NASA/TM–20260003925
NESC-RP-20-01610

# Impacts of Reduced Pressure Atmospheres on Environmental Control and Life Support Systems (ECLSS) Architectures

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May 2026

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**Acknowledgments**

The assessment team would like to acknowledge the considerable technical contributions of Mr. Jay Perry for his technical analysis of systems and documentation of content in sections 7.1.1.2 and 7.2.12. Additional technical input was provided by subject matter experts in life support, including Dr. Jill Williamson, Mr. Kevin Takada, Mr. Greg Gentry, Mr. Michael Salopek, Mr. Juan Agui, Dr. R. Vijayakumar, and Dr. James Broyan. Further thanks goes to the ISS Program Office, particularly for support from Ms. Alesha Ridley in setting up discussions with Boeing and Collins Aerospace. The team would like to acknowledge the technical support of subject matter experts in Crew Health Systems, including Mr. William Misek, Ms. Jane Gensler, Dr. William Wallace, Dr. Thomas Limero, Dr. Dan Gazda, Dr. Murray Darrach, Dr. Kerry Lee, Mr. Richard LaFrance, Ms. Catherine McLeod, Dr. Andrew Boone, Mr. S. Reynold Chu, Mr. Kevin Dries, Mr. Christopher Allen, Dr. Sarah Wallace, Ms. Katherine Westhoff Larner, Mr. Chad Morrison, and Mr. Greg Morony. The team would also like to thank the technical reviewers of the report, including Mr. Bob Beil, Dr. Dan Dorney, Mr. Steve Gentz, Mr. Rex Graves, and Dr. Jon Holladay.



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# NASA Engineering and Safety Center
# Technical Assessment Report

## Impacts of Reduced Pressure Atmospheres on Environmental Control and Life Support Systems (ECLSS) Architectures

**TI-20-01610**


**Morgan Abney**

**Robert Bagdigian**


**March 17, 2022**

## Report Approval and Revision History

NOTE: This document was approved at the March 17, 2022, NRB.

| | |
|---|---|
| Approved: TIMMY WILSON | Digitally signed by TIMMY WILSON<br>Date: 2022.03.28 16:12:17 -04'00' |
| NESC Director | |

| *Version* | *Description of Revision* | *Office of Primary Responsibility* | *Effective Date* |
|---|---|---|---|
| 1.0 | Initial Release | Dr. Morgan B. Abney, NASA Technical Fellow for Environmental Control/ Life Support, MSFC | 3/17/2022 |

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# Technical Assessment Report

## 1.0 Notification and Authorization

Mr. Danny Harris, project manager of the Human Exploration and Operations Mission Directorate's Advanced Exploration Systems Next Space Technologies for Exploration Partnerships (NextSTEP) Habitat Project, requested an independent assessment to evaluate state-of-the-art Environmental Control and Life Systems (ECLSS). This includes safety, engineering, operational, and programmatic risks of operating the state-of-the-art (SOA) hardware at reduced pressure and increased oxygen ($O_2$) percentages for Exploration habitats. Mr. Harris further requested proposed recommendations to mitigate those risks. Additional stakeholders include the Gateway and Human Landing System (HLS) ECLSS system managers as liaisons to commercial providers.

## 2.0 Signatures

Submitted by: NESC Lead

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Dr. James C. Knox

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

## 3.0 Team Members

| Name | Discipline | Organization |
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## 3.1 Acknowledgments

The assessment team would like to acknowledge the considerable technical contributions of Mr. Jay Perry for his technical analysis of systems and documentation of content in sections 7.1.1.2 and 7.2.12. Additional technical input was provided by subject matter experts in life support, including Dr. Jill Williamson, Mr. Kevin Takada, Mr. Greg Gentry, Mr. Michael Salopek, Mr. Juan Agui, Dr. R. Vijayakumar, and Dr. James Broyan. Further thanks goes to the ISS Program Office, particularly for support from Ms. Alesha Ridley in setting up discussions with Boeing and Collins Aerospace. The team would like to acknowledge the technical support of subject matter experts in Crew Health Systems, including Mr. William Misek, Ms. Jane Gensler, Dr. William Wallace, Dr. Thomas Limero, Dr. Dan Gazda, Dr. Murray Darrach, Dr. Kerry Lee, Mr. Richard LaFrance, Ms. Catherine McLeod, Dr. Andrew Boone, Mr. S. Reynold Chu, Mr. Kevin Dries, Mr. Christopher Allen, Dr. Sarah Wallace, Ms. Katherine Westhoff Larner, Mr. Chad Morrison, and Mr. Greg Morony. The team would also like to thank the technical reviewers of the report, including Mr. Bob Beil, Dr. Dan Dorney, Mr. Steve Gentz, Mr. Rex Graves, and Dr. Jon Holladay.

# 4.0 Executive Summary

The goal of this assessment was to identify and qualitatively characterize potential impacts to the performance, thermal control, and material selection of International Space Station (ISS) Environmental Control and Life Support (ECLS) hardware if implemented in cabin atmospheres having lower total pressure and higher $O_2$ concentration than the conditions for which the hardware was originally designed and certified. Specifically, nominal cabin atmospheres of 10.2 pounds per square inch absolute (psia) with 26.5% $O_2$, and 8.2 psia with 34% $O_2$, collectively termed "Exploration Atmospheres" here to differentiate from ISS nominal atmosphere, were considered. Due to anticipated challenges with cabin $O_2$ control at the lower pressures, $O_2$ concentrations up to 40% were considered for 8.2 psia when assessing flammability. A total of 33 subsystems and/or components within the ECLSS, including emergency systems, Crew Health Care Systems (CHeCS), and Crew Habitation Systems, were evaluated using available design data and historical literature.

The assessment identified seven considerations common across multiple subsystems. These included 1) reduced performance of fans, blowers, and air movers due to decreased air density; 2) performance changes in packed beds due to the combined effects of changing kinetics and heat transfer; 3) performance changes of ambient-referenced hardware, such as valves, regulators, sensors, and bellows; 4) potential simplification of gas-liquid separation approaches in partial gravity; 5) reduced heat rejection capability of hardware in cabin air; 6) increased flammability of materials; and 7) increased risk of toxicity due to offgassing in reduced volume vehicles (i.e., reduced dilution volume).

Of the 33 subsystems evaluated *(see Table 2)*, nine were acceptable for use in the 10.2 psia/26.5% $O_2$ environment with no modifications. Only three of the subsystems examined were acceptable for use in an 8.2 psia/34 to 40% $O_2$ environment with no modifications (i.e., Pressure Control Assembly (PCA), Crew Active Dosimeter (CAD), and the Hybrid Electronic Radiation Assessor HERA)). All other subsystems required additional analysis, testing, and/or design modifications to be used for Exploration.

Of particular concern was flammability of ISS ECLSS heritage materials in the 8.2 psia environment. NASA has data for many materials in a 30% $O_2$ environment, but limited material flammability data above this $O_2$ limit. Further, many commonly used ISS materials are flammable above 30% $O_2$. This results in a required change of materials in 21% of the assessed sub-systems for the 10.2 psia/26.5% $O_2$ environment and 70% of the assessed subsystems for the 8.2 psia/34% $O_2$ environment. In limited cases, alternative materials are available to meet performance and flammability requirements. However, in the majority of cases for the 8.2 psia/ 34% $O_2$ environment, alternate materials will need to be developed.

The observed impacts of reduced pressure on performance, thermal control, and materials will result in consequences to Exploration vehicle mass, volume, power, and schedule. In general, no substantial mass or volume impacts to any particular subsystem or piece of equipment were uncovered in this assessment, with the possible exception of the Sabatier Carbon Dioxide Reduction Assembly. Potential power impacts were uncovered primarily with fans and blowers if operated at greater speeds as an approach to mitigate performance losses from decreased air density. Potential schedule impacts are varied, and historical experience shows that seemingly small changes can lead to significant challenges and increased cost and schedule [refs. 81-83]. However, readily apparent schedule risks can be seen in hardware for which testing is required to provide the data needed to make mitigation selections, understand performance, and the need to recertify all equipment for its intended operating conditions.

Specific NESC recommendations for analysis and testing of critical components and subsystems at Exploration conditions were made to quantify the identified impacts and inform design modifications as necessary (Section 8.3).

## 5.0 Assessment Plan

This assessment sought to determine 1) the effects of Exploration cabin environments on crew-serving system hardware used on the ISS, and 2) how those effects change the mass, power, and volume design points and schedule planning specifically for the NextSTEP Lunar Surface Habitat (LSH) and Exploration Command Module (ECM). Additional future missions expected to benefit from the mass, power, and volume data collected include Gateway, Mars Transit, and Mars surface missions.

Two environments were evaluated. The first, a pressure of 8.2 $\pm$0.2 psia and corresponding $O_2$ of 34 $\pm$2% by volume, was based on NASA direction for Exploration [ref. 1] and a number of previous studies of missions with high extravehicular activity (EVA) [refs. 2, 3]. The second, 10.2 psia and 26.5% $O_2$ by volume, was based on experience with the Space Shuttle Program (SSP) orbiter where the cabin would be transitioned from a 14.7 psia and 21.7% $O_2$ atmosphere prior to EVA [ref. 4].

Six crew-serving systems were initially identified for evaluation, including ECLS, intravehicular activity (IVA) and EVA hardware, crew health care hardware, crew habitation systems (simplified to "crew systems" for brevity throughout the report), and emergency equipment. However, for Exploration, the in-vehicle IVA and EVA hardware will be new designs with requirements for Exploration environment compatibility. Therefore, a review of ISS IVA/EVA hardware was omitted from this assessment.

Three categories of impacts were evaluated for each piece of crew-serving hardware. Thermal evaluations sought to identify impacts of the lower pressure environment on active and passive thermal control of components and systems. Performance evaluations sought to identify changes in functional capability and performance in the Exploration environments. Material evaluations sought to identify risks of increased flammability and offgassing of materials used in SOA hardware at the increased $O_2$ concentrations.

Content specifically excluded from this assessment included the effects on crew health, avionics, power systems, existing ISS science payloads, international partner hardware, vehicle structure, other hardware not directly supporting crew survivability, and candidate developmental technologies that have not flown as flight experiments with the exception of ISS upgrades.

Five tasks were planned to complete this assessment:

1. ***Task 1: Compile Scoped Hardware List***

   The objectives of Task 1 were to coordinate with ISS Program hardware subsystem managers to compile a complete list of in-scope hardware on ISS and Multi-Purpose Crew Vehicle (MPCV) crew module (CM) and to prioritize the list by items most likely to be included in LSH or ECM missions and to be impacted by the specified environments.

2. ***Task 2: Data Gathering***

   The objective of Task 2 was to collect available information on all systems identified in Task 1, including hardware specifications, schematics, hazard reports, critical design review packages, verification and validation packages, and design certification review.

3. ***Task 3: Documentation Review***

   The objective of Task 3 was to conduct a methodical review of available documentation, per the designated priority and data availability.

4. ***Task 4: Analyze and Discuss Impacts***

   The objective of Task 4 was to compile the results in Task 3; collaborate with LSH/ECM consultants; and estimate the effects on mass, volume, power, and schedule. Update meetings with the primary stakeholder were planned every 6 weeks. However, a stakeholder representative attended biweekly meetings and provided real-time feedback in lieu of separate meetings.

5. ***Task 5: Complete Report***

   The objective of Task 5 was to refine and finalize report data and generate findings, observations, and NESC recommendations.

All tasks were completed per the plan, except where noted otherwise.

## 6.0 Problem Description and Background

An important consideration when planning a human space exploration mission (or an enterprise of interdependent and interacting human missions) is the combination of spacecraft internal cabin atmosphere conditions that will best enable safe and efficient mission execution. Although human physiology presents limits beyond which atmosphere conditions are no longer safe or sufficient for prolonged human exposure, there remains flexibility within those limits to choose a set of conditions that best serve mission objectives. That choice, however, can have substantial development, design, and operational consequences and should be made with informed care.

Among the cabin atmospheric conditions that must be considered and chosen, the two most germane to this assessment are the total pressure and $O_2$ content. Human physiology depends on $O_2$ transfer across the lung/circulatory system boundary. This transfer is driven by the $O_2$ partial pressure within the lung alveoli. It is critical that a spacecraft cabin atmosphere sustain a sufficient $O_2$ partial pressure to drive $O_2$ transfer in the lungs. A lower cabin total pressure must contain a higher percentage of $O_2$ to sustain a given $O_2$ partial pressure within the lungs. For a more complete discussion, the reader may refer to NASA/TP-2013-217377 [ref. 3].

One of the attractive benefits of a relatively low cabin pressure is its effect on EVA. EVA suits must meet the competing demands of reliably containing internal pressure while enabling high mobility and dexterity for the wearer. For this reason, these suits are designed and operated at relatively low internal pressure (~4.3 psia). To sustain sufficient $O_2$ partial pressure in the wearer's lungs, EVA suit $O_2$ concentrations must be high and have historically been 100% to avoid the complexities of mixed gas control within small internal volumes. One of the potential health hazards that must be avoided when operating a low-pressure suit is decompression sickness. When a crew member transitions from a spacecraft cabin environment containing $O_2$ and a diluent, such as nitrogen ($N_2$), to an EVA suit internal environment, care must be taken to ensure that the pressure reduction does not induce decompression sickness. If the difference between spacecraft and suit pressures is relatively high, complex and time-consuming prebreathe protocols must be followed to purge $N_2$ from the crew member's lungs before suit pressure can be safely reduced. If the difference between spacecraft and suit pressures is relatively low, prebreathe protocols can be reduced and potentially eliminated.

A consequence of raising $O_2$ concentration to sustain $O_2$ partial pressure in a low-pressure environment is that the flammability of materials increases with increasing $O_2$ concentration. The reduction in the number of candidate materials that can be used in higher $O_2$ environments represents a significant challenge in designing and operating a spacecraft.

There are other consequences of lower cabin total pressures. As cabin pressure decreases, so does air density. At lower density, the heat-carrying capacity of air is reduced as is the efficiency of convective heat transfer. The result is that at lower cabin pressures, air-cooling of spacecraft equipment becomes more of a challenge. Achieving a given degree of convective heat transfer at lower relative pressures requires higher air velocities that can be achieved only via higher fan speeds, aerodynamic design optimization for lower pressure operation, multiple fan operation, or some combination of those factors.

Lower cabin pressure may influence the operating and non-operating pressures contained within spacecraft systems if those pressures are referenced to cabin pressure through regulators or tank bellows or monitored by gauge pressure sensors. Leakage rates (i.e., internal to external and vice versa) between systems and the cabin environment may change sufficiently at lower cabin pressure to affect hazard potentials and controls, necessitating design or operational changes. In some instances, a reduction to internal system operating pressure of a component/system, driven by a reduction in external cabin pressure, may affect the baseline equipment performance (e.g., gas/liquid separators and the Sabatier Carbon Dioxide Reduction Assembly, as discussed later).

## 6.1 Past and Present Spacecraft Atmosphere Design Points

Table 1, adapted from NASA/TP-2010-216134 [ref. 5], summarizes the total pressure and $O_2$ concentration design points for past and present human spacecraft and EVA suits. In all cases, the design points were chosen with consideration given to meeting mission objectives while balancing design, operational, and programmatic constraints.

