

Integrated Atmosphere Resource Recovery and Environmental Monitoring Technology Demonstration for Deep Space Exploration

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Exploring the frontiers of deep space continues to be defined by the technological challenges presented by safely transporting a crew to and from destinations of scientific interest. Living and working on that frontier requires highly reliable and efficient life support systems that employ robust, proven process technologies. The International Space Station (ISS), including its environmental control and life support (ECLS) system, is the platform from which humanity's deep space exploration missions begin. The ISS ECLS system Atmosphere Revitalization (AR) subsystem and environmental monitoring (EM) technical architecture aboard the ISS is evaluated as the starting basis for a developmental effort being conducted by the National Aeronautics and Space Administration (NASA) via the Advanced Exploration Systems (AES) Atmosphere Resource Recovery and Environmental Monitoring (ARREM) Project. An evolutionary approach is employed by the ARREM project to address the strengths and weaknesses of the ISS AR subsystem and EM equipment, core technologies, and operational approaches to reduce developmental risk, improve functional reliability, and lower lifecycle costs of an ISS-derived subsystem architecture suitable for use for crewed deep space exploration missions. The most promising technical approaches to an ISS-derived subsystem design architecture that incorporates promising core process technology upgrades will be matured through a series of integrated tests and architectural trade studies encompassing expected exploration mission requirements and constraints.

Nomenclature

<i>C</i>	=	Celcius
<i>CFM</i>	=	cubic feet per minute
<i>CFU</i>	=	colony forming units
<i>ft</i>	=	foot
<i>kg</i>	=	kilogram
<i>kPa</i>	=	kilopascal
<i>lb</i>	=	pound
<i>m</i>	=	meter
<i>mg</i>	=	milligram
<i>psia</i>	=	pound per square inch absolute
<i>%</i>	=	percent

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I. Introduction

PROVIDING acceptable cabin atmosphere quality aboard crewed space vehicles and habitats has significant continuity throughout the United States' (U.S.) space exploration program. Spanning the crewed space exploration missions and vehicles beginning with Project Mercury through the International Space Station (ISS) program, the common atmosphere quality management requirements include maintaining cabin pressure and composition. To achieve this end a robust ventilation system and equipment that conditions and revitalizes the atmospheric gases are components of the spacecraft design. Conditioning equipment typically removes and disposes of carbon dioxide (CO₂), trace chemical, and particulate contaminants; maintains temperature and humidity; and supplies breathing gases. Monitoring various parameters such as pressure and composition are provided at a minimum. Hazard analyses identify emergency conditions that the crewmembers must be protected against. Equipment to monitor for such conditions, personal protective equipment, and recovery/remediation equipment to restore the cabin environment to normal conditions are provided as required. The set of equipment to accomplish all of these functions forms the core of an atmosphere resource recovery and environmental monitoring subsystem.

A. Technological Evolution and Requirements

Excellent historical summaries describing crewed space exploration vehicle AR subsystem equipment are provided by Diamant and Humphries¹, Martin², and Wieland³. Review of these summaries shows the atmosphere revitalization (AR) subsystem design complexity has evolved to enable mission objectives and duration. The basic process technologies have been fairly standard. For example, media for purifying the cabin atmosphere such as granular lithium hydroxide (LiOH), granular activated carbons (GAC), and platinum group metal-based oxidation catalysts that operate at ambient or elevated temperature are common across all programs. However, the equipment physical embodiment—fit and form—has been tailored to the vehicle and mission architecture. This is illustrated by the adaptation of CO₂ removal process technology to the ISS. The extended duration Skylab missions presented an early technical challenge that was addressed by using regenerable zeolite sorbents for CO₂ control. The Skylab equipment used a 2-bed approach that vented both CO₂ and water overboard. The ISS, however, needed to recover the water to reduce logistics requirements; therefore, ISS adapted the process technology used in the Skylab CO₂ removal process to a physical embodiment that allows for water recovery. Further advances have been incremental incorporating new process technologies their technical maturity permit.

Table 1. Cabin atmosphere design parameters for the ISS at 101.3 kPa.⁴

PARAMETER	VALUE
Total pressure (kPa)	97.9-102.7
Carbon dioxide partial pressure (kPa)	0.7-1
Oxygen partial pressure (kPa)	19.5-23.1
Nitrogen partial pressure (kPa)	<80
Relative humidity (%)	25-70
Temperature (°C)	17.8-26.7
Ventilation (m/second)	0.05-0.2
Particulate concentration (mg/m ³)	<0.05 average; <1 peak
Total trace chemical concentration (mg/m ³)	<25
Leakage rate (kg/day)	<0.23

No matter the mission objective, spacecraft cabin atmosphere management parameters are common although over the years there have been periodic revisions as knowledge has been gained on human physiological responses to spaceflight environments. Requirements of primary concern address cabin pressure, CO₂ partial pressure, oxygen (O₂) partial pressure, trace chemical contaminant concentrations, and particulate matter concentration as well as maintaining cabin temperature and humidity levels within healthy and comfortable limits. Table 1 summarizes common design parameters developed for the ISS Program. In addition to these, other design parameters and human metabolic loads are the following:⁴

- 1) Trace chemical contaminants less than spacecraft maximum allowable concentration (SMAC)⁵
- 2) Metabolic oxygen consumption: 0.49-1.25 kg/person-day, 0.84 kg/person-day average
- 3) Metabolic moisture production: 0.87-4.3 kg/person-day, 1.82 kg/person-day average
- 4) Metabolic carbon dioxide production : 0.52-1.5 kg/person-day, 1 kg/person-day average
- 5) Microbial generation rate: 3,000 CFU/person-minute
- 6) Particulate generation rate: 1×10^9 particles/person-day

It is noteworthy that the metabolic demand is strongly influenced by activity level and will vary for mission concepts that require exercise to counteract microgravity exposure. Likewise, the frequency and duration of extravehicular activity (EVA) influences specific operational and capacity aspects of a spacecraft AR subsystem.

B. Objectives for Technological Advancement

The Atmosphere Resource Recovery and Environmental Monitoring (ARREM) for Long Duration Exploration Project's main objectives are to mature integrated AR and Environmental Monitoring (EM) subsystems derived directly from the ISS AR subsystem architecture that will reduce developmental and mission risk; lower lifecycle costs, and demonstrate operational process design and system architectural concepts for future human missions beyond Earth orbit. The ISS AR and EM architectures are loosely coupled which may cause developmental and operational inefficiencies. Because the true function of environmental control and life support (ECLS) system is first and foremost ensuring crew health—people cannot be healthy with stale, muggy air; bad water; and poor cabin pressure and composition control—it is imperative that the technical solution for the AR and EM subsystems be closely coupled. The ARREM Project is focused on key technical and architectural improvements in the physico-chemical process technologies employed aboard the ISS for AR subsystems that increase reliability, functional capability, and consumable mass recovery as well as reduce requirements for power, volume, heat rejection, and crew involvement.

The objectives and goals of the AR and EM subsystem technology maturation tasks within the ARREM Project are summarized as follows:

- 1) Demonstrate an evolved ISS state-of-the-art (SOA) AR and EM subsystem architecture via targeted advancements that benefit ISS operations in Low Earth Orbit (LEO) and exploration missions beyond LEO.
- 2) Assess equipment embodiments that offer the greatest potential for maximizing process technology and hardware component commonality across a variety of mission scenarios and vehicle concepts anticipated in a flexible exploration framework.
- 3) Advance the technical maturity of candidate process technologies for flexible AR and EM subsystem architectures to achieve risk reduction and developmental economy to flight project development programs.
- 4) Develop a set of resource recovery capabilities that can be added in modular fashion to a common set of core, modular AR and EM subsystem equipment to allow mission planners flexibility to extend crewed mission durations without compromising core equipment functionality.

