.C., Parrish, K.J., Roman, M.C., and Jan, D.L., "Integrated Atmosphere Resource Recovery and Environmental Monitoring Technology Demonstration for Deep Space Exploration," AIAA 2012-3585, 42nd International Conference on Environmental Systems, San Diego, California, 2012.
[16]Perry, J.L., Abney, M.B., Frederick, K.R., Greenwood, Z.W., Kayatin, M.J., Newton, R.L., Parrish, K.J., Takada, K.C., Miller, L.A., Scott, J.P., and Stanley, C.M., "Functional Performance of an Enabling Atmosphere Revitalization Subsystem Architecture for Deep Space Exploration Missions," AIAA-2013-3421, 43rd International Conference on Environmental Systems, Vail, Colorado, 2013.