***Table 1. Past and Present Spacecraft Cabin Atmospheres***

| Program | Nominal Cabin Pressure, psia | Nominal Cabin $O_2$ Concentration, Volume % | EVA Suit Pressure, psia | EVA $O_2$ Prebreathe Time, minutes | EVA Prebreathe Conditions |
|---|---|---|---|---|---|
| Mercury | 5 | 100 | - | - | - |
| Gemini/Apollo | 5 | 100 | 3.75 | 0 | - |
| Skylab | 5 | 70 | 3.75 | - | - |
| Shuttle | 10.2 | 26.5 | 4.3 | 40 | In-suit after 36 hours at 10.2 psia |
| | 14.7 | 21 | 4.3 | 240 | In-suit |
| ISS/United States | 14.7 | 21 | 4.3 | 120-140 | Mask and in-suit; staged with exercise |
| | | | | 240 | In-suit |
| Salyut, Mir, ISS/Russia | 14.7 | 21 | 5.8 | 30 | In-suit |
| Commercial Crew Program (CCP) | 14.7 | 21 | N/A | N/A | N/A |
| MPCV CM | 10.2 - 14.7 for Gateway Operations | 21 – 26.5 | 4.3 – 8.1 psid to cabin | Scenario-dependent | In-suit |
| | 10.2 for Lunar Lander Operations | 26.5 | | | |

For example, aboard the ISS, where research into the physiological effects of living in microgravity is a primary mission objective, it is desirable to maintain cabin atmosphere at conditions closely resembling "normal" sea-level conditions on Earth. By doing so, the physiological effects of microgravity can be better understood without influences from atmospheric effects. The ISS was designed and is operated to approximate an Earth-equivalent atmosphere of 14.7 psia with 21% $O_2$. Since EVA is not a frequently occurring event on the ISS, the operational complexity and time-consuming impacts of executing prebreathe protocols is accepted as a necessary consequence of operating the ISS in a manner that better fulfills its high-priority research objectives. The ISS environmental control system is designed to control the cabin atmosphere within the bands of 13.9-15.2 psia and $O_2$ partial pressure of 2.83-3.35 psia with a maximum allowable of 24.1 vol% $O_2$ [ref. 5]. All other on-board equipment has been designed and certified to safely operate and meet performance requirements within these ranges.

## 6.2 Spacecraft Cabin Atmospheres for Exploration

Unlike the ISS, the primary objectives of planned human Exploration missions are not focused on scientific investigations of the effects of micro-gravity on human physiology and health (although such investigations will most likely continue to be executed within the constraints and resources available as a secondary focus). The primary objective of transit missions will be to transport crew safely and reliably to and from the lunar and Martian vicinities, and are being formulated to work in tandem with the Gateway. Lunar and Martian surface missions, however, will focus on the human exploration of the environment outside of the pressurized habitat environment and will, by necessity, involve frequent EVA. In such an exploration-focused, frequent-EVA scenario, the complexities and time commitment of prebreathe protocols become less desirable from an operations standpoint than is tolerated on the ISS [ref. 3]. Means to enable frequent EVA events are of greater importance. One of the most enabling means is to design Exploration surface habitat(s) to operate at cabin atmospheric pressures low enough to reduce or eliminate prebreathe protocols. For planning purposes, and for the purpose of this assessment, the potential atmosphere conditions that are being considered are 10.2 psia/26.5% $O_2$ and 8.2 psia/34% $O_2$. Note that the ability of available hardware to control within these limits may dictate that Exploration systems be designed and certified at higher $O_2$ concentrations.

## 6.3 ISS Hardware in Exploration

The long and successful operation of systems aboard the ISS has yielded an invaluable portfolio of potential systems to incorporate into the designs of Exploration habitats, with prolonged experience with their operational and reliability characteristics. Leveraging these systems to form the foundation of future Exploration habitats is an attractive means of minimizing reliability uncertainty, which can drive logistics costs [ref. 6], and avoiding the high development costs of bringing developmental systems to certifiable states. However, incorporating ISS systems into Exploration habitats and transit vehicles can be complicated by the need to operate the ISS systems in atmospheric conditions for which they were not designed or certified. Consequently, the primary purpose of this assessment was to provide a first-order evaluation of the impacts of reduced pressure/increased $O_2$ atmospheres on ISS crew-supporting systems. The systems evaluated in this activity included specific hardware from the ISS ECLSS, CHeCS, and the habitation system.

Table 2 provides a list of all hardware assessed.

*Table 2. List of Assessed Hardware*

| Crew System | Subsystem Assessed |
|---|---|
| *Life Support* | Avionics Air Assembly (AAA) |
| | Brine Processor Assembly (BPA) |
| | Common Cabin Air Assembly (CCAA) |
| | Carbon Dioxide Removal Assembly (CDRA) |
| | Carbon Dioxide Reduction Assembly (CRA) |
| | ISS & MPCV Portable Fire Extinguisher (PFE) |
| | Emergency Mask, Fire, and Ammonia Cartridges |
| | Orion Smoke-eater Filter (OSEF) |
| | Intermodule Ventilation Fan (IMV) |
| | Oxygen Generation Assembly (OGA) |
| | Pressure Control Assembly (PCA) |
| | Trace Contaminant Control System (TCCS) |
| | Urine Processor Assembly (UPA) |
| | Universal Waste Management System (UWMS) |
| | Water Processor Assembly (WPA) |
| *CHeCS* | Acoustic Monitor (AM) |
| | Anomaly Gas Analyzer (AGA) |
| | Air Quality Monitor (AQM) |
| | Crew Active Dosimeter (CAD) |
| | Colorimetric Water Quality Monitoring Kit (CWQMK) |
| | Flywheel Exercise Device |
| | Hybrid Electronic Radiation Assessor (HERA) |
| | MinION DNA sequencer |
| *Crew Systems* | Cordless Vacuum Cleaner |
| | Crew Quarters |
| | Galley Rack |
| | ISS Food Warmer |
| | ISS and MPCV Sleeping Bags |

## 6.4 Approach to Assessments

Throughout this assessment, efforts were made to identify, understand, explain, and qualitatively characterize potential impacts to the performance, thermal control, and material selection of ISS hardware if implemented in cabin atmospheres having lower total pressure and higher $O_2$ concentration than the conditions for which the hardware were originally designed and certified. Impact descriptions have been intentionally expressed qualitatively. Specific, quantitative expressions of weight, power, volume, or schedule impacts were not attempted, since doing so would depend on a deeper understanding of the mission- and vehicle-specific system trade-offs that continue to be developed by the various potential providers. In general, one provider might put a premium on minimizing mass, a second provider might choose to minimize volume, and a third might prioritize development time and cost. Other providers might place their own relative values on all these and other metrics. In such an environment, it is impossible to identify a single "best" mitigation solution for each identified impact. For this reason, this assessment identifies the specific hardware that would be impacted, describes how and to what extent, and offers qualitative suggestions for potential mitigations. However, the developers of Exploration systems must determine the best mitigation approach for their intended application.

Evaluation of each subsystem was influenced by the availability and quality of data and the assessments team's confidence in the accuracy and thoroughness of their review. Table 3 provides an overview of the depth of and team confidence in the assessment of each evaluated subsystem. An explanation of the rating dimensions follows:

- ***Depth*** of assessment (i.e., what/how much information was available?)
  - Green: All or vast majority of needed information or data was gathered (i.e., >75% of basic system information). Data, previous analysis, or subject matter expert insight was available.
  - Yellow: Moderate quantity of information was gathered (i.e., 25-75% of basic system information). Some data or previous analysis/subject matter expert insight was available. Some information was unknown, unclear, or outdated.
  - Red: Very little to no information was gathered (i.e., < 25% of basic system information). No or limited data and previous analysis were available to the team.
- ***Confidence*** in assessment (i.e., how thorough was the assessment?)
  - Green: Assessment complete or nearly so. Remaining work, if any, not expected to substantially change result. Result supported by data, analysis, and rigorous assessment.
  - Yellow: Assessment has progressed sufficiently to expect to form hypothesis; more work expected. Result backed by conceptual analysis and assessment.
  - Red: Little to no assessment completed. Assessment results based on minimal information. Likely to contain high uncertainty and error.

***Table 3. Assessment Depth and Confidence Summary for All Assessed Subsystems***

| Subsystem | Depth | Confidence |
|---|---|---|
| ECLSS | | |
| AAA | 25 - 75% | |
| BPA | 25 - 75% | |
| CCAA | >75% | |
| CDRA | >75% | |
| CRA | 25 - 75% | |
| ISS PFE | < 25% | |

| Subsystem | Depth | Confidence |
|---|---|---|
| MPCV PFE | < 25% | |
| Emergency Mask | < 25% | |
| Fire and Ammonia Cartridges | < 25% | |
| OSEF | < 25% | |
| IMV | 25 - 75% | |
| OGA | 25 - 75% | |
| PCA | 25 - 75% | |
| TCCS | >75% | |
| UPA | >75% | |
| UWMS | 25 - 75% | |
| WPA | >75% | |
| **CHeCS** | | |
| Acoustic Monitor | 25 - 75% | |
| AGA | 25 - 75% | |
| AQM | >75% | |
| CAD | >75% | |
| CWQMK | >75% | |
| Flywheel Exercise Device | 25 - 75% | |

| Subsystem | Depth | Confidence |
|---|---|---|
| **HERA** | 25 - 75% | |
| **MinION** | >75% | |
| **Crew Systems** | | |
| **Cordless Vacuum Cleaner** | 25 - 75% | |
| **Crew Quarters** | 25 - 75% | |
| **Galley Rack PWD** | 25 - 75% | |
| **Galley Rack FRIDGE** | < 25% | |
| **Galley Rack Food Warmer** | 25 - 75% | |
| **ISS Food Warmer** | >75% | |
| **U.S. Sleeping Bag** | 25 - 75% | |
| **MPCV Sleeping Bag** | 25 - 75% | |

For more than 60% of the subsystems assessed, the team considered the review to be complete or nearly complete (green). For ~24% of the subsystems, the team felt that the assessment had provided a solid initial review with more work expected to fully characterize the impact. Notably, for all the ISS emergency systems, only limited documentation could be found (internal or external to NASA) or was provided for review, resulting in a high degree of uncertainty on the final results *(F-21)*.

## 7.0 Assessment Summary

The specific details justifying this finding for a specific subsystem are provided in the relevant sections below. However, most systems had some impact due to reduced pressure and/or increased $O_2$ environments. Impacts were summarized and color-coded using eight definitions, outlined in Table 4.

***Table 4. Impact Summary Color Code Definitions***

| |
|---|
| **No data from which to assess, or conflicting data preventing determination.** |
| **No impacts expected, no changes required for Exploration** |
| **Limited data, but no problem expected** |
| **Impacts expected, but anticipated to be used at reduced performance** |
| **Impacts expected, minor changes required** |
| **Impacts expected, moderate changes required** |
| **Significant changes required for Exploration** |
| **No data, but required changes expected** |

A thorough discussion of each subsystem is provided in subsequent sections, but Table 5 summarizes the impacts for all subsystems across seven categories, including performance at 10.2 psia/26.5% $O_2$, performance at 8.2 psia/$\geq$34% $O_2$, thermal, materials at 10.2 psia/26.5% $O_2$, materials at 8.2 psia/$\geq$34% $O_2$, and offgassing in Exploration vehicles with significantly smaller volumes than the ISS (i.e. ~386-600ft$^3$ (11-17 m$^3$)) at 10.2 psia and 8.2 psia. Notably, only three of the assessed subsystems resulted in no performance, thermal, or material impacts: the PCA, the CAD, and HERA *(F-1)*.

***Table 5. Summary of ISS Subsystem Performance, Thermal, and Material Impacts for Use in Exploration Environments***

| Subsystem | Performance @ 10.2 psia | Performance @ 8.3 psia | Thermal | Materials @ 10.2 psia | Materials @ 8.3 psia | Offgassing @10.2psia | Offgassing @8.2psia |
|---|---|---|---|---|---|---|---|
| AAA | | | | | | | |
| BPA | | | | | | | |
| CCAA | | | | | | | |
| CDRA | * | * | | | | | |
| CRA | | | | | | | |
| ISS Water-Mist PFE | | | | | | | |
| MPCV Water-Spray PFE | | | | | | | |
| Emergency Mask | | | | ** | ** | | |
| Fire/Ammonia Cartridges | | | | ** | ** | | |
| Orion Smoke Eater Filter | | | | | | | |
| IMV | | | | | | | |
| OGA | | | | | | | |
| PCA | | | | | | | |
| TCCS | | | | | | | |
| UPA | | | | | | | |
| UWMS | | | | | | | |
| WPA | | | | | | | |
| Acoustic Monitor | | | | | | | |
| AGA | | | | | | | |
| AQM | | | | | | | |
| CAD | | | | | | | |
| CWQMK | | | | *** | | | |
| Flywheel | | | | | | | |
| HERA | | | | | | | |
| MinION | | | | *** | *** | | |
| Cordless Vacuum Cleaner | | | | | | | |
| Crew Quarters | | | | | | | |
| Galley Rack PWD | | | | | | | |
| Galley Rack FRIDGE | | | | | | | |
| Galley Rack Food Warmer | | | | | | | |
| ISS Suitcase Food Warmer | | | | | | | |
| US Sleeping Bag | | | | | | | |
| MPCV Sleeping Bag | | | | | | | |

* CDRA Blower will require redesign for Exploration environments.

** Materials of construction are flammable, but accepted for use via ISS Program approved Materials and Fracture Control Certification (MATL-07-006C for Ammonia Cartridge, MATL-13-031 for Emergency Mask, and MATL-11-040C for Fire Cartridges). Storage bags require replacement for Exploration environments.

*** Reagents may have reduced shelf life due to increased oxidation rates.

## 7.1 Multisystem Considerations

During this assessment, several common observations were made across multiple subsystems. A general description of these multisystem impacts is provided. Specifics to each subsystem are provided in subsequent sections.

### 7.1.1 Performance

#### 7.1.1.1 Fans, Blowers, Air Movers

Blowers are commonly used air-movers in numerous life support systems. They feature a centrally rotating shaft spinning a blade or set of blades with a specific incidence angle. While spinning, these blades effectively "cut" the air and push it forward. For every rotation, the volume occupied in front of the blades is exited at an increased relative pressure. As such, a fan/blower is a constant volume device (i.e., for every rotation, the same volume is moved). Fans or blowers used for convective cooling applications requiring constant mass flow rates across ISS and Exploration environments will need to spin faster by a factor of the ratio of their atmospheric densities.

In the design of a fan or fan blades, an important consideration is the pressure, or density, of the air to be moved. The air density is important when determining key features (e.g., fan blade attack angle and cross-section diameter). This is to ensure that when the blade cuts through the air, the air will be left in the proper flow regime to move forward (i.e., aerodynamic optimization). Incorrect or suboptimal aerodynamic fan blade optimization can have numerous unintended and detrimental effects, including excess noise, heat of compression, increased power consumption, and/or lifecycle reduction. Most ISS fans and blowers were designed for operation in 14.7 psia and 21% $O_2$, producing an air density of about 0.075 $lb_m/ft^3$ (1.2 $kg/m^3$), although some were certified for lower-pressure operation during contingency events. Operation of ISS fans and blowers outside their certification parameters (e.g., Exploration atmospheres) will likely cause performance impacts (e.g., excess noise, increased power consumption, and/or decreased lifecycle *(F-2)*.

#### 7.1.1.2 Packed Beds and Particulate Filters

Canisters loaded/packed with sorbents, catalysts, and exchange-resins are known as packed or fixed beds. Fixed beds are used in spacecraft systems, as they are simpler to operate and have reduced attrition compared to fluidized beds. Along with particulate filters, packed beds are commonly used in life support systems for capturing contaminants from liquids and gasses. Their use in liquid systems is not expected to be impacted by changes in atmospheric pressure due to the lack of an interface with the ambient atmosphere (i.e., most liquid systems operate at a positive gauge pressure and should not be affected by ambient air pressure changes). Use of ion-exchange resins is limited to liquid systems in ISS ECLSS.