C. Functional Trade Spaces and Mission Considerations

Functional elements of AR and EM subsystems include process technologies and equipment components to condition, and monitor a crewed spacecraft cabin's atmosphere as well as recover resources to reduce logistics resupply demand. Environmental monitoring services may be needed to detect and monitor recovery from cabin atmosphere contamination events caused by thermal decomposition (fire) or chemical releases. Atmosphere revitalization and EM functions have traditionally been accomplished by several subsystems within a vehicle architecture. For example, the subsystems aboard the ISS include temperature and humidity control (THC), atmosphere revitalization (AR), fire detection and suppression (FDS), atmosphere control and supply (ACS), and crew health care (CHcC). Environmental monitoring spans all of these subsystems. The focus of the ARREM project is AR and ACS coupled with EM functions derived from the CHcC, ACS, and FDS areas. A functional trade space approach to defining the primary developmental areas has been developed and is summarized by Fig. 1.⁶ The functional trade spaces summarized by Fig. 1 provide the framework for defining options within AR and EM functional trade spaces as well as providing a summary guide for the potential interaction between trade spaces.

Evaluating the feasibility for adapting existing AR and EM subsystem process designs and equipment physical embodiments is the first step toward defining a candidate process design and architecture. The approach defines what is known and identifies areas for improvement and potential technical gaps. The range of process technologies and physical equipment embodiments employed aboard the ISS and Shuttle as well as candidates for use aboard the Multi-Purpose Crew Vehicle (MPCV) to accomplish the major AR and EM functions have been evaluated for their applicability to crewed exploration missions exceeding one year duration. Specific attention is given to ISS process technologies and equipment embodiments as being most applicable to long duration mission concepts because they allow for resource recovery. Equipment approaches employed by the Shuttle and MPCV are considered for shorter duration aspects of a 1-year exploration mission duration which "portable" equipment may be beneficial or for mission durations less than one year.

Where improvements to the ISS basic AR and EM subsystem functionality are necessary to enable long duration crewed missions, suitably mature process technologies under development by research and technology programs sponsored by the National Aeronautics and Space Administration (NASA) were considered. The gravity environment, either micro-gravity or hypo-gravity, was evaluated at the component level as necessary. Fortunately most AR and EM process technologies and equipment physical embodiments are insensitive to the gravity environment. The exceptions are equipment used for gas-liquid separations. Challenges presented by operating

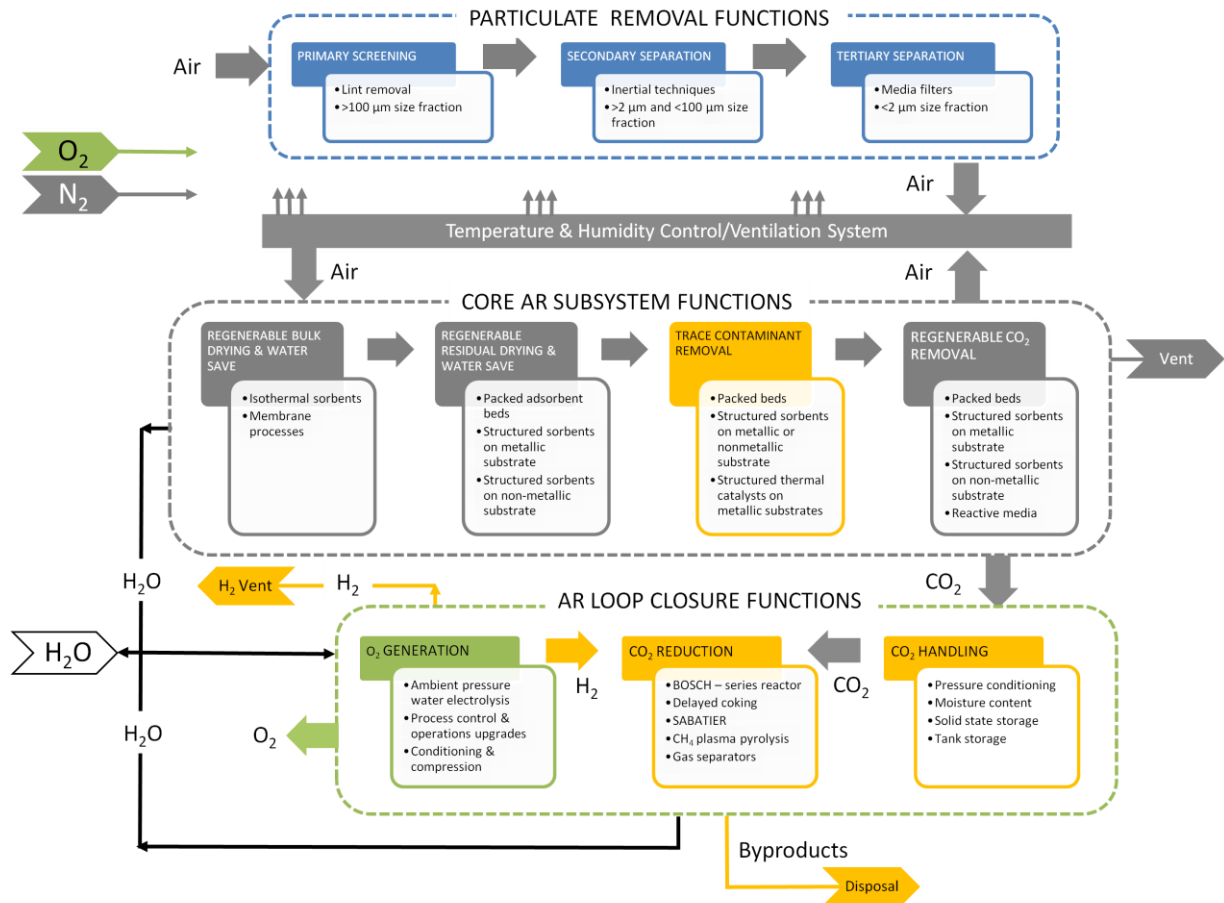


Figure 1. Atmosphere management functional trade spaces.⁶

at spacecraft cabin pressures <101 kPa (14.7 psia) were evaluated and found to be associated with delivering proper process gas flow to the AR and EM subsystem components, removing excess heat from components, and assuring compatibility with O₂ partial pressure >30%. Nearly all existing AR and EM process technologies and equipment are designed for operation at 101 kPa cabin pressure and approximately 20% O₂ partial pressure.

1. Vehicle vs Habitat - System Design Considerations

Regardless of the platform, the basic atmosphere quality parameters apply. Differences exist, however, in vehicle cabin pressure and mission duration. Potential impacts associated with these differences are summarized by the following discussion. Existing equipment embodiments are capable of handling a range of crew metabolic load dynamics as demonstrated by flight operational performance.

2. Cabin Pressure Considerations

The desire to employ cabin pressure <69 kPa (<10 psia) requires higher oxygen partial pressure. Some mission concepts are assuming a 55 kPa (8 psia) cabin pressure to more efficiently and safely conduct frequent EVA operations. The lower cabin pressure requires oxygen partial pressure exceeding 30% in some instances. Existing AR and EM equipment and materials of construction used in the Shuttle and ISS cabins are not certified for 55 kPa and >30% oxygen conditions. As well, the lower pressure alters flow rate control through equipment as well as thermal management of equipment due to the lower cabin atmosphere density and changes in heat capacity. While fans and blowers used are constant volume devices, most performance requirements are based on standard volumetric flow conditions rather than actual volumetric flow conditions. In general the fans and blowers may be operated at higher speeds to compensate to an extent; however, the motor and impeller designs may require alteration to lessen efficiency losses. Heat exchangers used for air cooling equipment will suffer from altered performance and will require redesign to accommodate the reduced pressure environment.

3. Mission Duration Considerations

Some exploration vehicle applications such as for surface exploration and short duration crew transportation may require more “portable” AR and EM subsystem equipment designs depending on how they are intended to be used. For short-term sorties from a “base camp” habitat up to two weeks some Shuttle-derived AR and EM equipment may be considered if recovering carbon dioxide and water are not necessary. Otherwise, process technologies that may allow resource recovery are necessary. Longer duration sorties away from a “base camp” habitat may require considering “open loop”, regenerable techniques or operating ISS-derived AR equipment in an “open loop” mode bypassing capabilities to recover resources. Trade assessments must be conducted to determine to what extent resource recovery may be required during sortie periods. Habitat modules, either for long duration transit or surface exploration objectives, may benefit directly from ISS-derived AR equipment concepts. The overall degree of “loop closure” will be dictated by the specific mission architecture.

II. Technology Maturity Basis Overview

The starting basis for future AR and EM subsystems resides in the shuttle orbiter and ISS programs. The following discussion summarizes the present state of technical areas of interest for future developmental focus.

A. Cabin Ventilation Equipment

The AR subsystem depends on the cabin ventilation equipment to ensure good atmosphere turnover to maintain total air quality. Various fans are used to circulate the atmosphere in the cabin and within avionics bays and racks. Dedicated blowers are used as needed to circulate process air through AM equipment. Overall, the fan technology employed is commonly the axial variety.⁷ Impeller, motor, and housing designs are specific in all cases to optimize each fan for its specific application. Examples of dedicated AR equipment blowers are the ISS carbon dioxide removal assembly (CDRA) and trace contaminant control system (TCCS) blowers. These dedicated blowers employ air bearings and are vane-axial, mixed flow variety. Both blowers share the same housing and motor designs but have differing impeller designs tailored to their specific application. The CDRA blower operates at a higher speed than the TCCS blower and has a digital motor controller while the TCCS blower motor controller is analog. Direct application of Shuttle and ISS fan designs such as the cabin fans, avionics fans, intermodule ventilation fans, and dedicated AR equipment blowers may be possible with some modification. Evaluating existing designs for acoustic properties and employing “quiet fan” design considerations are expected to reduce “after design” acoustic treatment needs.

While basic component technology can be applied to future vehicles and habitats, the ventilation distribution design which is primarily ducting will have to be adapted specifically to the vehicle platform. Components of the ventilation system on board the ISS have been long-lived requiring little logistics supply.

B. Cabin Atmosphere Conditioning Equipment

Conditioning equipment provides for microbial control, particulate control, trace chemical contaminant removal, carbon dioxide removal, humidity control, and heat removal. Basic process technologies include screens, high efficiency particulate air (HEPA) filter elements, sorbents, and oxidation catalysts.

1. Carbon Dioxide Removal

The Shuttle used expendable LiOH cartridges for CO₂ removal and demonstrated an immobilized amine-based vacuum swing (VS) process for longer duration missions. The ISS uses Shuttle LiOH cartridges as a tertiary backup to the U.S. and Russian carbon dioxide removal processes. The amine VS process has been further developed as an “open loop” combined humidity and CO₂ removal process that was selected as the core AR equipment process technology by the MPCV Project. Both LiOH- and amine-based processes may be best suited for short duration, open loop exploration mission objectives. If recovering the CO₂ and moisture is needed, however, other process technologies will need to be considered because the present amine material used in the amine VS process emits ammonia (NH₃) and a variety of other volatile compounds that add an additional trace contaminant burden and may require further CO₂ processing and conditioning before sending the CO₂ to a reduction process. These other regenerable CO₂ removal and concentration processes may be derived from the Skylab and ISS CO₂ removal equipment. The regenerable ISS EVA metal oxide (MetOx) media that stores the CO₂ could be adapted to sortie mission vehicles that depart from a “base camp” habitat or vehicle for a period of time. Upon return the metal oxide can be thermally regenerated to recover the CO₂.

The ISS CDRA is derived from the Skylab 2-bed molecular sieve process design but tailored to provide a “water saving” feature whereby moisture removed from the process air is returned to the cabin for recycling. Like the Skylab 2-bed molecular sieve process, the CDRA employs 13X zeolite desiccant bed media and 5A zeolite CO₂

adsorbent media. The CDRA also uses silica gel in the desiccant bed as a further moisture recovery enhancement for the ISS application. The unit contains an air saving pump to prevent atmosphere losses overboard during open loop operating mode. The CDRA is also capable of operating in a closed loop operating mode whereby the concentrated CO₂ is delivered to a reduction process. This operational capability was demonstrated successfully for the first time in flight aboard the ISS in October 2010 when a Sabatier-based CO₂ reduction unit was operated aboard the ISS to recover resources from the CDRA and oxygen generation assembly (OGA). Waste methane (CH₄) is vented overboard. Both the CDRA and Sabatier-based reduction process technologies can be directly applied to deep space exploration mission vehicles and habitats. Physical embodiments are expected to be different from those on board the ISS.

The ISS CDRA has operated reasonably well since the root cause of initial startup problems was identified. Most operational problems were found to arise from zeolite bed containment design deficiency. The bed material containment failed and the pellets spilled into the process ducts. Pellets migrated through the system and fouled valve surfaces and lodged in the air save pump. Once a bed containment redesign was implemented, problems with valves and other downstream components were significantly reduced, though low level dust production is suspect due to lingering valve failures. However, bed material size attrition that produces fine dust that clogs the bed containment screens has persisted to be a problem. It should be noted that the original design predicted that the bed on-orbit replaceable unit (ORU) would last the life of the ISS. However changes in the bed material manufacturing process resulted in a material with inferior crush strength and coupled with a flawed bed containment design the problems mounted. An initial bed ORU redesign addressed the bed containment design and now has achieved an improved service life for the bed and all downstream components. The result is that the CDRA bed ORU must be replaced at approximately 1-year (or longer) intervals. The second bed redesign (-3) relocated the most restrictive screen to a location with much greater area, and after one year in operation, has shown no increase in differential pressure. Significant pressure increase had been observed within 6 months for the -2 configuration. Each CDRA bed ORU weighs 40 kg (88 lb). Replacement up to once/year results in approximately 80 kg/year logistics resupply for the present design. A third bed ORU redesign is seeking to further refine the bed containment design to extend the service interval. This redesign includes a more robust bed material containment design over the -3 bed ORU design and an option to clean the internal screens on-orbit. On-orbit operation of the -4 bed ORU will be necessary to demonstrate improvement so a 1-year replacement interval is used for evaluation purposes at this time. In all, the ISS CDRA process is suited for extension to deep space exploration vehicles and habitats that require a flexible open-/closed-loop system with a water saving capability. A future version should use a more durable bed material which may be used in the ISS -4 bed ORU design. Heat exchanger, blower, and heater component designs may require modification to accommodate efficient operation at lower cabin pressures. Selector valves should include a wiper feature on the seals to prevent fouling and extend service life.