Air purification and carbon dioxide ($CO_2$) removal systems generally use sorbents and catalysts retained in packed beds via spring loading to retain compaction during settling. Mass transfer mechanisms for adsorption and catalysis processes in packed beds are similar, thus flow characteristics will be affected by total pressure reduction in same way. Also, adsorption and catalysis processes require gas molecules to diffuse from the free stream within the packed bed to the vicinity of the active surface, where they are captured via intermolecular forces onto a sorption site. For a catalyst process, the reactant molecule undergoes chemical reaction after adsorption occurs, and then the product molecule is released to diffuse back to the free stream.

For an adsorption process, the molecule remains in the sorbed state until the end of the process, when it is liberated via heating and/or reduced partial pressure before diffusing back to the free stream. The term used to refer to the amount of an adsorbate that can be bound to the sorbent surface is *capacity*. Capacity is an equilibrium state between the adsorbed phase and the free stream gas phase, and largely depends on pellet temperature and partial pressure of the constituent in the free stream as well as the available catalytic surface area. As such, it is expected that the capacity of a packed sorbent bed will be unchanged by a pressure change alone.

The kinetics of sorption processes will have dependence on the total pressure. The effect of total pressure on packed bed flow and sorbate diffusion—with implications for sorption kinetics, is discussed below, as these are common to both sorption and catalysis processes. The kinetics of chemical reactions in catalysis, however, are beyond the scope of this assessment.

Sorbents used in atmosphere revitalization systems include granular activated carbon (GAC) in the TCCS for adsorption of high molecular weight (MW) contaminants. Zeolite is used in the CDRA for adsorption of $CO_2$, and limited data suggests improved kinetics at <5 psia operation pressure *(O-1)*. Silica gel and zeolites are used for water vapor capture as a preconditioning step prior to the $CO_2$ removal step in the CDRA to increase $CO_2$ removal efficiency.

Packed beds that process cabin air, or gases at pressures referenced to cabin air pressure, will experience reduced pressure drop at reduced cabin pressure. As a result, packed beds in ECLSS will require redesign to achieve the required performance. For sorbent beds, the interstitial velocity of the flow must be maintained. For catalysts, the gas hourly space velocity (GHSV) must be maintained *(F-3)*.

For the interstitial velocity assumption, the pressure drop across a packed bed can be modeled by the Forchheimer equation with Ergun coefficients [ref. 7]. Components of this equation that are influenced by total pressure are density and viscosity. Density is linearly proportional to total pressure. As a relative indicator, viscosity drops by about 14%, from 14.7 to 5 psia. Pressure drop is reduced for lower density and viscosity, thus somewhat greater than proportionally lower pressure drops can be expected at lower pressures. This will reduce the demand on system blowers.

Another facet of packed bed flow is dispersion, or mixing effects due to turbulence. This includes flow splitting and rejoining around particles, Taylor dispersion, channeling, and wall effects [ref. 8]. Based on a review of five commonly used equations for dispersion [ref. 9], dispersion will not be affected by total pressure changes if interstitial velocity is kept constant,.

Sorbate transport from the free stream to the sorbed state is via four different mass transfer mechanisms (i.e., external film, macropore, and barrier and distributed micropore resistance), as illustrated in Figure 1 [ref. 10].

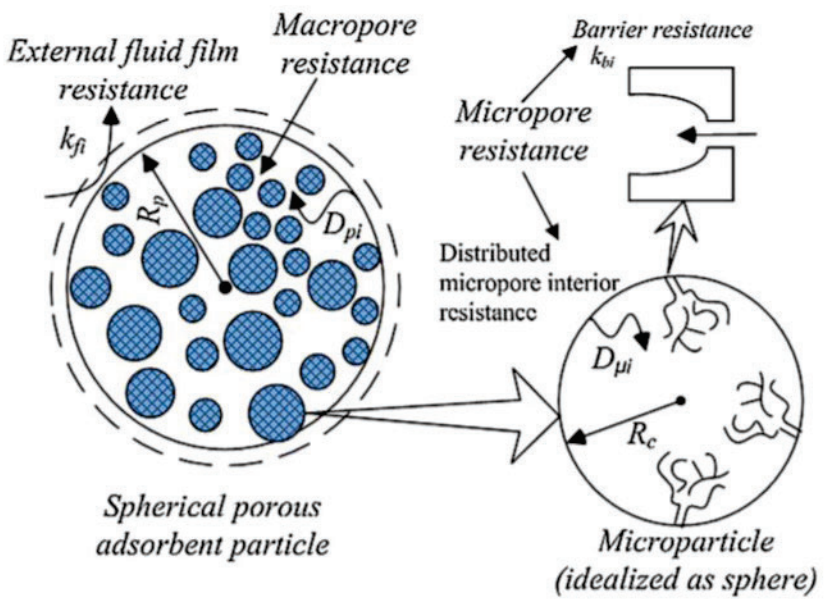


***Figure 1. Depiction of Fixed-bed and Zeolite Mass Transfer Mechanisms***

External film resistance will increase roughly as the cube root of total pressure decreases [ref. 11]. This mechanism is generally assumed to be negligible since intraparticle resistance is generally greater. However, this factor may become important at reduced pressure.

Macropore resistance, or the resistance due to the larger pores between zeolite crystals, or sorption sites for monodisperse sorbents (e.g., silica gel and activated carbon), can be estimated via Knudsen diffusion and molecular diffusion. Knudsen diffusion dominates for small macropores, but is considered independent of pressure. Molecular diffusion, based on the Chapman-Enskog theory, is inversely proportional to total pressure [ref. 12]. As a result, it can be expected that the macropore resistance will decrease for reduced pressures, thus diffusion will increase for this mass transfer mechanism, often the limiting resistance in adsorption kinetics.

Barrier resistance and micropore resistance occur in a regime where the pore diameter is of the same order as the molecule diameter, which is dominated by the attractive forces of the sorbent walls. Adsorption mass transfer or kinetics will increase with decreased total pressure if the macropore or micropore resistance remains the dominant transfer resistance. For these mass transfer mechanisms, no changes are expected due to reductions in total pressure.

Film resistance will increase, but is assumed to be less than the macropore or micropore resistance (to be confirmed). It is important to note that improved kinetics, which increase the rate of mass transfer, will cause a faster rate of heat of adsorption generation that must be addressed in the process energy balance.

Packed bed heat transport is governed by the gas phase energy balance equation, which includes transient heat storage, gas convection, gas conduction, and heat transfer from the adsorbent to the column wall via Newton's law of cooling. As with mass transfer, it is assumed that interstitial velocity will be kept constant regardless of total pressure to preserve adsorption efficiency [ref. 9].

Heat storage or heat capacity (i.e., "per-unit" volume) and gas convection are inversely proportional to total pressure (i.e., decreasing heat transport at lower pressures). Gas conduction does not depend on pressure until the molecular flow regime is reached, which occurs only at vacuum conditions. Fortunately, cabin air heat capacity—"per-unit" volume—and thermal conductivity parameters are not highly sensitive to compositional changes associated with Exploration environments (*Appendix A, items c and e, and Table A-1*).

Technically, heat transport from the free stream to the substrate includes the same mechanisms present in mass transfer. However, in practice, heat conduction occurs much more rapidly than molecular diffusion, such that heat transfer is not governed by intraparticle transport mechanisms. Instead, heat transfer from the sorbent to the free stream is limited by film diffusion and is governed by the same equation form as mass transfer. Thus, heat transfer from the pellet to free stream will decrease roughly as the cube root of total pressure decreases [ref. 11]. Heat transport in a packed sorbent bed will be reduced at lower pressures. This will (1) reduce the rate of heat removal from an adsorbing bed, and (2) impede the cooling of a packed bed via process air following a desorption cycle in preparation for subsequent adsorption.

Early studies via multiphysics simulation (*Appendix A.d)* indicate the difference in cooling rate due to a change in total pressure from 15 to 10 psia is not significant. Further studies may be conducted with simulations that have been verified to include all heat and mass transfer mechanisms relevant for reduced pressures. Heat transfer from the sorbent pellet to the free stream will be reduced leading to higher pellet temperatures and reduced adsorption capacity**.**

Packed bed cooling and the impact of the reduced heat transfer may be evaluated via multiphysics simulation to fully evaluate the impacts.

In summary, mass and heat transfer in the adsorption process are influenced oppositely by reductions in total pressure (i.e., mass transfer is enhanced and heat transfer is reduced). Reduced pressure has a complex, nonlinear effect on heat and mass transfer, such that conclusions on the net difference in efficiency for packed sorbent and catalyst beds cannot be deduced directly *(F-4)*.

Particulate filters are expected to experience no impacts with filtration performance in Exploration atmospheres; this is because of the size exclusionary principles in which particulate filters work [ref. 13]. Additionally, with no changes to the filter's fibrous structure and porosity, it will have the same or slightly improved filtration efficiency at the 8.2 and 10.2 psia pressures *(F-5)*.

#### 7.1.1.3 Ambient-referenced valves, regulators, sensors, bellows

ISS ECLSS hardware commonly uses items that "reference" to the ambient cabin environment, (e.g., valves, regulators, and sensors). These components gain some of their control ability via calibration against a specified atmospheric pressure. As a result, mechanical devices that reference the cabin atmosphere for operation (e.g., valves, regulators, sensors, bellows, and microgravity phase separators) will not perform as expected in an environment outside their designed, calibrated, and qualified pressure range *(F-6)*.

For instance, hardware relief valves have a setpoint at which they open, often set by a combination of a calibrated force of the internal spring as well as the differential force between the cabin atmosphere and working fluid pressure. The valve opens when the force of the fluid is greater than the spring force plus the force of cabin pressure. If the force of the cabin pressure is decreased with respect to the working fluid pressure, then the fluid will overcome the spring force and actuate the valve at a lower fluid pressure than intended. This would result in a loss of control via an uncalibrated spring. The magnitude of impact to cabin-referenced relief valves is inversely proportional to the pressure difference between the reference and setpoint. If, for instance, a relief valve was set to actuate at 5,000 psid and calibrated for 14.7 psia ambient environment and then used in an 8.2 psia environment, the change in fluid pressure once the valve opened would be negligible. This is because of the setpoint pressure/spring force relative to the reference pressure.

Another relevant example is bellows tanks. Not all of these tanks are referenced to ambient, and those are excluded from this discussion. Bellows that are referenced to ambient set the fluid pressure by a combination of the atmospheric force plus the bellows spring force. Using a bellows tank designed for nominal ISS environments in Exploration atmospheres will cause a loss of control of the fluid pressures set by the tanks. This could manifest with impacts (e.g., a tank not filling or emptying completely) or larger downstream or upstream impacts. An example of a larger impact could be decreased separation efficiency of a gas-liquid separator, with the liquid-side pressure being set by an upstream or downstream bellows tank. Potential mitigation could involve recalibration of bellows spring force or design of systems for a lower pressure.

#### 7.1.1.4 Acoustics

It is generally expected that the acoustic environment within a habitat will be impacted if the atmospheric pressure within the cabin is reduced compared to that maintained in the ISS. Noise sources generally radiate less efficiently in a reduced-density gas, resulting in reduced sound pressure levels in the environment, although the effect is strongly frequency-dependent (high frequencies can be perceived as louder due to lower absorption attenuation). This phenomenon will apply to both the propagation of ambient equipment noises that are desired to be minimized in a habitable vehicle and to intentional sounds, such as voice communication and audible alarms, that are desired to be clearly conveyed. Anecdotal evidence attributed to Skylab crewmembers indicated that the 5 psia environment was quiet, but required extra effort to talk [ref. 84].

Human hearing and measurement microphone responses are expected to be only minimally impacted by the pressure/density change because the diaphragms/eardrums are back-vented for pressure equalization. With microphones, the response at their resonance frequency increases with lower pressures because they are less damped, but the broad frequency response does not significantly change [ref. 85].

Further complicating any prediction about whether a lower cabin pressure will be “better” or “worse” acoustically is the possibility (as discussed elsewhere in this report) that fans and blowers will need to be operated at higher speeds to meet performance requirements at lower cabin pressure. A cabin atmosphere pressure of 10.2 psia or 8.2 psia is expected to have both beneficial and detrimental impacts on the acoustic environment that the crew is exposed to and to the verbal and audible alarm communications on which they will depend. Ultimately, the net effect(s) of a reduced pressure environment on cabin acoustics cannot be predicted with certainty without accurate modelling of the specific vehicle and systems *(F-7)*.

#### 7.1.1.5 Gas-Liquid Microgravity Separators

Typically, in a 1-g environment, gravity-based approaches (e.g., settling tank) can be used for separation of gases from liquids. In microgravity, where there is negligible buoyancy force, more complex processes (e.g., inertial, membrane, and/or cyclonic separation) are used. Phase-separator design is dependent on a variety of parameters (e.g., gas/liquid quality; mission gravity environment; required separation efficiency; and phase temperature, pressure, and composition) and is optimized for the targeted mission and/or architecture. Rotary separation, an example of inertial separation, uses a motor and hydrophilic/hydrophobic coated surfaces to provide external force for separation. Membrane separation typically employs hydrophilic membranes and/or surfaces to position the liquid-gas interface and withdraw liquid [ref. 14]. Cyclonic separation is a flow-driven separation where two-phase flow is injected tangentially into a cylinder [ref. 7]

As the pressure and temperature is considered in the design of gas-liquid separators, a change in pressure from the design point/range may cause a decrease in separation performance *(F-8)*. In Exploration environments, a decreased ambient pressure can affect separation process pressure in multiple ways. For example, the cabin air may be the process air and thus the separator pressure is directly affected (i.e., CCAA separator). Another example is in the case of the Sabatier reactor, which is operated at a negative gauge pressure as a hazard mitigation. Maintaining a sub-ambient mode of operation in an Exploration environment would further reduce the operating pressure of the Sabatier and consequently decrease the pressure in the downstream rotary separator.

Tangentially, gas-liquid separation can be simplified in a partial-gravity environment; this is applicable for intended surface Exploration missions and offers the ability to greatly simplify system architecture.

### 7.1.2 Thermal

#### 7.1.2.1 Forced Convection

For the proposed Exploration atmosphere environments, the ability of ECLSS equipment to transport/dissipate heat using forced air advection/convection will be significantly impacted. This is due to the decreasing cabin air pressure results in a corresponding decrease in air density. The impact to ECLSS thermal performance can be quantified by examining the steady-state heat transfer equation for one-dimensional (1-D) internal fluid flow:

$$Q = A * V * \rho * Cp * (T1 - T2) \qquad \text{Eq. 1}$$

Where:

$Q$ = heat rejected from fluid
$A$ = cross-sectional area of internal duct
$V$ = velocity of fluid through internal duct
$\rho$ = density of fluid
$Cp$ = specific heat of fluid
$T1$ = fluid inlet temperature
$T2$ = fluid outlet temperature

As illustrated in Figure 2, Equation 1 can be used to simulate the heat transfer associated with cabin air flowing through a generic air/water Heat eXchanger (HX).