The ISS Russian Segment provides carbon dioxide control using the Vozdukh unit. This equipment consists primarily of two desiccant beds and three carbon dioxide sorbent beds. Reports indicate the desiccant beds may be filled with silica gel and the carbon dioxide sorbent beds may be filled with a “solid amine” material.⁸

2. Trace Contaminant Control

Trace chemical contaminants are removed from the Shuttle and ISS cabin atmosphere using granular activated carbon (GAC) and oxidation catalysts. The Shuttle uses an ambient temperature carbon monoxide (CO) oxidation catalyst (ATCO) that is 2% platinum supported on GAC in addition to GAC. Spacelab used an engineered mixed media sorbent bed in the transfer tunnel scrubber that contained phosphoric acid (H₃PO₄)-treated GAC, GAC, and ATCO media. The ISS TCCS uses H₃PO₄-treated GAC for removing volatile compounds and a 0.5% palladium on alumina thermal oxidation catalyst to remove CH₄ and CO from the cabin atmosphere. The TCCS carbon bed assembly (CBA) which weighs 37 kg has been demonstrated to have a 4.5-year service life which preserves a 25% operational margin. The catalytic oxidizer assembly (COA) is designated as a wear-out item, meaning that the unit is expected to last the life of the ISS. The sorbent bed assembly (SBA) which weighs 4.1 kg and is located downstream of the COA has a 4-year service life. Other TCCS components have been in operation for a decade without replacement.

The Russian micro-impurity removal block (Russian acronym BMP) uses expendable activated carbon, regenerable activated carbon, and catalytic oxidation—ambient temperature for CO and high temperature for CH₄—to provide the trace contaminant control function. Either the U.S. Segment TCCS or the Russian Segment BMP is capable of providing the full trace contaminant control function for the ISS when operating along. All of these process technologies are directly applicable to exploration missions.

The TCCS annual logistics mass for the ISS has been approximately 9 kg/year. No logistics resupply mass for the Russian BMP is available; however, the unit operated aboard Mir was estimated to require 5.7 kg/year logistics mass.⁹ Typical bed service life is 5 years. Overall, The ISS TCCS process technology can accommodate deep space

exploration missions exceeding 4 years without requiring logistics supply based on more than a decade of flight operation.

An area of concern for many AR process designs is that the long-term availability of commercial suppliers of adsorbent and catalyst media. The commercial market experiences business cycles that include acquisitions and mergers. In the process some products that were readily available on the commercial market may become unavailable. This has occurred with some ISS AR equipment. As a result, new adsorbent and catalyst candidates must be screened and further developed to meet future deep space exploration needs. Efforts in this area have identified commercial products possessing greater adsorptive capacities for design-driving trace contaminants such as ammonia.¹⁰ Also, using a mixed media bed as well as using up-to-date trace contaminant control design requirements that better define the ammonia (NH₃) generation rate load may further reduce the bed size compared to ISS equipment designs. Using an advanced catalyst material coated onto expanded metal mesh has been demonstrated to perform comparably to the 0.5% Pd on alumina catalyst pellet but require about 15% less average power to operate. Integrating the TCCS components with the carbon dioxide removal system components in a novel way could also eliminate the need for the SBA.

3. *Particulate Matter Removal and Disposal*

Debris exclusion is provided by screens and filters of varying mesh rating. To protect ventilation systems from fouling, debris screens rated to 280 microns nominal/300 microns absolute are used by the Shuttle. Filtration to 40 microns can be provided as needed but is not standard. The ISS U.S. Segment employs replaceable filter elements, called the bacteria filter element (BFE), that consist of a 20-mesh (841 micron opening) screen backed by pleated HEPA-rated media (99.97% efficient for 0.3-micron size particulate matter). Intermodule ventilation intakes use screens similar to those used by the Shuttle. Application of the basic debris screen and screen/HEPA filter element process technology can be applied directly to deep space exploration vehicles and habitats. The physical embodiment will have to be tailored to the application.

The ISS inter-module ventilation (IMV) inlet screens and the face of the replaceable BFEs are cleaned periodically by the crew to remove accumulated lint and large particulate matter. The ISS BFEs have been demonstrated to have a 2.5-year service life. Each BFE weighs 2.2 kg (4.85 lb) and accommodates 119 m³/h (70 ft³/minute) air flow. Using the ISS Laboratory Module as a deep space habitat comparative basis, there are 6 BFEs that are replaced every 2.5 years requiring 6 kg/year annual logistics mass. The existing BFE dimensions (fit and form) may not be suitable for future vehicles and habitats. A BFE-derived filter element concept or an indexing media filter concept under development by NASA Glenn Research Center can provide the function for much lower annual logistics resupply mass and launch mass.^{11, 12}

C. Oxygen Supply and Recovery

1. *Oxygen Supply*

Pressure management involves delivering atmospheric gases, supplying atmospheric gases, and cabin pressure regulation. Atmospheric gases are O₂ and a diluents gas, traditionally nitrogen for U.S. space vehicles. Atmospheric gas is supplied via pressurized tanks equipped with appropriate valves and regulators and, in the case of the Shuttle, cryogenic boiloff. The ISS also supplies O₂ via electrolyzing water. The U.S. O₂ generation assembly (OGA) uses a solid polymer-based electrolysis process while the Russian Elektron unit uses a liquid KOH electrolyte-based process. Pressurized tank storage provides backup for the electrolysis units. The Russian Segment supplements the electrolysis-based O₂ generators with solid fuel O₂ generator (SFOG) units to release chemically bound oxygen from a solid matrix.

2. *Oxygen Recovery*

Resource recovery equipment in the form of a Sabatier-based CO₂ reduction process was delivered to the ISS in 2010. The basic Sabatier-based process and equipment design used on board the ISS can be applied to future space exploration objectives for loop closure. While the degree of closure is not complete in that a CH₄ product is produced, this product may be either used by other systems, propulsion for instance, or further processed to recover more hydrogen (H₂) via a plasma pyrolysis process.¹³ Work to advance the Bosch process to viability may provide the highest degree of resource recovery if dictated by future exploration mission objectives.

D. Environmental Monitoring

Monitoring functions include composition sensing, emergency sensing, and pressure sensing. Composition sensing is broad and includes sensing temperature, airborne particulate load, CO₂ partial pressure, trace chemical contaminant concentrations, moisture content (humidity), and airborne microbial load. A variety of techniques are employed for these functions. Thermocouples and resistance temperature detectors are considered to be appropriate for exploration vehicle applications. Portable, commercially-available particle counting monitors manufactured by

TSI, Inc., the Dust Trak[®] and P-Trak[®] devices, have been demonstrated on board the ISS and may be candidates for exploration vehicles.¹⁴ Carbon dioxide partial pressure is monitored using electrochemical (ISS portable instrument), infrared (Shuttle), and mass spectrometer (ISS and MPCV) techniques. Trace chemical contaminant concentrations are monitored on board the Shuttle and ISS via collecting grab samples in flight and analyzing the sample on the ground. NASA grab samples are collected in evacuated canisters while Russian grab samples are collected by sorbent trapping. Near real-time trace contaminant monitors have been demonstrated on board the ISS. The instruments demonstrated include a Fourier transform infrared (FTIR) spectrometer developed by a European Space Agency (ESA)-sponsored team as the Analyzing Interferometer for Ambient Air (ANITA) demonstration^{15, 16}, a gas chromatograph/mass spectrometer (GC/MS) developed by a NASA Jet Propulsion Laboratory (JPL) team as the Vehicle Cabin Air Monitor (VCAM) demonstration¹⁷, a gas chromatograph/ion mobility spectrometer (GC/IMS) developed by Graseby/Smith's Analytical (United Kingdom) as the volatile organic analyzer (VOA)¹⁸, and a gas chromatograph/differential mobility spectrometer (GC/DMS) developed by Scionex Corporation as the Air Quality Monitor (AQM)¹⁹. Grab sampling techniques will not be appropriate for deep space exploration missions so one or more of the near real-time techniques will be necessary to monitor the cabin trace contaminant concentration load. Maintaining instrument calibration is a challenge for all techniques.

Emergency sensing has a specific focus for fire. Smoke detectors and combustion product monitors have been used across the Shuttle and ISS programs. Basic technologies can be extended to deep space exploration vehicles with improvement in the areas of false positives (smoke detectors) and combustion product instrument calibration.

Pressure sensing with a focus on O₂ partial pressure, total cabin pressure, and leak detection is common across the Shuttle and ISS programs. The techniques employed can be extended to deep space exploration vehicles.

III. Preliminary Exploration Readiness Assessment

In general, the underlying process technologies used to provide AR and EM functions for the Shuttle and ISS can be adapted to exploration vehicle and habitat architectures. Opportunity exists, however, to improve on various functional, fit, and form aspects of legacy equipment to yield mass, volume, and power reductions with accompanying reliability and maintainability gains. It would appear most efficient to use existing equipment configurations and merely adapt them to future exploration vehicles. This raises the major question of whether the present equipment embodiments are truly suitable and, if so, can duplicates be acquired after many years have passed. Unfortunately in many instances the original equipment suppliers are no longer available. Also, most of the equipment is tailored not only functionally, but especially with respect to fit and form, to address unique Shuttle and ISS vehicle specifications. Therefore it is not considered very promising to use Shuttle and ISS legacy equipment in their present physical embodiments. The most promising aspect of legacy equipment is that the underlying process technologies can be “repackaged” in potentially flexible ways to address the demands of deep space exploration vehicle and habitat architectures that have yet to be defined.

A. Cabin Ventilation Equipment

Equipment to provide ventilation and circulate the cabin atmosphere must be specifically engineered to the vehicle. Duct design and the major components must fit inside the volume envelope and provide the necessary ventilation distribution. Applying “quiet fan” design principles to future vehicle ventilation fans represents an opportunity to “engineer” acoustic considerations into fan design. The objective is to potentially eliminate after-design acoustic treatment that increases ventilation system pressure drop, mass, and volume. All other components are well understood but must be engineered to the vehicle architecture.

B. Cabin Atmosphere Conditioning Equipment

1. Carbon Dioxide Removal

Carbon dioxide management can be accomplished using the ISS CDRA process technology. In-flight and ground test and evaluation data strongly indicate that the leading option is an ISS CDRA-equipment platform and base process technology embodiment that incorporates all ISS lessons learned and serves as the CO₂ management equipment basis for deep space exploration vehicles and applications. Beyond the ISS CDRA equipment platform, the AES ARREM project and the ISS Program are evaluating more durable CO₂ sorbent media candidates which should address CDRA operational challenges experienced on board the ISS. Low power CO₂ removal (LPCOR) and engineered structured sorbent (ESS) concepts that may be more energy efficient than traditional packed sorbent beds have been under development for several years.^{20, 21} Elements of the LPCOR and ESS concepts may be suitable for upgrading the ISS CDRA process architecture for exploration vehicle and habitat applications. The AES ARREM Project intends to investigate such an architecture in detail.

It is also possible to incorporate aspects of the Skylab 2-bed molecular sieve design into the CDRA architecture to provide a wide range of operational modes ranging from dual moisture/CO₂ removal with venting to open loop CO₂ removal with water save, to closed loop CO₂ removal with water save. A 2-bed molecular sieve concept has been under development as risk mitigation to the MPCV Program.²² This concept is approaching readiness for brassboard equipment design and demonstration.

An amine-based CO₂ removal process has been under development for the MPCV. That process emits a substantial amount of NH₃ into the process air stream during operation that can reach the cabin. This added NH₃ load may cause up to a 46% service life reduction to ISS-like trace contaminant control equipment if operated continuously. The potential for an added NH₃ load presented by an amine-based process and the likely need to have a large capacity vacuum pump to reclaim the CO₂ present technically challenges to incorporating amines into a closed loop process architecture. More development is necessary to understand various amine formulations that reduce or eliminate NH₃ release and that can be regenerated with moderate heating.

2. *Trace Contaminant Control*

Trace contaminant control technologies used aboard the ISS are well suited for deep space exploration vehicle application. Bed materials may be improved by selecting an ammonia adsorbent with higher loading capacity and more energy efficient thermal oxidation catalyst material. Incorporating the best adsorbent media and oxidation catalysts into a process design similar to that of the Russian BMP unit may provide additional economies. The AES ARREM project intends to evaluate trace contaminant control adsorbents and catalysts from contemporary vendors to select the best performing candidates and then incorporate them into an equipment architecture that provides the best energy and logistics efficiencies.

3. *Particulate Matter Removal and Disposal*

Particulate and microbial control equipment used on board the ISS can be readily applied to future vehicles. The filter element physical design, however, must be tailored to the vehicle architecture. A common filter element design to cross exploration vehicle and habitat platforms is an important consideration. The filter element design and maintenance can be enhanced by considering a multi-stage particulate filtration/separator concept under development by NASA.²³

C. Oxygen Supply and Recovery

1. *Oxygen Supply*

Pressure management equipment used by the Shuttle and ISS is applicable to the deep space exploration mission vehicle and habitat. Oxygen supply by water electrolysis is an area for improvement. A more reliable electrolysis cell stack and some supporting components need to incorporate lessons learned from the ISS to meet the reliability demands of deep space exploration missions. Other aspects of pressure management involving an engineered atmospheric gas storage, distribution, and delivery system are specific to the vehicle and habitat architecture. While components used on board the Shuttle and ISS can serve as a model for future vehicles, the final design will be dictated by the vehicle/habitat specifications and mission architecture.

2. *Oxygen Recovery*

The Sabatier-based CO₂ management equipment aboard the ISS is fully applicable to deep space exploration vehicles and habitats that may require greater resource recovery. For missions lasting >1 year, the degree of further resource recovery will be dictated by mission objectives. Either plasma-based partial methane pyrolysis to acetylene to recover more hydrogen than Sabatier alone or a Bosch reactor concept to fully recover all H₂ and O₂ will be needed.

D. Environmental Monitoring

Monitoring represents a significant developmental area for deep space exploration missions.²⁴ A suite of instruments is required. Reliable, near real-time trace contaminant monitors and event monitors are needed. Instruments such as the ESA-sponsored ANITA (FTIR technology); JPL-developed VCAM (GC/MS also capable of oxygen, nitrogen, and carbon dioxide monitoring); JPL-developed Enose (targeted event monitor); Sionex-developed AQM (GC/DMS technology); commercially available particulate monitors (TSI Dust Trak and P-Trak); commercially available velocity and humidity monitors (TSI VelociCalc); and commercially available portable carbon dioxide monitors, oxygen monitors, and combustion product monitors should serve as the starting point. Developing reliable airborne microbial monitoring is a major challenge that has proven elusive and a lot of work remains in that area. Common needs assessments and performance specifications must be developed for deep space exploration missions in this area to properly guide development toward a useful product. Most temperature, pressure, and oxygen sensors from the ISS can be used. Fire and smoke sensing equipment needs to be improved to avoid false alarms caused by background airborne particulates.