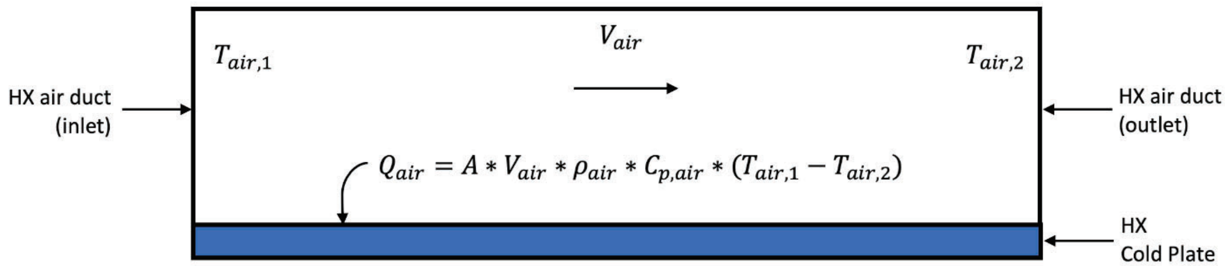


***Figure 2. One-dimensional Steady-state Heat Equation***

As shown in Table 6, air density varies linearly with pressure, while specific heat remains relatively constant.

***Table 6. Air Density and Specific Heat as Function of Ambient Pressure***

| **For $P_{amb}$ = 14.7 psia** | **For $P_{amb}$ = 10.2 psia** | **For $P_{amb}$ = 8.2 psia** |
|---|---|---|
| $\rho$ = 0.0743 lbm/ft$^3$ (1.191 kg/m$^3$) | $\rho$ = 0.0515 lbm/ft$^3$ (0.825 kg/m$^3$) | $\rho$ = 0.0418 lbm/ft$^3$ (0.67 kg/m$^3$) |
| $C_p$ = 0.2396 Btu/lb/°R (1.0025 kJ/kg/ºK) | $C_p$ =0.2395 Btu/lb/°R (1.0022 kJ/kg/ºK) | $C_p$ = 0.2395 Btu/lb/°R (1.0020 kJ/kg/ºK) |

Combining Equation 1 with the data in Table 6, the following relationship is derived:

$$Q_{Exp} = Q_{Nom} * P_{Exp}/P_{Nom} \qquad \text{Eq. 2}$$

Where:

$Q_{Exp}$ = heat rejected from air for Exploration cabin pressure (10.2 or 8.2 psia)
$Q_{Nom}$ = heat rejected from air for nominal cabin pressure (14.7 psia)
$P_{Nom}$ = nominal cabin pressure (14.7 psia)
$P_{Exp}$ = Exploration cabin pressure (10.2 or 8.2 psia)

From Equation 2, it is noted that a decrease in cabin air pressure will result in an equivalent decrease in heat rejection. This trend is shown explicitly in Table 7 for ISS and Exploration cabin pressures.

***Table 7. Heat Rejection as Function of Cabin Air Pressure***

| | **$P_{amb}$ = 14.7 psia** | **$P_{amb}$ = 10.2 psia** | **$P_{amb}$ = 8.2 psia** |
|---|---|---|---|
| **Heat Rejection** | $Q_{Nom}$ | $Q_{Exp} = 0.694 * Q_{Nom}$ | $Q_{Exp} = 0.565 * Q_{Nom}$ |

From Equation 1, it is noted that the decrease in heat rejection caused by decreasing cabin pressure can be offset by increasing the air inlet velocity (*V*). For an air/water HX, this can be achieved by increasing fan speed, which increases the air inlet volume flow rate (i.e., *Vdot = V*A*). Calculations are provided in Appendix A.

In summary, Exploration environment atmospheres have a decreased per-unit volume heat capacity due to decreased air density *(F-9)*. This will manifest as a decrease in the ability of equipment to reject heat via convection *(F-10)*.

The decrease in heat rejection capability will be directly proportional to the decrease in cabin air pressure. Despite this, analysis indicates that this apparent diminished thermal performance can most likely be mitigated by employing operational changes to ECLSS heat rejection equipment (i.e., running HXs at higher fan speeds). However, some potential concerns associated with implementing these operational changes include:

1. Elevated acoustic contribution and electric power consumption due to higher HX fan speed.
2. Potential for reduced fan performance (i.e., *Vdot*) when operating at decreased pressures.

### 7.1.3 Materials & Processes (M&P)

#### 7.1.3.1 Offgassing

Concentrations of off-gassed species are inversely proportional to vehicle volume, so a given mass of material that is acceptable for toxic offgassing in a large vehicle like the ISS may not be acceptable for smaller vehicles. As an example, concentrations in the MPCV CM (i.e., internal free volume 530 $ft^3$/15 $m^3$) would be a factor of 8 higher than in ISS (i.e., free volume for offgassing calculation uses 4167$ft^3$/118 $m^3$). Materials offgassing test data in the NASA Materials and Processing Information System (MAPTIS) database are reported in terms of maximum limit weights for the ISS and MPCV volumes. When hardware is tested for offgassing as an assembled item, the offgassing data are reported in terms of the maximum number of units that can be flown in the ISS or MPCV. These values can be converted to maximum limit weights or number of units for the volume of Exploration vehicles.

Toxic offgassing rates have historically been expected to have little dependence on pressure until molecular flow starts to occur (e.g., <1 E-3 torr). However, limited unpublished data, recently collected at White Sands Test Facility (WSTF), on the effects of pressure on toxic offgassing levels suggest that the effect of pressure in much higher pressure regimes is significant. Initial data measured offgassing levels 1.5-2 times higher at 8.2 psia compared to those at 11.9 psia (the standard pressure used by WSTF for offgassing testing because of the low ambient pressure at WSTF). Offgassing testing conducted by other organizations was typically conducted at 14.7 psia. Offgassing levels at 14.7 and 10.2 psia have always been assumed to be equivalent, an assumption that has not resulted in any problems. The WSTF test data at 11.9 psia falls midway between these pressures and is adequate for either without further correction. However, the effect is significant for 8.2 psia, and additional empirical data on the effect of pressure on toxic offgassing rates are needed to establish whether a correction factor can be applied to existing data for 8.2 psia environments *(F-11)*.

Although the use of existing MAPTIS data has not been prohibited, NASA-STD-6001 recommends that materials be retested if existing data are over 10 years old due to analytical instrument improvements and changes to material processing parameters. The use of existing MAPTIS data has not led to known problems, but new programs may choose to adopt the NASA-STD-6001 data age recommendation. Assessments in this report of toxic offgassing from ISS hardware under consideration for use in Exploration programs did not exclude the use of existing MAPTIS data. However, existing MAPTIS offgassing data older than 10 years, and especially from the 1980s and 1990s, may not reflect current material characteristics because of developments in analytical instrument sensitivity and materials manufacturing changes *(O-2)*.

Despite this, the continued use of these old data has not led to known problems with toxicity of pressurized spacecraft environments. Acceptable quantities of offgassing contaminants on the ISS are driven by the bulk volume and the ability of the contaminants to be diluted. However**,** toxic offgassing of current ISS hardware may be too high when used in smaller vehicles due to the reduced volume for dilution and will also be higher for 8.2 psia environments than at standard test pressures *(O-3)*.

### 7.1.3.2 Flammability

The flammability of polymeric materials is strongly dependent on percentage of $O_2$ concentration and more weakly dependent on $O_2$ partial pressure. NASA has extensive 1-g data on polymeric materials flammability in 24.1% $O_2$ at 14.7 psia (e.g., ISS maximum $O_2$ concentration other than in the airlock during EVA prebreathe) and 30% $O_2$ at 10.2 psia (the worst-case conditions for materials flammability in the SSP orbiter, the ISS Airlock during EVA prebreathe, MPCV CM, and CCP vehicles). However, NASA has limited material flammability data at $O_2$ concentration higher than 30% *(F-12a)*.

At this time, the maximum $O_2$ concentration has not been defined for all habitable Exploration elements that will operate on the lunar or Martian surface. HEO-DM-1006 [ref. 15] specifies that a nominal total cabin pressure of 8.2 psia and $O_2$ greater than or equal to 33.7% is needed for Exploration missions with high-frequency EVA. When provision is made for $O_2$ concentration control bands and sensor accuracy, the maximum $O_2$ concentration could be between 36 and 40%, but the exact numbers will depend on specific vehicle design and hardware capability. As such, this assessment evaluated hardware and material flammability up to 40% $O_2$ for the 8.2 psia environment. Many ISS materials have been shown to meet flammability requirements at 10.2 psia and 30% $O_2$, but are unlikely to meet the requirements at higher $O_2$ concentrations. Materials in this category include polymeric materials, foam thermal insulations (e.g., Armaflex and Solimide AC-550 polyimide), Bisco HT-200 sound block silicone, Soundcoat HT polyimide foam, Black KB 10 tape, blue duct tape, silicone-fiberglass insulations, flammable paint on metallic substrates, Nomex, and polyethylene covered in aluminum foil tape.

Metallic materials are usually nonflammable, even in 100% $O_2$ at ambient pressure, and relatively flammable metals (e.g., aluminum and titanium) will be nonflammable under standard flammability test conditions in the expected Exploration environments.

Essentially all existing test data for flammability of flight materials are from 1-g testing, and consequently, minimal flammability data exists at varying $O_2$ concentrations in partial-gravity environments *(O-4)*. However, limited data exists that suggest materials will be more flammable in partial gravity environments, because the gas flow velocities from natural buoyancy are greater than the flow velocities for worst-case combustion [refs. 86-89]. Additional work is being conducted to better understand these differences,[1] but definitive data will not be available to affect the HLS Program.

The impact of the higher material flammability will depend on the specific hardware design. Many custom ECLSS hardware items are largely metallic, and may be possible to use these items with minor modifications.

Items like the Armaflex foam thermal insulation used on the ISS coolant lines are acceptable for 30% $O_2$ at 10.2 psia, but likely to be flammable in habitable Exploration elements. No drop-in replacements exist, but some foams, like Zotek F30, would meet flammability requirements although extensive machining would be required *(F-12b)*.

If survival of vacuum exposure is required, that would present additional difficulties. Armaflex, Zotek F30, and other foams used for thermal insulation are closed-cell and can be damaged by vacuum exposure. Open-cell foams are needed for acoustic insulation and can survive vacuum

[1] In support of the HLS Program.

exposure, but do not meet the thermal insulation performance characteristics of the closed-cell foams. Although some closed-cell foams exist that would meet flammability requirements in habitable Exploration elements, with the exception of Solimide HT-340, no suitable open-cell foams exist at this time *(F-13)*.

Bisco HT-200 sound block silicones, used extensively for ISS ECLSS hardware, are acceptable for 30% $O_2$ at 10.2 psia, but will likely be flammable in habitable Exploration elements *(F-12c)*.

Commercial off-the-shelf (COTS) hardware usually has polymeric rather than metallic cases and is consequently more likely to be flammable in Exploration environments. In some cases, relatively minor modifications (e.g., covering exposed polymeric surfaces with aluminum tape) may be sufficient to protect the COTS hardware. If the hardware has a metallic case, it will usually be possible to show that the internal materials are self-extinguishing, but polymeric cases will likely be flammable in habitable Exploration elements.

Historically, programs with $O_2$ concentrations to 30% at 10.2 psia have accepted some flammable hardware by material usage agreement (MUA) based on the hardware being largely crew-tended while in use and stowed in a nonflammable container when not in use. Some flammable COTS hardware may be accepted via a MUA with similar controls for higher $O_2$ concentrations. However, many items that were accepted for the ISS are not likely to be acceptable for Exploration programs without modification. As an example, the cordless vacuum cleaner assessed in this report is an example of flammable hardware that has been accepted for the ISS. As it is fairly large, it would be unlikely to be acceptable without modification for Exploration atmospheres. In contrast, the CADs are small enough that they may be acceptable in Exploration environments regardless of flammability.

## 7.2 ECLSS

### 7.2.1 Avionics Air Assembly

***Description***

The AAA units pull cabin air through avionics racks via ducts to extract convective heat from internal avionics hardware [ref. 8]. Outlet ducting pulls the heated air out, using fans to generate the required airflow. Downstream of the fan is a HX supplied by moderate-temperature loop (MTL) coolant. The avionics heat is rejected to the MTL line and the air routed back to the cabin. Hardware using the AAA has a specified heat load to reject to the assembly. The air has specified minimum and maximum temperature limits, set by the dewpoint temperature and maximum touch temperature, respectively [refs. 16, 17].

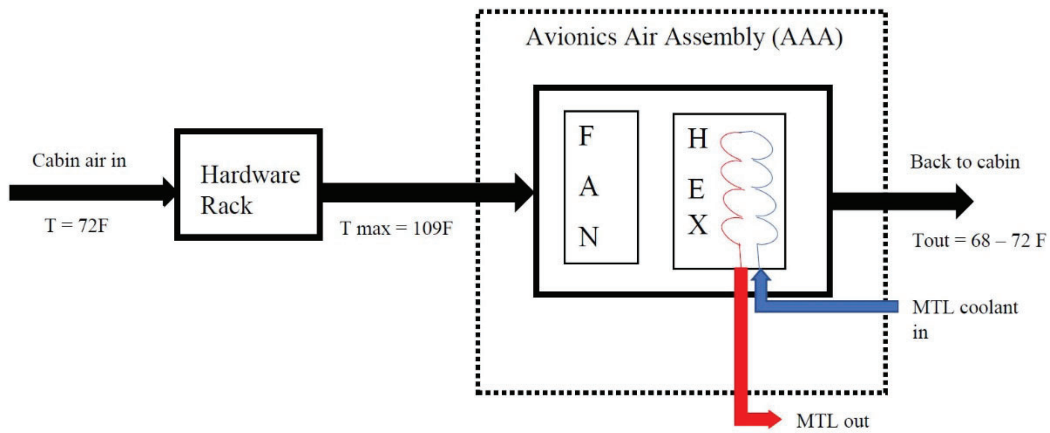


***Figure 3. AAA Diagram***

***Performance***

AAA fan performance will be decreased in low pressure environments without aerodynamic optimization of blade angles (*F-1*). Convective heat transfer will be decreased in the HX and avionics racks due to decreased air density. This may be overcome with changes to fluid velocities and/or HX area. Increased volumetric flowrate and power demand (i.e., increased fan speed) will be required through the racks (*Appendix A, items i and j)*.

***Thermal***

Lower density air has a decreased per volume heat capacity; the change in specific heat per mole is negligible. To sink the same specified heat load and stay within specified temperature limits, volumetric flow must be increased proportionally to the change in density and heat capacity. Additional increases may be needed to overcome decreased effectiveness *(see calculations in Appendix A, item j)*. For 10.2 psia, upwards of 40% increased volume flow through the racks is required for the same heat load and temperature limits *(item a)*. For 8.2 psia, upwards of 80% increased volume flow through the racks will be required for the same heat load and temperature limits *(item b)*.

***Qualitative M&P Evaluation***

A lack of specific and relevant data on materials identification and usage for AAA limited the M&P analysis. The AAA is mostly metal and is not anticipated to require redesign of its bulk material. Because the AAA is cooled by the ISS MTL, which maintains cabin temperatures above the dew point and is anticipated to be similarly cooled by Exploration vehicles, thermal insulation was not considered as part of the material evaluation.

***Components not assessed***

Specific materials used in the AAA design were not assessed due to lack of information. No sensors or valves or specific piece parts were considered in this assessment.