E. Summary of Readiness and Gap Identification

Findings of the AR and EM equipment functional assessment for enabling exploration objectives are the following:

- 1) Most basic AR process technologies, i.e. adsorbent media and catalysts, employed aboard the ISS for the core AR CO₂ and trace contaminant control functions are well suited for extension to long duration missions. Challenges pertaining to adsorbent media and catalyst durability as well as commercial availability must be addressed. Additional development in this area is necessary due to the time that will elapse between ISS technical solutions and future exploration missions.
- 2) Core trace contaminant control sorbents and oxidation catalysts employed aboard the ISS are suitable for long duration missions; however, advances in NH₃ sorbent capacities and power savings associated with engineered catalyst substrates will significantly reduce the size and power required for trace contaminant control equipment.
- 3) Water electrolysis-based O₂ generation employed aboard the ISS is well suited for long duration mission applications. Components of the ISS-developed O₂ generator need modification to reduce electrolysis cell stack membrane fluorine leaching to meet reliability and maintainability demands of such missions. Operational changes may simplify equipment with resulting reliability and maintainability improvements.
- 4) Sabatier-based CO₂ reduction under demonstration on board the ISS is directly applicable to missions lasting over 1 year. Techniques for further processing Sabatier-produced gases can be developed to further extend crewed mission duration by driving oxygen recovery closer to 100%.
- 5) AR and EM equipment deployed aboard the ISS will require evaluation to determine whether modification is necessary to accommodate the recommended range of cabin atmosphere conditions encountered across exploration design reference mission (DRM) concepts.
- 6) AR and EM equipment fit and form aspects of ISS-derived designs will change significantly to comply with deep space exploration detailed vehicle and mission requirements.
- 7) Blowers and heat exchangers will require evaluation to determine whether redesign to accommodate lower cabin atmospheric pressures is necessary.
- 8) Some wetted materials may have to be replaced to be compatible with O₂ partial pressures over 30%.
- 9) Some equipment onboard ISS may have to add safety containment or change process operating conditions to accommodate lower cabin atmospheric pressures.
- 10) Fire detection and material flammability are both strongly affected by O₂ concentration and gravity level driving a need for improved fire suppression techniques.

IV. AR and EM Subsystem Concept Development and Demonstration

A. Establishing the Basis for Comparison

The ISS AR and EM subsystem architectures serve as the basis for comparison because those systems have been proven over ten years of flight operations. From a developmental perspective it is important that equipment tested be at similar maturity states. While the ISS Program has no qualification-maturity equipment available as spares, a complement of high fidelity developmental equipment exists that includes CO₂ removal, CO₂ reduction, trace contaminant control, and O₂ generation developmental test articles. This developmental equipment has been installed in a specialized chamber in the ISS configuration. Testing conducted in 2012 will provide the performance basis for comparison as components from the ISS developmental equipment components are rearranged and new components developed to target areas for ISS AR and EM subsystem improvement are added. Test objectives for establishing the performance basis are the following:

- 1) Demonstrate simultaneous sustained operation of a ground-based *ISS* AR subsystem functional analog that may trace contaminant control, CO₂ removal, CO₂ conditioning and storage, CO₂ reduction, and O₂ generation.
- 2) Demonstrate the robust function of key facility support items including, but not limited to, trace chemical contaminant injection, space vacuum simulation, sub-atmospheric pressure maintenance, human metabolic simulation, temperature control, humidity control, chamber atmosphere composition control, and in-line gas phase major constituent and trace chemical compound analysis.

Figure 2 shows a simplified process schematic for the performance basis testing. As shown by Fig. 2, this architecture has CO₂ removal and trace contaminant control equipment operating in parallel. Three performance basis test phases are designed to demonstrate the following:

- 1) Phase 1A—Demonstrate functional performance of the basic *ISS* AR subsystem using the CDRA in CO₂ vent mode and the TCCS operating in parallel.

- 2) Phase 1B—Demonstrate the partial functional performance of the basic ISS AR subsystem when operating in a resource recovery mode that includes integration with CO₂ conditioning, storage, and reduction equipment.
- 3) Phase 2—Investigate propagation of trace contaminants through the core ISS AR subsystem equipment with emphasis on the CDRA and CO₂ conditioning and storage equipment.
- 4) Phase 3—Demonstrate the full resource recovery functional performance of the ISS AR subsystem including the CO₂ removal, CO₂ conditioning and storage, CO₂ reduction and post-processing, oxygen generation, and trace contaminant control functions.

Results from performance basis testing provide confidence in the test support equipment and the basis for comparing an evolved ISS AR and EM subsystem architecture to ISS-like subsystem performance.

B. Concept Architecture Progression

The AR and EM subsystem architecture development will progress through three phases or cycles. Cycle 1 will explore using ISS AR and EM subsystem components arranged in a slightly different order to achieve some electrical power economies. Figure 3 shows a simplified process flow diagram for the Cycle 1 concept. The features to note in the Cycle 1 architecture shown by Fig. 3 include directly integrating the trace contaminant control components with the CO₂ removal components, incorporating a first stage methane purification concept as a first step toward more complete resource recovery, and incorporating a major atmospheric constituent monitoring concept. The carbon dioxide removal components include upgrades to the ISS design and the trace contaminant control components include advanced adsorbent and catalysts.

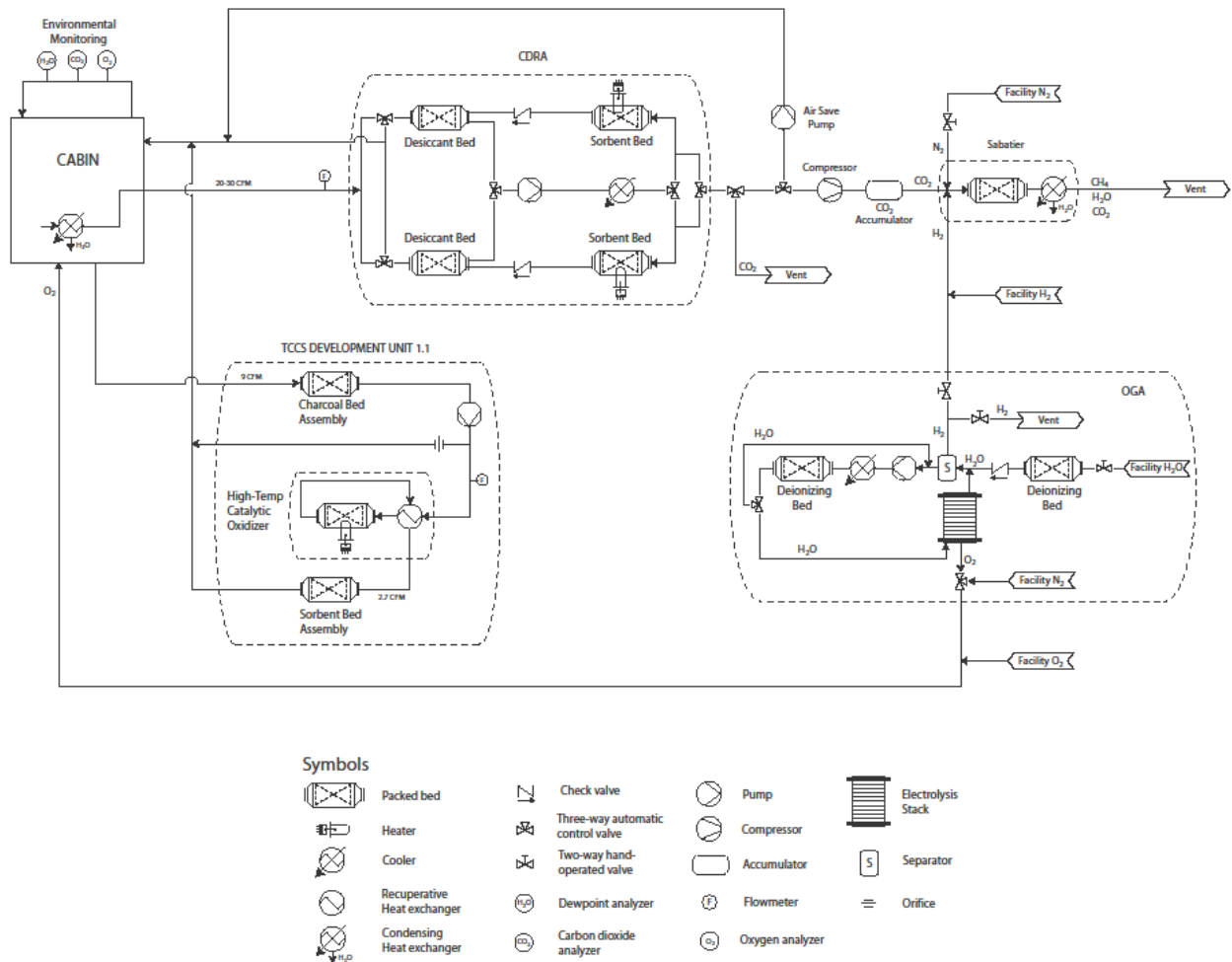


Figure 2. ISS performance basis architecture.

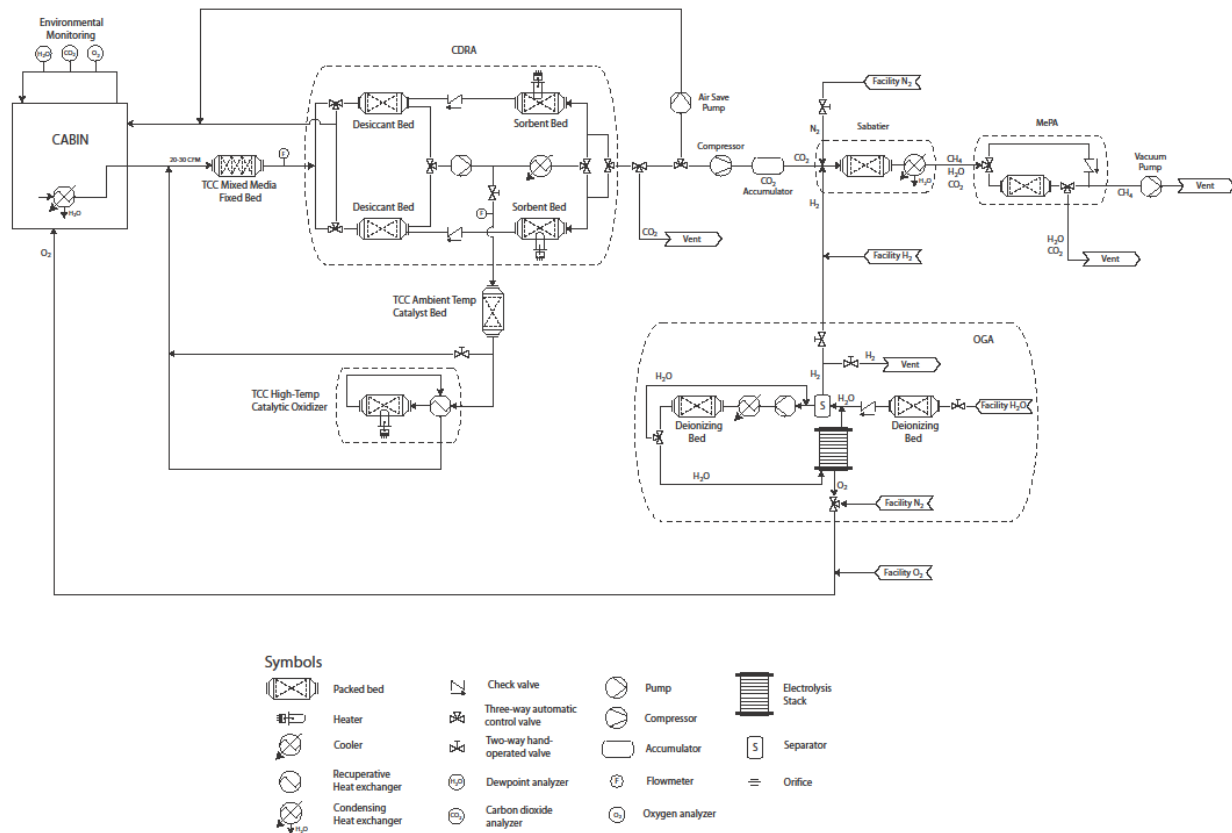


Figure 3. Cycle 1 integrated process architecture.

C. Testing Progression

Developmental progression from Cycle 1 through Cycle 2 to Cycle 3 will incorporate further component upgrades and technical options. Options for each functional trade space were defined for the AR and EM subsystem architecture in Fig 1. Developmental equipment products from NASA-sponsored efforts spanning >10 years target each functional trade space. Table 2 summarizes the candidate equipment configurations through the planned testing progression. The final product at the conclusion of Cycle 3 will be an AR and EM subsystem architecture that is suitable for detailed development toward high fidelity prototype equipment.

V. Conclusion

Reaching deep space exploration objectives with crewed vehicles presents numerous significant technical challenges. A highly reliable ECLS system is among these challenges. A status assessment of the ISS AR and EM subsystems highlights their technical strengths and weaknesses and feasibility for application to long-term crewed space exploration missions. An evolutionary approach toward addressing the ISS AR and EM technical weaknesses while building on their strengths will be central to enabling future deep space exploration missions.

Table 2. Integrated testing and developmental progression for AR and EM functional trade spaces.

	TRADE SPACE	CYCLE 1	CYCLE 2	CYCLE 3
CHAMBER OUTFITTING	Carbon Dioxide Removal	CDRA-4 unit or developmental CDRA unit repack with CDRA-4 flight sorbents	<u>Bulk Desiccant:</u> LPCOR membrane or isothermal bulk desiccant (IBD) <u>Residual Desiccant:</u> LPCOR NovelAire or H2O Microlith CO2 Removal: CDRA-4 Packed Beds or Alternative Sorbent	<u>Bulk Desiccant:</u> same as 2013 <u>Residual Desiccant:</u> same as 2013 <u>CO2 Removal:</u> LPCOR 2-Stage Compressor or CO2 Microlith or CARE
	Resource Recovery	HS Sabatier with Methane Purification Assembly (MePA), ISS piston compressor & CO2 accumulator; ISS OGA	HS Sabatier with MePA, Sub-scale PPA and ASepA; ISS piston compressor & CO2 accumulator; ISS OGA;	HS Sabatier, MePA, Full-Scale PPA, Full-Scale ASepA, PCI Sabatier; O2 compression
	Trace Contaminant Control	Sol-gel PCO reactor; Microlith HTCO unit; mixed	Sol-gel PCO reactor or Honeywell PCO panels	PCO, mixed media sorbent/catalyst bed; Microlith
	Particulate Removal	Commercial high-efficiency filter	Commercial high-efficiency filter	Indexing media filter with inertial separator
	Environmental Monitoring	First-round commercial MCA	Second-round COTS MCA; Commercial VOC analyzer	Third-round commercial MCA; VEM/mGM/TELS/RASCaL
DEVELOPMENT	Carbon Dioxide Removal	<u>Bulk Desiccant:</u> LPCOR membrane and isothermal bulk desiccant (IBD) <u>Residual Desiccant:</u> LPCOR NovelAire and H2O	<u>Bulk Desiccant:</u> LPCOR membrane and IBD <u>Residual Desiccant:</u> LPCOR NovelAire and H2O Microlith	<u>CO2 Removal:</u> LPCOR 2-Stage Compressor and CO2 Microlith and CARE
	Resource Recovery	1-CM and 4-CM PPA, Acetylene Separation Assembly (ASepA) ; O2 compression	Full-scale PPA and Full-Scale ASepA; O2 compression	Bosch process development
	Trace Contaminant Control	Photocatalyst development; ISS TCCS lessons learned	Photocatalyst characterization; ISS	ISS TCCS operations lessons learned
	Particulate Removal	Indexing media filter; inertial separations	Indexing media filter; inertial separations	Filter media life extension
	Environmental Monitoring	VEM; mGM; TELS; RASCaL array	VEM; mGM; TELS; RASCaL array	ISS VCAM, AQM, and ANITA operations lessons learned