### 7.2.2 Brine Processor Assembly

***Description***

In Fall 2020, the BPA, shown in Figure 4 [ref. 18], was delivered to the ISS and set to further close the water loop by dewatering pretreated urine brine from the UPA. The assembly uses

Paragon Ionomer-membrane Water Processor (IWP) technology [refs. 10, 19]. The IWP acts as a membrane-distillation process to recover water from concentrated urine brine from the UPA. A high flowrate (10 cfm, 17 $m^3$/hr) of cabin air is used as a sweep gas across a dual-layer bladder containing the brine. Water is selectively diffused across the ionomer membrane, leaving behind most contaminants, and exits with the sweep gas. The effluent is moisture-laden and contains trace contaminants. The BPA targets recovery of 80% of available water from 5.94 gallons (22.5L) of brine within a 26-day cycle [ref. 20].

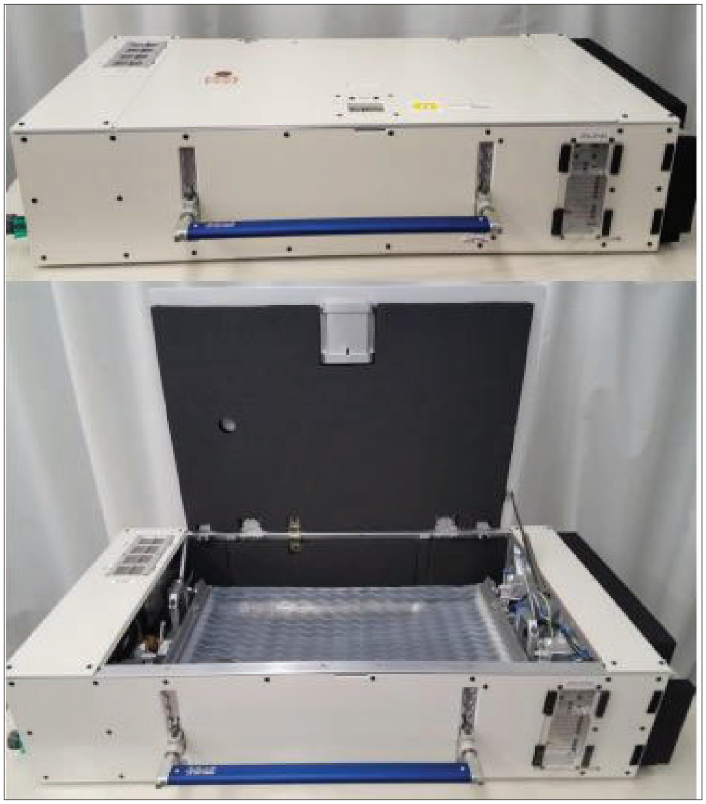

***Figure 4. BPA Shown with Bladder Access Panel Closed (top) and Open (bottom)***

### *Performance*

BPA performance is largely driven by the cabin air temperature and relative humidity (RH) [ref. 10]. These conditions are assumed to be constant across Exploration vehicle environments as RH is set by crew comfort and has been shown in this assessment to be constant (*Appendix A, item h),* and temperature is controlled by the BPA preheater. Therefore, diffusion of water across the membrane is not expected to be affected, as partial pressures of water on either side of the membrane will be the same in Exploration. Decreased air density could have impacts on momentum transfer and mixing of water vapor with the sweep gas, though this effect is likely negligible given the high fluid flow rates (i.e., 10 cfm) through the BPA.

Performance of the exhaust fan will be impacted due to decreased air density. This is due to flow effects occurring on blade surfaces and could be mitigated with aerodynamic optimization for lower-pressure environments. It is assumed BPA will need the same effective volumetric flow rate of air in Exploration as nominal ISS environment.

The bladder used in the BPA is semipermeable, and as stated, the primary driving force for water vapor permeation is the concentration gradient between the bladder and sweep gas. However, cabin pressures below that for which the ISS BPA was certified may induce weeping of brine fluid through the device's bladder (*F-15*).

***Thermal***

BPA avionics hardware receives cooling from cold plates, natural convection, and forced convection via process air [ref. 9]. Forced and natural convection heat transfer rates will be decreased in low pressure environments due to decreased air density. This may cause a higher steady-state touch temperature of hardware that could be mitigated with an increased amount of ventilation (i.e., AAA flow).

***Qualitative M&P Evaluation***

The BPA uses materials flammable in ISS environments (i.e., bladder). These materials are contained within an aluminum box with air flow less than 10 cfm. It was accepted for use on the ISS based on data in JSC 29353 [ref. 21] showing that a vented aluminum container with a constant air flow rate of 10 cfm is able to contain an internal fire. This assessment applies for environments to 30% $O_2$ at 10.2 psia, but additional flammability testing will be required to determine if the hardware is acceptable in 34-40% $O_2$ at 8.2 psia *(F-15)*. The brine processor bladder was specifically tested for offgassing in the ISS, and results show that it is acceptable for offgassing in smaller volume vehicles. The other BPA materials were verified acceptable for the ISS based on MAPTIS materials data, but would require reassessment and, depending on the vehicle volume, offgassing testing as an assembly for the Exploration vehicles.

BPA has been shown on the ISS to cause issues with odor and accumulation of trace contaminants above the odor threshold [ref. 90]. This effect will be exaggerated in Exploration-sized vehicles (*O-5*) where there is less volume to dilute odorous contaminants, and will likely necessitate trace contaminant control in the form of a GAC bed. This consideration is most applicable to BPA, compared to other ECLSS hardware that vents to cabin, due to the high vent flow rates of BPA (i.e., 10 cfm (0.283$m^3$/min)) and near-continuous operation (~26-day dewatering cycles).

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, were not assessed.

### 7.2.3 Common Cabin Air Assembly

***Description***

The CCAA, shown in Figure 5 [ref. 22], provides temperature and humidity control for cabin air, as well as ventilation to ensure adequate mixing of constituents in the ISS microgravity environment. The CCAA can accommodate a volume equal to U.S. Lab Module on the ISS while maintaining margin on fan rotations per minute (RPM). The CCAA has been certified to operate in 10.2 psia/30% $O_2$ environments in the ISS airlock [refs. 7, 23].

In nominal operation, cabin air is pulled into the CCAA via fans and combined with moisture-laden air leaving CDRA and TCCS, where it passes a condensing heat exchanger (CHX). The resulting cooled, saturated air is returned to the cabin with a slip-stream fed to CDRA [refs. 7, 13].

Within the CHX, hydrophilic "slurper" bars pull the condensed water, via airflow drag and suction, from the downstream separator to the slurper, where it is collected and delivered to the wastewater orbital replacement unit (ORU) bellows tank [ref. 13].

The flow through the CCAA is controlled via the Temperature Control Check Valve (TCCV). Based on the crew setpoint for temperature, the TCCV changes the split fraction of air through the CHX. Humidity is therefore not directly controlled, but managed through mixing via the CHX and TCCV [ref. 13].

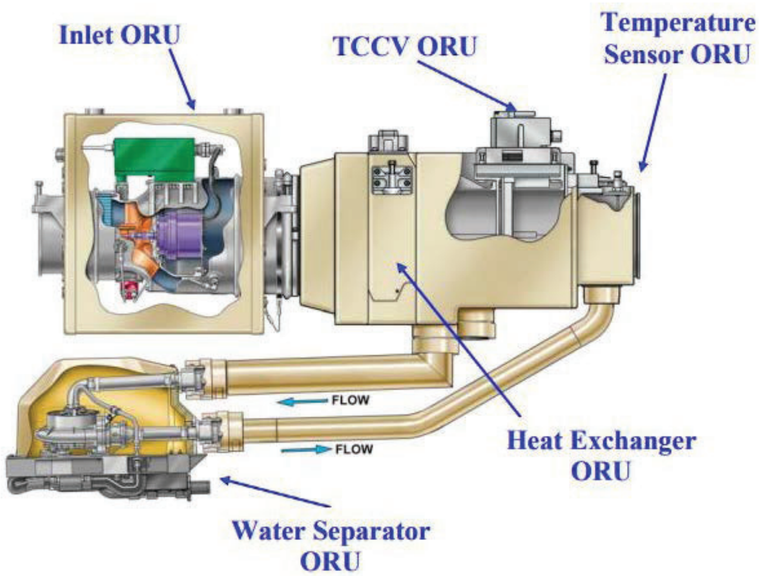


***Figure 5. Simplified CCAA Cutaway Schematic***

### *Performance*

CCAA will see decreased sensible HX performance caused by decreased air density *(F-9, F-10)*. This could be mitigated by increased air flow rates through the CCAA.

Without aerodynamic optimization, fan performance will be impacted by flow effects in lower pressure requiring increased volumetric flow to maintain the crew within temperature limits (*F-9, F-10*).

Fan flow impacts are likely manageable for 10.2 psia due to the RPM margin of the CCAA fan to compensate for decreased performance. Larger impacts, such as a larger or redesigned fan, may be required for 8.2 psia. The CCAA has been certified to operate in 10.2 psia/30% $O_2$ environments in the ISS airlock. This is a smaller volume than a single CCAA unit is typically employed for, but provides insight on fan performance and M&P compatibility. The specific requirements for CCAA will depend on vehicle size, architecture, and mission specifics.

Additionally, the force of airflow drag will be decreased in Exploration environments due to decreased atmospheric density, which may decrease the efficiency of the CCAA slurper bars to collect condensate *(F-16a)*.

### *Thermal*

For the same RH and temperature, the dewpoint and absolute humidity of cabin air will be the same in Exploration environments as in nominal ISS environments *(see Appendix A (h))*. This means that, at these conditions, the partial pressure of water vapor is the same across environments. Therefore, there will be no thermodynamic changes to the phase transition as a result of the pressure change as the temperature gradient across the HX (coolant/process fluid) will be the same. Impacts to heat transfer are caused by decreased heat transfer coefficient of lower-density air *(F-9, F-10)*. This can be mitigated by higher air flow rates through the CCAA.

***Qualitative M&P Evaluation***

The CCAA hardware is primarily metallic, so flammability and toxic offgassing should not be a concern for those parts. The foam insulation is a silicone, but the specific foam is not identified. The exposed foam has a fire-retardant coating for ISS 24.1% $O_2$, suggesting that it will be flammable in all Exploration atmospheres. In many cases, the foam is internal, between the metallic hardware and case, which may be an acceptable configuration even though the foam is flammable.

The CCAA CHX has foam exposed on the rear side of the hardware. This configuration is unlikely to be acceptable for Exploration due to the flammability and exposed surface area concerns *(F-16b)*.

A relatively simple modification to the hardware would be to replace all the foam on the HX with Zotek foam, which is nonflammable in Exploration environments. However, regardless of the foam used, toxic offgassing would have to be reevaluated for Exploration vehicles smaller than the ISS. As noted, if there is a requirement for vacuum exposure, that would be a problem for closed-cell insulation foams. Solimide HT-340 is an open-cell foam that should be acceptable for flammability, but will have unacceptable thermal performance.

Within the CCAA, each bacterial filter element consists of pleated borosilicate HEPA media containing 0.3-µm pores mounted in a rectangular aluminum frame. Pleated glass is nonflammable in the Exploration atmospheres and will be acceptable in Exploration environments.

CCAA hardware contains many acoustic enclosures and panels. The inlet ORU acoustic enclosure is constructed of graphite composite material with rubber (e.g., Bisco HT-200 sound blocker noted as probably flammable in HLS-type atmospheres, but acceptable for 30% $O_2$, 10.2 psia) and felt bonded to the inside. The HX ORU inlet duct has a thin, fragile composite acoustic cover. The graphite composite is nonstructural and will likely be acceptable for flammability to 30% $O_2$, 10.2 psia, but may need to be replaced for higher $O_2$ concentrations.

***Components not assessed***

Specific hardware, materials, and components of the CCAA were not assessed due to lack of available design information. This includes any materials of construction not identified (e.g., sensors or piece parts).

### 7.2.4 Carbon Dioxide Removal Assembly

***Description***

The CDRA is a $CO_2$ scrubber using zeolite adsorbents to selectively remove crew-generated metabolic $CO_2$ from cabin air to within safe partial-pressure limits. Like the recently flown and activated 4-Bed $CO_2$ Scrubber (4B$CO_2$) Technology Demonstration, these are 4-bed molecular sieve (4BMS) systems and share the architecture illustrated in Figure 6 [ref. 19]. Desiccant beds are used upstream and downstream of the zeolite beds to protect against moisture from blocking $CO_2$ adsorption sites. The assembly features two sets of desiccant-adsorbent beds that operate in alternating cycles to continuously and regeneratively remove $CO_2$ from cabin air. One set of beds is adsorbing $CO_2$ and $H_2O$ while the other two beds are desorbing $CO_2$, which may be used in the Sabatier $CO_2$ reduction system or vented. $H_2O$ adsorbed on the desiccant beds is returned to the CCAA. For desorption, a $CO_2$-laden zeolite bed is heated to 400 °F (204 °C) and exposed to a vacuum. This decreases the partial pressure of $CO_2$ and shifts the adsorption equilibrium such that $CO_2$ is driven off the bed. A blower is used to drive cabin air through the beds during adsorption, and process air is used to cool desorbed beds from desorption to adsorption temperatures during the beginning of half-cycles. CDRA is certified for nominal ISS environments [refs. 16, 24]. The $4BCO_2$, the next-generation replacement for CDRA, uses the same basic architecture but incorporates numerous design improvements.

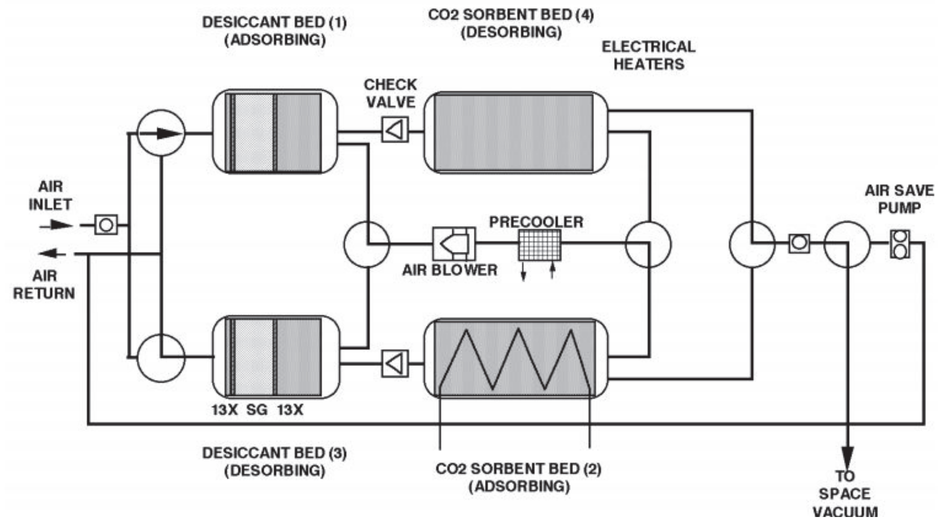


***Figure 6. 4BMS Schematic***

### *Performance*

Adsorption performance of the zeolite beds is driven by the partial pressure of $CO_2$ [refs. 16, 25, 26]. The required average removal rate of $CO_2$ is specified by the number of crew members (i.e., 2.23 lbm/CM-day (1.04 kg $CO_2$/CM-day) average [ref. 91]), but the required instantaneous removal rate is based on variable metabolic generation rates by the crew. The capacity of zeolite beds is driven by both $CO_2$ partial pressure and temperature and thus is also expected to be unaffected by a pressure change alone [refs. 17, 27, 28].

Limited data suggest improved kinetics of zeolite adsorption in lower pressures (e.g., suit pressures) due to decreased molecular inference by $N_2$, which changes the rate-limiting $CO_2$ diffusion resistance [ref. 17]. Lower cabin pressure could cause a higher rate of heat transfer, but would not affect the absolute amount of heat to be transferred/rejected (i.e., the adsorption rate is increased, but not the molar heat of reaction). The net performance impacts to CDRA due to reduced cabin pressure are uncertain due to the difficulty in predicting the combined effects of potentially improved adsorption kinetics, reduced blower mass flowrate, and internal convective heat transfer impacting bed heating and cooling (*F-17*).

The blower driving flow through the CDRA will face impacts due to changes in air density. The design basis for volume flow is expected to be the same as nominal 14.7 psia operation for the same number of crew members at constant partial pressure of $CO_2$ due to $CO_2$ partial pressure and temperature-driven diffusion kinetics and capacity of the sorbents.

It is likely the CDRA blower or 4BCO$_2$ blower (mag-lev) under development will not meet the required volumetric flow in Exploration environments. As per reference 25, 2K-070836-rev2 Table 5-6, the blower has no minimum specified operating pressure. The 4BCO$_2$ blower minimum pressure requirement is well above the reduced pressures being evaluated.

***Thermal***

Zeolite and desiccant bed capacity are a function of temperature. To desorb beds, they are heated to 400 °F (204 °C) and exposed to a vacuum. Before being used in an adsorption cycle, beds are cooled for the beginning of the cycle via process air. The minimum temperature during adsorption is about 50 °F (10 °C) [ref. 16].

The process air is used to reject the heat of adsorption from the beds. The heat of adsorption for $CO_2$ on zeolite is about 400 BTU/lb (930 kJ/kg), and about 1800 BTU/lb (4187 kJ/kg) for $H_2O$ on zeolite/desiccant sorbent [ref. 16]. Thus, there may be an impact to thermal control, half-cycle time, and/or desiccant or adsorbent bed capacity caused by decreased heat rejection. It is likely this effect will be noticed in the desiccant beds with higher heats of adsorption *(Appendix A, item k)*.

***Qualitative M&P Evaluation***

A number of materials used in CDRA will not meet flammability requirements for Exploration environments, including black KB 10 tape, blue duct tape, Armaflex AP pipe insulation, and silicone-fiberglass insulation blanket.

Armaflex AP is used as pipe insulation on CDRA and passes flammability in 30% $O_2$. However, when covered by the black KB 10 tape, the configuration is flammable *(F-12d)* [ref. 92]. KB 10 tape and blue duct tape are used on the silicone-fiberglass insulation blanket over the desiccant/adsorbent ORU and would need to be replaced for Exploration. Finally, the silicone-fiberglass blanket used on the system may require replacement. All other exterior hardware is metallic and nonflammable. Acceptable modifications are feasible for 30% $O_2$ at 10.2 psia, but the Armaflex AP pipe insulation is likely to be flammable at higher $O_2$ concentrations (*F-12a)*. Replacing the KB 10 tape with an L-T-80 aluminum tape may be sufficient to control flammability in Exploration atmospheres.

Similar materials were used for 4BCO$_2$, including Armaflex insulation and KB10 tape on the low-temperature loop (LTL) lines.

***Components not assessed***

Much of the performance assessment is assumed to apply to CDRA and 4BCO$_2$. Specific sensors and piece parts were not assessed.

### 7.2.5 Carbon Dioxide Reduction Assembly

***Description***

The CRA utilizes the Sabatier reaction to perform chemical reduction of metabolic $CO_2$ for $O_2$ recovery. $CO_2$ from CDRA is stored at high pressures in an accumulator tank, and OGA water electrolysis reaction provides hydrogen ($H_2$) feedstock. In the packed-bed reactor, $CO_2$ and $H_2$ gas react over a Ru/$Al_2O_3$ catalyst to produce methane and water. Methane is vented to space, and water is sent to the WPA via the wastewater bus for processing [refs. 29, 30]. The process requires high temperatures to initiate the exothermic reaction, but achieves high conversion at lower temperatures [ref. 31]. On the ISS, AAA air is used to maintain an axial reactor temperature gradient with high inlet temperature and lower outlet temperature. A CHX and gas-liquid separator are used to separate gaseous products and unconverted reactants from water. The reactor is operated below cabin ambient pressure (i.e., ~11-13 psia) to prevent hazardous scenarios of $H_2$ or methane venting/leaking out of the reactor and into the cabin [refs. 20, 21]. If the same hazard mitigation approach of sub-ambient pressure operation is chosen for Exploration Sabatier hardware, then the reactor pressure would need to be decreased below the cabin pressure (i.e., less than 10.2 or 8.2 psia) *(F-18a)*.

Alternative approaches could include adding a pressure dome, like that found on OGA, to act as a layer of containment for operation with positive gauge pressure, but would introduce mass penalties, and the trades would depend on mission specifications.

***Performance***

Decreased pressure within in the Sabatier reactor will have thermodynamic and potentially kinetic impacts on the process. Thermodynamically, the lower pressure operation will decrease $CO_2$ conversion [refs. 22, 32]. However, this decrease is expected to be negligible given the high equilibrium coefficients at the outlet temperature and targeted pressures of the system (i.e., at 200 °C, $K_{eq}^{14.7psia}$ = 8.6E8, $K_{eq}^{10.2psia}$ = 4.1E8, $K_{eq}^{8.2psia}$ = 2.7E8). Kinetically, reduced pressure would be expected to reduce the reaction rate of the Sabatier reactor.

***Thermal***

A constrained temperature gradient along the Sabatier reactor is maintained via AAA air to keep the reaction stable. This AAA air has a decreased per volume heat capacity and will require increased volume flow. This air flow is likely sufficient to control temperature, but will depend on specifics (e.g., flow path of coolant air).

***Qualitative M&P Evaluation***

The Sabatier available materials information was limited for a full assessment. Exposed materials appear to be metallic with the exception of Teflon-insulated electrical wiring, the Dapco 2030-coated compressor fiberglass-epoxy composite acoustic cover, and a silicone duct. The acoustic cover and duct are nonflammable in 30% $O_2$, 10.2 psia, but likely to be flammable in 34-40% $O_2$ at 8.2 psia. Internal materials appear to be acceptable for flammability to 30% $O_2$, 10.2 psia, but it is not clear how the component housings will provide protection for flammable internal materials at higher $O_2$ concentrations. The CRA compressor has a high risk for flammability because of the nonmetallic acoustic cover and the large number of polymeric materials inside the cover *(F-12a)*.

The Sabatier was verified acceptable for toxic offgassing in the ISS volume by analysis of materials data, but this analysis is likely inadequate for Exploration vehicle and habitat volumes.

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, were not assessed.

### 7.2.6 MPCV CM Water-Spray and ISS Water-Mist PFE

***Description***

The MPCV PFE, shown in Figure 7 [ref. 33], is a water-spray fire extinguisher certified for use in the CM and analyzed due to its intended use at the reduced cabin pressure/increased $O_2$ content [ref. 34]. It differs from the ISS PFE, which uses water-mist.


***Figure 7. ISS Water-Mist PFE Development Unit***

***Performance***

The ISS water-mist and MPCV water-spray PFEs are certified for use in a 10.2 psia and 30% $O_2$ environment [ref. 24]. Lower-pressure Exploration atmospheres could impact water-spray PFE characteristics, including changes to plume dispersal, water flow rate, required water quantity, and corresponding tank size (*F-19*). Increased $O_2$ concentrations could decrease the ability of water-spray and/or water-mist PFEs to extinguish a fire (*F-20*).

***Thermal***

There are no apparent thermal impacts for the MPCV or ISS PFEs due to operation in Exploration environments.

***Qualitative M&P Evaluation***

The exterior of the MPCV PFE is metallic or painted metal (e.g., red epoxy paint on titanium pressure vessel). This configuration is nonflammable for 30% $O_2$ at 10.2 psia and may be nonflammable for 34-40% $O_2$ at 8.2 psia.

No flammability data are available for flammable paint on metallic substrates at 34-40% $O_2$ and 8.2 psia (*F-12e*).

The ISS PFE is a titanium tank covered with red Nomex. The ISS PFE is certified for 30% $O_2$, 10.2 psia and, with the exception of the Nomex cover, should be acceptable for the highest

Exploration atmosphere $O_2$ levels. The Nomex cover used on the ISS PFE will not meet flammability requirements at the highest Exploration $O_2$ concentrations (*F-16f*). However, Nomex may be acceptable if treated with a fire retardant. Toxic offgassing of the PFE should not be a concern for Exploration vehicles and habitats.

***Components not assessed***

The assessment was limited to a high-level overview of the assembly and subassemblies. The nozzle and plume dispersion were not assessed.

### 7.2.7 Emergency Mask: Fire and Ammonia Cartridges

***Description***

The emergency respirator cartridges use a series of adsorbents and catalysts to remove contaminants from astronauts' influent breathing gas during emergency scenarios [refs. 28, 35-37].

The fire cartridge, shown in Figure 8 [ref. 38], is designed to oxidize carbon monoxide (CO) into $CO_2$ and filter other contaminants from the ISS cabin air in a post-fire scenario for up to 90 minutes [ref. 26]. It utilizes a catalyst of gold nanoparticles combined with iron oxide, as well as a layer of GAC and a polytetrafluoroethylene (PTFE) particulate filter to oxidize CO, and capture fire products, ammonia, and particulates [ref. 26]. It is certified for use in the ISS airlock at 10.2 psia and 30% $O_2$.

***Figure 8. Emergency Mask with Fire Cartridge***

***Performance***

There are no expected impacts to adsorbent or catalyst capacity caused by decreased pressure, as particulate filter capacity is dependent on the absolute amount of particulate generated by fire. However, the cartridge may have reduced performance due to kinetic changes or the reduced pressure drop impacts. This may necessitate geometric changes to the filter for 8.2 psia.

*Thermal*

Reduced cooling of adsorbents/catalyst due to decreased heat capacity of process (i.e., breathing) air could cause an increased steady-state temperature. If sufficiently high, this temperature could decrease cartridge capacity at the lowest pressure condition of 8.2 psia. It is likely the effect of decreased cooling will be negligible, due to small bed size relative to the crew respiratory rate.

*Qualitative M&P Evaluation*

The ammonia cartridges that attach to the emergency mask are flammable, but acceptable in Exploration atmospheres for contingency use. The fire cartridges passed flammability testing in the ISS 24.1% $O_2$, but would not be expected to pass in higher $O_2$ concentrations. However, the cartridges may be using the same rationale as for the ammonia cartridges. Orange Nomex bags are used to store the emergency masks, ammonia cartridges, and fire cartridges. This material is nonflammable for up to 30% $O_2$ 10.2 psia, but would have to be modified for 34-40% $O_2$ at 8.2 psia (e.g., fire retardant treatment) (*F-12f*). The emergency mask is mainly a Nomex-based layup that passed flammability in 24.1% $O_2$, but has large areas of materials that are flammable in 24.1% $O_2$ (e.g., neck dam, visor). The masks are likely flammable in all Exploration atmospheres, but may be acceptable for contingency use, in which they will be effectively crew-tended at all times.

Based on the toxic offgassing test conducted on the emergency mask, the total number of masks was limited to 38 for the ISS volume [ref. 93]. Toxic offgassing of emergency masks may be too high when used in Exploration vehicles and habitats, and could prevent sufficient quantities from being available for emergency response *(O-3a)*. For example, only four masks would be allowed for the MPCV volume, so the allowed number might not be sufficient for Exploration vehicles. If that became a problem, then the hardware may amenable to being baked to reduce offgassing at a moderate temperature (e.g., 120 °F).

*Components not assessed*

Specific piece parts were not assessed.

### 7.2.8 MPCV Smoke-Eater Filter

*Description*

The OSEF is designed to provide on-orbit post-fire cleanup of particulates and harmful gases released during a fire event onboard the MPCV CM. The smoke-eater installs directly into the CM particulate air filter. It uses a detachable prefilter to capture particulates and a primary filter, consisting of a sorbent layer and oxidation catalyst, to remove contaminant gases. It is certified for 10.2 psia, 30% $O_2$ [ref. 39].

*Performance*

There is no concern for 10.2 psia/30% $O_2$, as it is certified for this environment [ref. 29]. No changes in adsorbent capacity or catalyst performance are expected due to pressure change. No impacts are expected to particulate filter performance or capacity. It is anticipated that the design would use the same volumetric flow rates in 8.2 psia as 10.2 psia for the same volume of air to be scrubbed. However, the hardware may have kinetic impacts related to fluid velocity necessitating sorbent or catalyst bed dimensional change.

***Thermal***

Decreased heat capacity of process air may result in higher steady-state temperatures, which could decrease sorbent capacity or catalyst performance.

The OSEF has not been tested or certified for 8.2 psia *(F-12)*.

***Qualitative M&P Evaluation***

The OSEF is certified for flammability in 30% $O_2$ at 10.2 psia. The design may be acceptable for flammability in 34-40% $O_2$ at 8.2 psia. The exposed material that is not aluminum is the pre-filter element, which is identified as being borosilicate fiberglass with a proprietary fluoropolymer coating. Fiberglass can be flammable because of the sizing, but this construction has a fluoropolymer coating that may not be flammable at these $O_2$ concentrations. Toxic offgassing is not a concern for this hardware.

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, and specific catalysts and sorbents were not assessed.

### 7.2.9 Intermodule Ventilation Fan

***Description***

The IMV is used to mix cabin air between modules on ISS. It ensures proper mixing of atmospheric gases (e.g., $O_2$ released by OGA, humidity released by the Urine Processor Separator Plumbing Assembly (SPA), the BPA, the crew, and $CO_2$-mixing for removal by CDRA) [ref. 8].

***Performance***

The IMV blower provides constant volume mixing. The volume of air required to be moved is not expected to change for Exploration. Therefore, no impacts to operation in low pressure are expected.

***Thermal***

The IMV controller is cooled with the process gas stream. As such, the controller may see higher steady-state operating temperatures due to decreased natural and forced convection *(F-12, F-13)*, which may necessitate alternative cooling approaches for Exploration.

***Qualitative M&P Evaluation***

An evaluation of IMV materials was not possible due to lack of data.

***Components not assessed***

Specific materials, sensors, and the specific blower were not evaluated due to lack of available data.

### 7.2.10 Oxygen Generation Assembly

***Description***

The OGA uses a cathode-feed water electrolyzer to provide $O_2$ for crew metabolism, a process illustrated in Figure 9 [ref. 40]. The rotary separator removes $H_2$ from circulating feedwater. $O_2$ is produced on the anode side of the cell stack and vented to cabin. A pressure dome, which is operated under vacuum, prevents diffusion/leakage of product $H_2$ into areas with cabin air ($O_2$), preventing combustion-related hazards. The water recirculation loop travels outside of the pressure dome to recycle unreacted water through the cell stack [ref. 41]. Electrostatic forces play a large role in migration and separation of species across the cell stack.