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References

- ¹Diamant, B. L. and Humphries, W. R. "Past and Present Environmental Control and Life Support Systems on Manned Spacecraft", SAE 901210, 20th International Conference on Environmental Systems, 1990.
- ²Martin, C. E. "Environmental Control and Life Support System Historical Data Summary: Apollo through Space Station Freedom," MDC 92W5038, McDonnell Douglas Aerospace, December 1992.
- ³Wieland, P. O. "Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems, Appendix I, Update—Historical ECLSS for U.S. and U.S.S.R/Russian Space Habitats", NASA/TM-2005-214007.
- ⁴Wieland, P. O. "Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station," NASA/TM-1998-206956/Volume 1, p. 24.
- ⁵James, J. T. "Spacecraft Maximum Allowable Concentrations for Airborne Contaminants," JSC 20584, 2008.
- ⁶Perry, 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.
- ⁷Martin, C. E. "Fan and Fan Power Historical Overview, Trade-Off Study, and Recommendations," Technical Memorandum No. PD 10-400 92-1, McDonnell Douglas Aerospace, 1992.

⁸Mitchell, K. L., Bagdigian, R. M., Carrasquillo, R. L., Carter, D. L., Franks, G. D., Holder, D. W., Hutchens, C. F., Ogle, K. Y., Perry, J. L., and Ray, C. D. "Technical Assessment of Mir-1 Life Support Hardware for the International Space Station," NASA TM-108441, 1994, p. 30.

⁹Ibid., p. 52.

¹⁰Luna, B., Somi, G., Winchester, J., Grose, J., Mulloth, L., and Perry, J. "Evaluation of Commercial Off-the-Shelf Sorbents and Catalysts for Control of Ammonia and Carbon Monoxide, AIAA 2010-6062, 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

¹¹Agui, J. H. and Stocker, D. P. "NASA Lunar Dust Filtration and Separations Workshop Report," NASA/TM-2009-215821, December 2009.

¹²Agui, J., Mackey, J., Vijayakumar, R., Rana, M., and Ericson, C. "Testing of Regeneration Filtration Concepts for Future Spacecraft Applications," AIAA-2011-5202, 41st International Conference on Environmental Systems, Portland, Oregon, 2011.

¹³Abney, M., Miller, L. "Sabatier Reactor System Integration with Microwave Plasma Methane Pyrolysis Post-Processor for Closed Loop Hydrogen Recovery," AIAA-2010-6274. 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

¹⁴Urban, D., Griffin, D., Ruff, G., Cleary, T., Yang, J., Mulholland, G., and Yuan, Z. "Detection of Smoke from Microgravity Fires," SAE 2005-01-2930. 35th International Conference on Environmental Systems, Rome, Italy, 2005.

¹⁵Stuffer, T. and Honne, A. "ANITA Air Monitoring on the International Space Station, Part 1: The Mission," SAE 2008-01-2042. 38th International Conference on Environmental Systems, San Francisco, California, 2008.

¹⁶Honne, A., and Stuffer, T. "ANITA Air Monitoring on the International Space Station, Part 2: Air Analyses," SAE 2008-01-2043. 38th International Conference on Environmental Systems, San Francisco, California, 2008.

¹⁷Darrach, M., Chutjian, A., Bornstein, B., Croonquist, A., Garkanian, V., Haemmerle, V., Heinrichs, W., Hofman, J., Karmon, D., Kenny, J., Kidd, R., Lee, S., MacAskill, J., Madzunkov, S., Mandrake, L., Schaefer, R., Thomas, J., and Toomarian, N. "Measurements of the International Space Station Cabin Air Using the Vehicle Cabin Atmosphere Monitor. AIAA-2011-5218.

¹⁸Limero, T., and James, J. "The Volatile Organic Analyzer (VOA) aboard the International Space Station," SAE 2002-01-2407. 32nd International Conference on Environmental Systems, San Antonio, Texas, 2002.

¹⁹Limero, T., Cheng, P., Reese, E., and Trowbridge, J. "Results of the Air Quality Monitor's Experiment to Measure Volatile Organic Compounds Aboard the International Space Station," AIAA-2010-6278. 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

²⁰Varghese, M., Mulloth, L., Luna, B., and Hogan, J. "Development Status of a Low-Power CO₂ Removal and Compression System for Closed-Loop Air Revitalization," AIAA-2010-6060. 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

²¹Perry, J., Howard, D., Knox, J., and Junaedi, C. "Engineered Structured Sorbents for the Adsorption of Carbon Dioxide and Water Vapor from Manned Spacecraft Atmospheres: Applications and Testing 2008/2009," SAE 2009-01-2444. 39th International Conference on Environmental Systems, Savannah, Georgia, 2009.

²²Miller, L. and Knox, J. "Development and Testing of a Sorbent-Based Atmosphere Revitalization System 2008/2009," SAE 2009-01-2445. 39th International Conference on Environmental Systems, Savannah, Georgia, 2009.

²³Agui, J. H., and Stocker, D. P. "NASA Lunar Dust Filtration and Separations Workshop Report," NASA/TM-2009-215821. 2009.

²⁴Jan, D. "Environmental Monitoring as Part of Life Support for the Crew Habitat for Lunar and Mars Missions," AIAA 2010-6092. 40th International Conference on Environmental Systems, Barcelona, Spain, 2010.

Bibliography of Other Materials Consulted

"Airborne Particulate Matter in Spacecraft," NASA Conference Publication 2499, 1988.

Perry, J. L., Cole, H. E., and El-Lessy, H. N. "An Assessment of the International Space Station's Trace Contaminant Control Subassembly Process Economics," NASA/TM-2005-214008, 2005.

Perry, J. L. "International Space Station Bacteria Filter Element Service Life Evaluation," NASA/TM-2005-213846, 2005.

Perry, J. L., James, J. T., Cole, H. E., Limero, T. F., and Beck, S. W. "Rationale and Methods for Archival Sampling and Analysis of Atmospheric Trace Chemical Contaminants On Board Mir and Recommendations for the International Space Station," NASA TM-108534, 1997.

Martin, C. E. "Air Handling and Atmosphere Conditioning Systems Overview, Analyses, and Future Recommendations: A Trade-Off Study Summary Report," MDC 92W5039, McDonnell Douglas Aerospace, 1992.

Martin, C. E. "Fire Detection and Suppression Historical Overview, Analyses, and Future Recommendations," Technical Memorandum No. PD 10-400 92-2, McDonnell Douglas Aerospace, 1992.

Martin, C. E. "Internal Pressure Historical Overview, Analyses, and Future Recommendations," Technical Memorandum No. PD 10-400 92-3, McDonnell Douglas Aerospace, 1992.

Tatara, J. D. and Perry, J. L. "Performance of Off-the-Shelf Technologies for Spacecraft Cabin Atmospheric Major Constituent Monitoring," NASA/TM-2004-213392, 2004.

Wieland, P. O. "Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems," NASA RP-1324, 1994.

Wieland, P. O. "Living Together in Space: The Design and Operation of the Life Support Systems on the International Space Station," NASA/TM-1998-206956/Volume II, 1998.