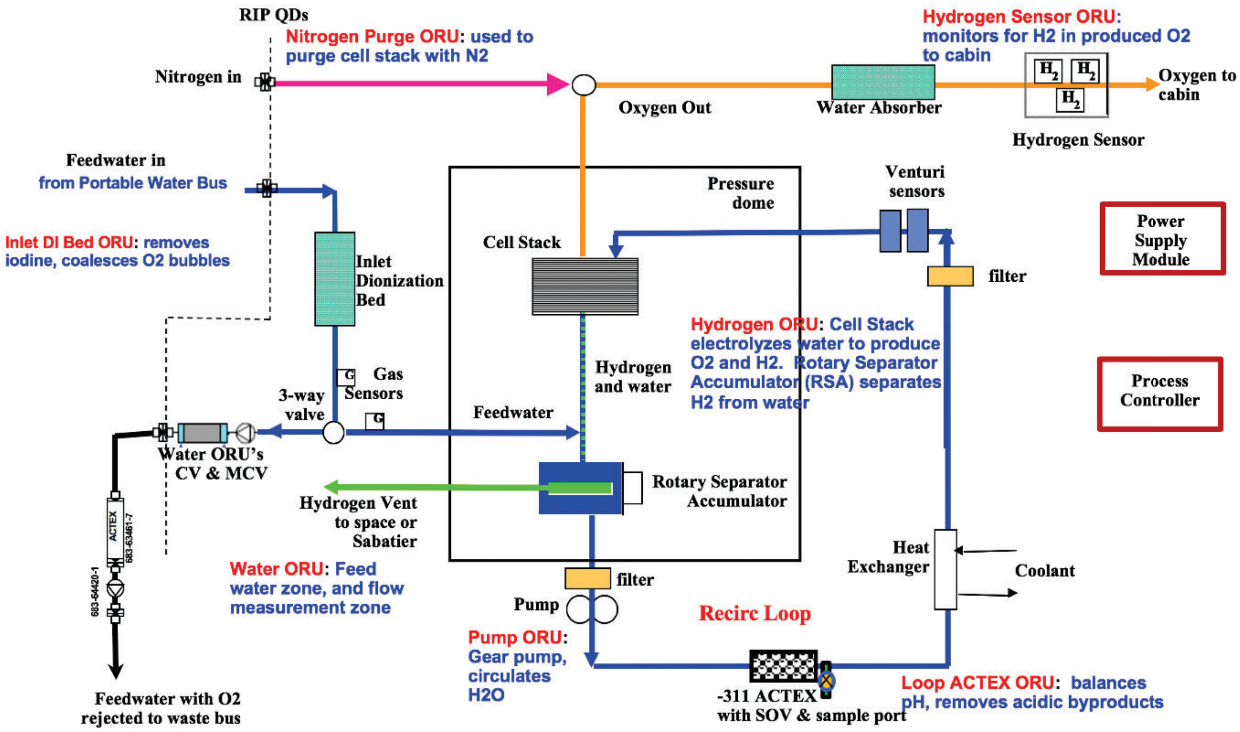


*Figure 9. OGA Simplified Schematic*

### *Performance*

The $O_2$ side of the cell stack is exposed to ambient cabin air through the $O_2$ vent. Operation of the ISS OGA in Exploration environments will decrease the $O_2$-side stack pressure
The increased pressure differential between the anode (i.e., ambient) and cathode (i.e., 26-28 psia) may cause system impacts. First, water electrolysis occurs on the anode side of the stack. Protons generated during electrolysis travel to the cathode (i.e., water recirculation loop side) causing protonic drag and effectively pulling excess water from the anode. It is possible that the increased pressure drop across OGA cells will overcome the protonic drag within the cell stack and allow liquid water to be released into the $O_2$ product stream *(F-22a)*.

A second possible impact is related to OGA leak venting. In the OGA rack, the AAA disperses any $O_2$ leak, diluting it to a maximum local concentration of 29%. This is acceptable for the ISS cabin, where $O_2$ is nominally 21%. However, for Exploration atmospheres where $O_2$ is elevated, an $O_2$ leakage from OGA could result in an unacceptable hazard within a rack, and an alternative hazard mitigation would be required *(F-22b)*.

Other impacts to the OGA are caused by a possible decrease in pressure of the wastewater bus *(see section 7.2.5)*. If the recirculation loop pressure is decreased, then possible impacts include dissolved $H_2$ coming out of solution in the recirculation loop, required changes to the rotary separator accumulator high/low setpoints, and out-of-range sensors *(F-22c)*.

None of these impacts is expected to affect the ability of the OGA to electrolyze or produce $O_2$ at the required rate. Rather, the impacts represent safety and operational concerns. One possible solution is to lower the $O_2$-side (i.e., anode) stack pressure with a backpressure regulator on the outlet. However, this would have consequences and M&P concerns. Specifically, $H_2$ sensors are used in the $O_2$ vent stream to monitor $H_2$ concentrations and shut down OGA in the event $H_2$ reaches high enough quantities to be a safety risk. These sensors are susceptible to deactivation by water. To prevent this, a water absorber is upstream of the sensors. Decreased cabin pressure may reduce the performance of the OGA $H_2$ sensors and/or cause premature failure due to increased water content in the product $O_2$ *(F-22d)*.

***Thermal***

OGA is less thermally impacted due to the architecture being predominantly liquid cooled. The system may experience higher steady-state temperatures due to decreased convection with ambient air. However, this could be mitigated with increased coolant flow.

***Qualitative M&P Evaluation***

The OGA is sealed inside a metallic pressure dome, and the parts that are exposed to elevated $O_2$ levels (up to 100%) have been verified to be acceptable [ref. 94]. The major components external to the pressure dome are contained in metallic boxes and not likely to be a flammability concern for Exploration environments. Polymeric materials external to the boxes are limited to Teflon-insulated electrical wiring (i.e., nonflammable in Exploration environments), and other insulation, which is likely to be flammable in Exploration environments. The OGA may be acceptable for all Exploration environments with changes to the insulation.

There is an operational hazard of OGA on ISS concerning pressure drops in the recirculation loops following shutdown. In the event of a shutdown, the recirculation loop is not purged and contains product $H_2$ and unreacted water. This hazard arises from the scenario where product $O_2$, present at the $O_2$ side of the cell stack, diffuses into the recirculation loop. Within the recirculation loop, the $O_2$ and $H_2$ combine and react to form liquid water, which condenses and lowers the pressure of the recirculation loop. This drop in pressure could allow for the diffusion of ambient air into the recirculation loop. In this scenario, ambient $O_2$ within the OGA recirculation loop could accumulate in the separator during start-up and combine with residual product $H_2$ to create a hazardous scenario for flammability and/or explosion *(F-22e)*.

There is reason to believe the risk of this scenario is decreased, as the driving force for diffusion of air into the loop is decreased (reduced pressure differential between ambient and internal OGA). The concentration gradient (i.e., driving force) for $O_2$ diffusion, however, is constant as the partial pressure of $O_2$ is constant.

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, were not assessed.

### 7.2.11 Pressure Control Assembly

***Description***

The PCA features high pressure $N_2$ and $O_2$ tanks, a pressure control panel (PCP) for pressure monitoring and control, and a vent relief valve set for monitoring and controlling cabin atmosphere. The PCP takes atmospheric total and partial pressure readings and commands valves controlling high-pressure $N_2$ and $O_2$ tanks. The flow from these tanks is reduced in pressure via an orifice for accurate flow control. These valves can be commanded into “off,” “on,” or “partial-on” positions to release $O_2/N_2$ into the atmosphere as needed. The PCP is used to supplement $O_2$ produced by OGA and make up for lost $N_2$ [refs. 42-44]. Overall, no performance, thermal, or materials impacts were identified (*F-1a*).

***Performance***

High-pressure atmospheric gases are stored in pressure vessels controlled by regulators. These vessels feed an in-line orifice to reduce pressure to manageable values. When commanded by PCA, gasses are released in an “on” or “partial-on” valve configuration. There are few to no anticipated performance impacts with this system in Exploration. Correlations may be needed for the lower ambient pressure to better understand flow rates of gas as it enters the cabin. Additionally, vent resizing may be needed for the same reason.

***Thermal***

There are no anticipated thermal impacts to the PCA.

***Qualitative M&P Evaluation***

A detailed assessment was not conducted for the PCA. It is predominantly metallic, with Teflon-insulated electrical wiring providing power to the controllers. All the electronics should be in metallic boxes or housings. No materials flammability or toxic offgassing issues are anticipated for PCA hardware in Exploration atmospheres.

***Components not assessed***

Specific piece parts, including valves, regulators, orifices, and temperature and pressure sensors, were not assessed.

### 7.2.12 Trace Contaminant Control System

***Description***

The TCCS is used in spacecraft atmosphere revitalization. The TCCS acts on the trace contaminant load emitted via equipment offgassing and human metabolism to provide cabin concentrations within maximum allowable limits appropriate for the mission duration. Without an active TCCS, these contaminants may accumulate to toxic  levels. In the ISS TCCS, as shown in Figure 10 [ref. 45], a fan pulls cabin air through a fixed GAC bed to remove high MW contaminants and ammonia. The flow rate through the GAC bed is driven by controlling the ammonia generation load within maximum allowable concentration limits appropriate for the mission duration. After the GAC bed, a flow split occurs where two-thirds of the process air is routed back to the cabin. The remainder of the air is heated in a regenerative HX and delivered to a high-temperature catalytic oxidation reactor to remove low MW contaminants via oxidation. The flow rate through the catalytic oxidizer and split fraction after GAC bed is driven by controlling the formaldehyde generation loads within the appropriate maximum allowable concentration limits. A granular lithium hydroxide (LiOH) bed located downstream of the catalytic oxidizer removes any acidic byproducts produced by the catalytic reactor. The TCCS exhaust is routed to the cabin ventilation system upstream of the CCAA to promote mixing. Some incidental trace contaminant removal may occur via absorption in humidity condensate. However, active TCC equipment design best practice takes no credit for incidental contaminant removal [ref. 46].

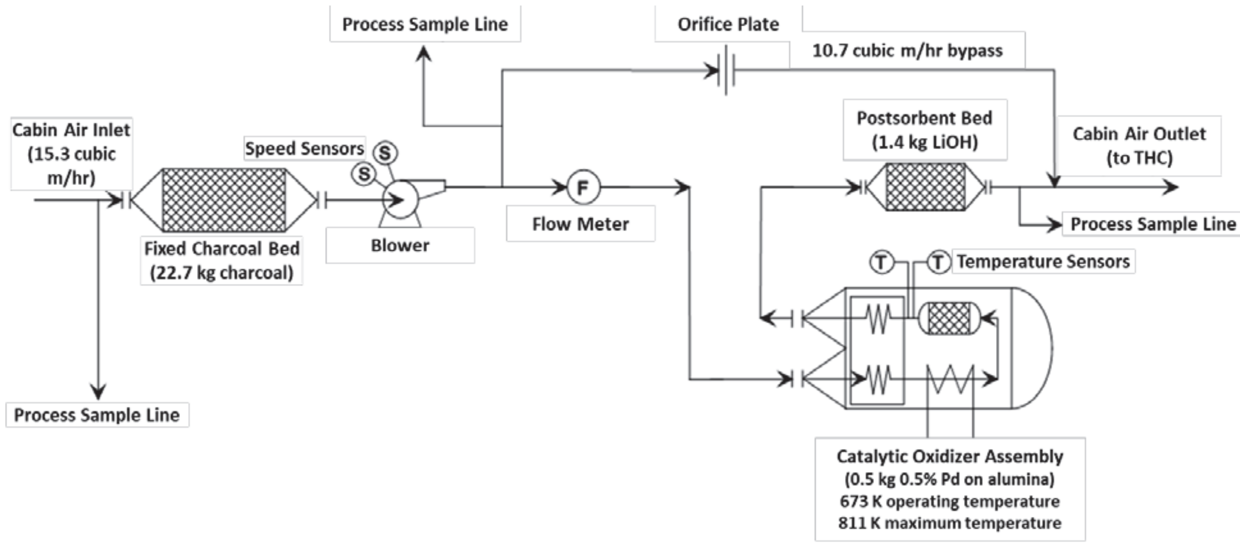


***Figure 10. TCCS Schematic***

### *Performance*

There are no anticipated impacts to carbon bed capacity due to pressure decrease. A dimensional change to the carbon bed (i.e., aspect ratio) may be needed to achieve the required residence time for proper kinetics *(F-5)*. No impacts to catalytic reactor performance are anticipated due to pressure decreases. The fan will have performance impacts due to aerodynamic concerns.

Future TCCS equipment designs are expected to use offgassing rates per unit of internal, nonstructural equipment mass and human metabolic emissions, as has been used for the ISS TCCS design, but with adjustments made based on flight experience [ref. 95]. As such, for the same per-unit offgassing and human metabolic emission rates, the same active TCC effective flow is required. The contaminant emission rates do not require adjustment for total cabin pressure because they are natural diffusion-based processes and not sensitive to pressure. Within the cabin, the atmospheric constituents expand to fill the available volume. Lower cabin pressures may contribute to higher linear diffusion velocities within the cabin atmosphere due to the longer mean free path in a less dense atmosphere, which may aid trace contaminant dispersion in the cabin.

### *Thermal*

The heat of adsorption of the carbon bed and heat of compression from the blower are rejected via process air. Decreased air density in Exploration environments may increase the steady-state temperature of the carbon bed, which could slightly decrease capacity *(F-5)*. This effect is anticipated to be negligible because the contaminants are in the dilute regime.

The high temperature catalytic reactor may need less heat supplied by the heater to reach the reaction temperature, potentially offering power-saving benefits. This is because heating the same volume of air in Exploration to the same temperature as the ISS is akin to heating a lesser absolute mass of air (less $N_2$), and thus less heat is required.

### *Qualitative M&P Evaluation*

The TCCS is primarily metallic on the exterior, with electronics contained in a metallic box and Teflon-insulated electrical wiring. There are no known concerns with the external hardware for flammability or toxic offgassing in Exploration atmospheres. Internally, the TCCS contains an activated carbon bed that is flammable, but is assumed acceptable because of the absence of ignition sources. The ISS TCCS carbon bed is not used regeneratively, but a fire risk exists with carbon beds used regeneratively unless it is ensured that they are allowed to cool to ambient temperature before subsequent exposure to cabin air.

***Components not assessed***

Specific piece parts, including valves and temperature sensors, were not assessed.

### 7.2.13 Urine Processor Assembly

***Description***

The UPA performs vapor compression distillation on pretreated crew urine to recover ~85% of water from pretreated urine [ref. 48]. Peristaltic pumps are used to deliver pretreated urine, brine, and distillate. The next generation of pumps will have alternate designs, but were not evaluated as they have not been implemented. As illustrated in Figure 11 [ref. 47], the SPA separates free water from the DA vent gases; the separated liquid is combined with the distillate stream and the separated gases vented to cabin. Bellows tanks are used to store pretreated urine and concentrated urine brine (i.e., Advanced Recycle Filter Tank Assembly, Wastewater Storage Tank Assembly).

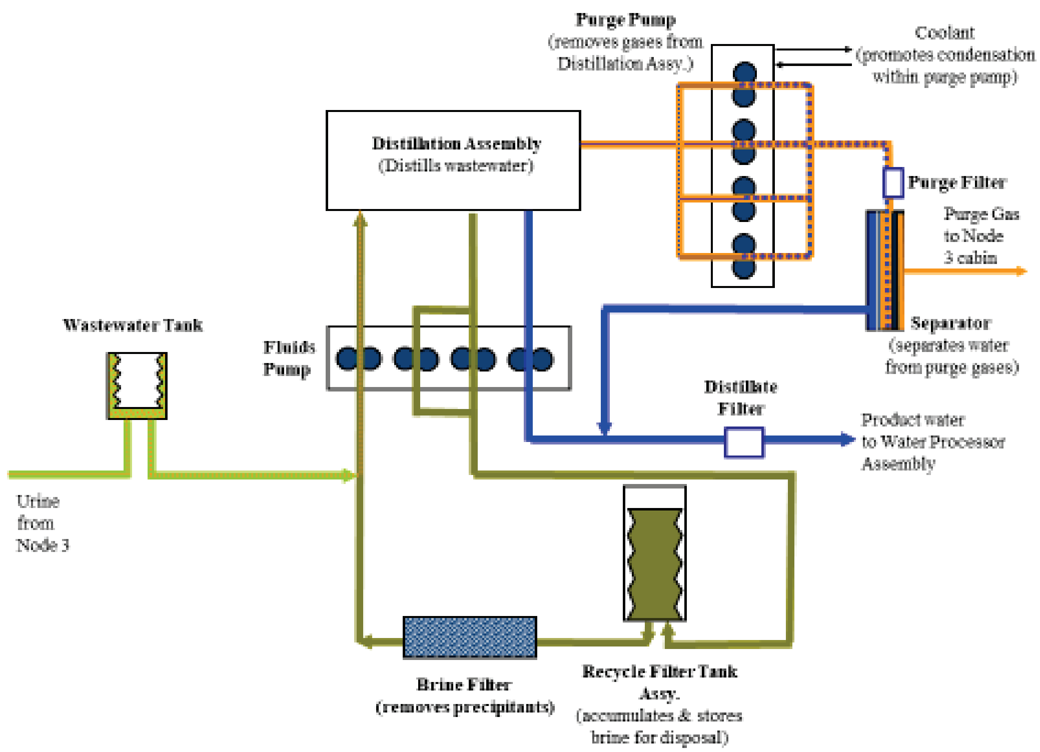


***Figure 11. Simplified UPA Schematic***

***Performance***

Performance of the distillation assembly is not anticipated to be impacted due to pressure decrease. Fluid pressures are not expected to change due to ambient pressure change, or to be slightly affected in the case of ambient-referenced bellows and mitigated. The UPA is anticipated to recover water nominally in Exploration with minimal changes.

The SPA is a hydrophobic membrane gas/liquid separator used to recover water in the purge gas from the DA and return it to the Fluids Control and Pump Assembly (FCPA) product water line. Separated gases are vented to cabin, and the gas side of the membrane is exposed to ambient cabin. The gas separation efficiency of the UPA's SPA may be decreased due to a lower shell-side pressure (i.e., reduced driving force) if the FCPA is vented to a reduced pressure cabin (*F-23*).

Some pressure switches will be impacted (e.g., in the SPA). However, these may be mitigated through set point recalibration.

The UPA system pressure is set by the Wastewater Storage Tank Assembly (WSTA) and fluid pumps and could be decreased via impacts to WSTA bellows tank. This is not likely to present downstream impacts to the UPA, as the system pressure is predominantly determined by the FCPA following the WSTA, and any pressure changes caused by WSTA may be negligible. This may present upstream issues for the UWMS urine separator. Larger impacts may be mitigated though modification of bellows.

An important note for Exploration environments as they relate to UPA is source contamination control. DA gases are purged through the SPA and vented to the cabin. As the source of DA feed is pretreated urine, this vent gas will contain trace contaminants. At a low flow rate, venting of the SPA may present an issue of odor and contaminant accumulation in Exploration-sized vehicles. As such, cabin venting may require source (or point-of-use) contamination control for Exploration missions (*O-5*).

***Thermal***

UPA is primarily liquid-cooled via process fluid. However, some level of cooling occurs from natural and forced convection. There may be a higher steady-state temperature of the UPA hardware as a result of decreased air density that could be mitigated via AAA cooling.

***Qualitative M&P Evaluation***

The UPA is predominantly metallic, apart from Teflon-insulated electrical cables. Solimide AC-550 polyimide thermal insulation and Bisco HT-200A barium-sulfate-filled silicone acoustic insulation are used internally. These materials are nonflammable to 30% $O_2$, 10.2 psia, but are likely flammable in a 34-40% $O_2$, 8.2 psia environment) *(F-12c)*. Although flammable, these materials may be acceptable because they are contained within the metallic exterior. If nonflammable thermal insulation is required, the Solimide AC-550 could be replaced by Solimide HT-340 or Zotek F30, which are acceptable for 34-40% $O_2$, 8.2 psia environments according to existing data [ref. 96]. Silicones are usually flammable in 30% $O_2$, 10.2 psia, but Bisco HT-200A is nonflammable to at least 34% $O_2$.

The UPA is acceptable for toxic offgassing in Exploration vehicle volumes.

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, were not assessed.

### 7.2.14 Universal Waste Management System

***Description***

The UWMS, shown in Figure 12 [ref. 49], collects and separates crew waste in microgravity using airflow drag. The UWMS features a commode seat for crew use and airflow within the commode to collect solid waste into a fecal bag for disposal. A hose and funnel assembly, which is handheld by the crew, is used to collect liquid waste (i.e., urine) via airflow drag. Collected urine is pretreated with a chromic acid solution to mitigate microbial concerns and sent to a rotary separator to remove air. Pretreated crew urine is delivered to the UPA WSTA for storage and processing. The airflow through the commode and urine funnel is driven by a fan contained in a shared assembly with the urine separator. The system, diagrammed in Figure 13 [ref. 41], features redundant fans. Packed beds within the commode featuring GAC and other sorbents are used for odor capture from air exiting the commode and urine separator [refs. 39, 50].

***Figure 12. UWMS Configured for ISS***

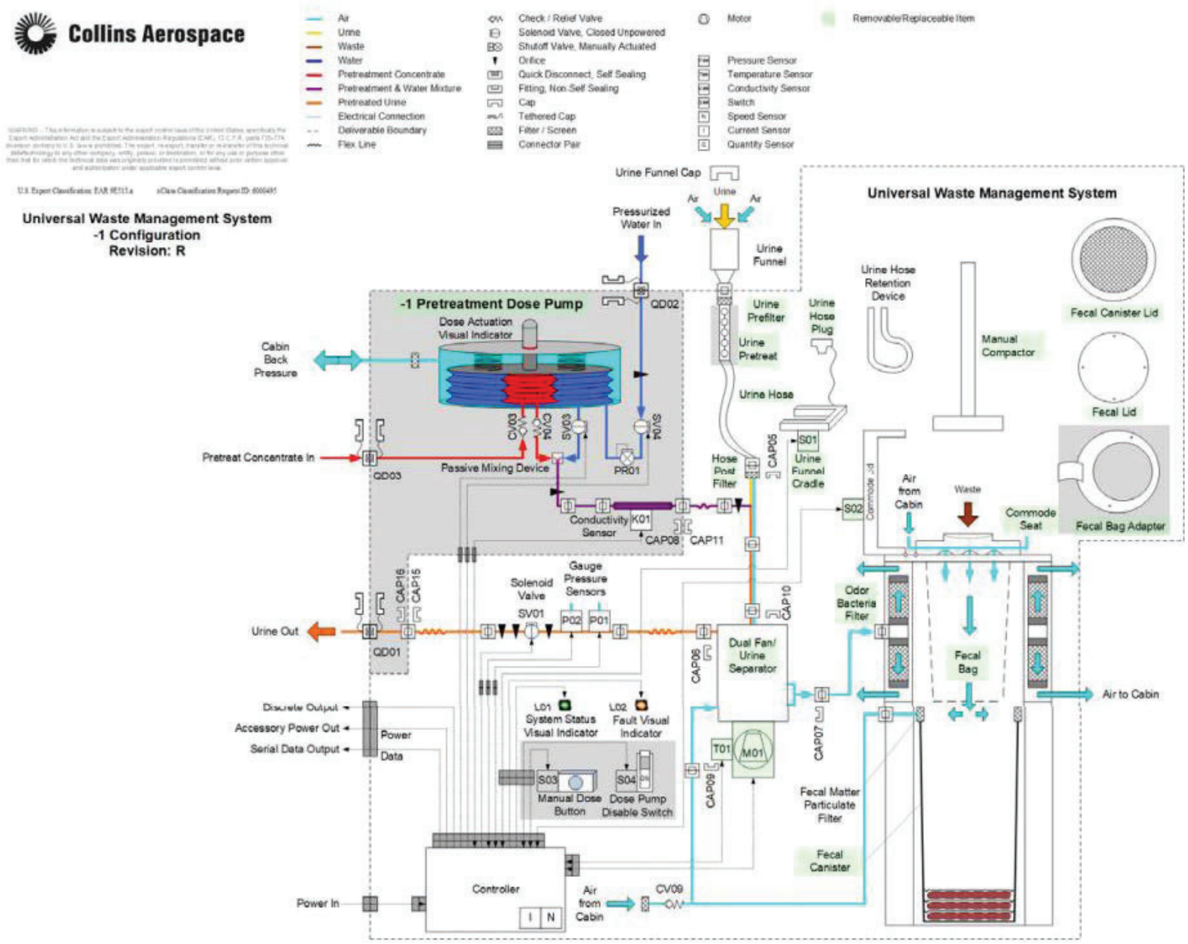


*Figure 13. UWMS Schematic*

### *Performance*

For constant fluid velocities, the drag force exerted by airflow to move liquid and solid waste in the UWMS will be decreased in Exploration environments, which will decrease the effective capture of this system *(F-24)*. The required force to capture wastes is unknown. This impact can likely be mitigated through increased flow rates, though density impacts will still be inherent to the fluid flow (*Appendix A, item n)*. Further, decreased performance of the internal fan is expected without aerodynamic redesign.

The odor adsorption system may have reduced performance due to kinetics, which may necessitate GAC bed dimensional changes to mitigate the loss in performance. There are no anticipated impacts to capacity caused by pressure.

Additional impacts to urine/air separation may also occur due to a change in ambient pressure, resulting in decreased water/gas separation efficiency. The backpressure on the urine/air separator from the WSTA bellows tank is used to limit the quantity of air entrained in the urine at the outlet of the urine/air separator. A decrease bellows tank pressure may allow additional gas in the liquid urine, which will affect UPA performance.

Additionally, the pretreatment dose pump utilizes the ambient cabin backpressure and pressurized water to inject pretreatment solution into urine. This reference to the cabin may lead to Exploration environment performance impacts due to decreased atmospheric pressure.

***Thermal***

The UWMS urine/air separator motor and electronics are cooled via airflow. Convective cooling will be decreased and likely result in higher steady-state temperatures, possibly exceeding component specifications or touch-temperature limits *(F-9, F-10)*. This concern can be mitigated through increased airflow rates needed for capture impacts, but additional AAA flow may be needed depending on usage frequency.

The GAC bed may experience decreased cooling due to the decrease in natural and forced convection, causing higher steady-state temperatures and potentially decreased capacity *(F-4)*. This effect is likely negligible, but could be mitigated through increased cooling (e.g., increased velocities, AAA flow).

***Qualitative M&P Evaluation***

The UWMS commode structure is aluminum, but the UWMS has several exposed polymeric materials that would be potential issues for Exploration atmospheres. The hardware is certified for 24.1% $O_2$ at 14.7 psia, but with the possible exception of the urine hose assembly, is acceptable to 30% $O_2$ at 10.2 psia. The fecal canister lid is likely flammable beyond 30% $O_2$ at 10.2 psia, but may be small enough to be acceptable. The urine hose appears to be covered by Halar sleeving and is likely acceptable for 30% $O_2$, 10.2 psia, but will likely be flammable in 34-40% $O_2$ at 8.2 psia. The Velcro strips inside the fecal canister are longer than allowed by the standard Velcro rules [ref. 21], but are internal to the canister and not considered a concern.

The UWMS will require reassessment for toxic offgassing in smaller volumes than ISS, and some or all components are likely to require testing at the component level for Exploration vehicles and habitats *(O-3b)*.

***Components not assessed***

The solid-liquid separator, separator motor, and specific piece parts, including valves and temperature and pressure sensors, were not assessed.

### 7.2.15 Water Processor Assembly

***Description***

The WPA processes wastewater on the ISS and supplies the crew with potable water. The assembly utilizes multiple processes to remove different contaminants from wastewater.

Wastewater, from humidity condensate, UPA distillate, and Sabatier product water (when the CRA is installed and operational) is stored in a wastewater bellows tank prior to processing. During processing, wastewater flows through the Mostly Liquid Separator (MLS), a rotary separator, to remove gas bubbles. Removed gases are passed through a filter to remove odorous compounds and vented to the cabin. The degassed wastewater is pumped through a particulate filter and two multifiltration beds in series. The partially processed water is passed through two HXs and preheated before being injected with $O_2$ and flowed to a packed bed catalytic oxidizer. Here, low MW compounds are oxidized to $CO_2$/carbonate/bicarbonate products. A membrane gas-liquid separator removes unreacted $O_2$ and vents to the cabin. The product water is passed through ion-exchange beds and dosed with iodine biocide before passing through a conductivity sensor to determine acceptability. If acceptable, the water is stored until needed. If unacceptable, the water is reprocessed [refs. 51, 52].

***Performance***

The WPA MLS contains low- and high-level sensors to monitor water quantity. These sensors will be exposed to a change in gas-core volume that may affect performance *(F-25)*.

This potential performance impact would be due to a change in molar volume of the gas core associated with lower pressure. This impact is unlikely to have serious effects, and worst-case would be repositioning of low, low-low and high, high-high level sensors.

The Gas Liquid Separator (GLS) is a membrane separator used to remove excess $O_2$ from the catalytic oxidizer effluent. It uses cabin air as a sweep gas and vents the effluent to the cabin.

The gas-side pressure in the WPA GLS will be decreased in Exploration environments, effectively increasing the pressure gradient across the membrane. This is likely to result in an increase in separation performance as the driving force for separation is increased. However, the system could experience a decrease in catalytic oxidizer efficiency and potential flow issues throughout the water processing loop. It is not clear how the competing changes of increased membrane separation performance and decreased catalytic oxidizer performance will affect WPA system performance.

The wastewater ORU tank is used to store wastewater waiting to be processed by the WPA and in part sets the downstream system pressure. As mentioned, ambient referenced bellows tanks combine the ambient pressure and the pressure of their bellows (i.e., spring/stiffness) into the fluid pressure. Downstream of the wastewater ORU, the pumps add a specific delta pressure to the fluid, so the operating fluid pressure is set by the bellows pressure plus the pump delta pressure. The pressure at all systems downstream is determined by the supply pressure less any pressure drop through the lines and components. For Exploration, the bellows pressure will be decreased as the ambient pressure is decreased, resulting in decreased supply pressure to the system pump. Possible mitigations include modifications to the spring force of the bellows tank to compensate for the reduced ambient pressure and/or modifications to the design or operation of the pump.

***Thermal***

The WPA, its components, and its avionics are largely liquid-cooled through the process fluid. However, there will be convective thermal impacts to the GLS due to decreased air density of AAA coolant. The reduced cooling capability could be mitigated through increased AAA flow or potentially increased coolant in the liquid HXs.

***Qualitative M&P Evaluation***

The WPA is primarily composed of metallic parts. Notable exceptions include electrical cables and insulation. Electrical cables are Teflon-insulated and nonflammable beyond 40% $O_2$. Solimide AC-550 polyimide thermal insulation is used internally. It is nonflammable to 30% $O_2$, 10.2 psia but flammable in Exploration environments (34-40% $O_2$, 8.2 psia). Bisco HT-200A is used in the system and is likely flammable. Although AC-550 and HT-200A are flammable, they are likely acceptable because they are contained within the metallic exterior. If nonflammable thermal insulation is required, then Solimide AC-550 could be replaced by Solimide HT-340 or

Zotek F30, which are acceptable for Exploration environments according to existing data [ref. 96].

The WPA would likely be acceptable for toxic offgassing in all Exploration vehicle volumes.

***Components not assessed***

Specific piece parts, including valves and temperature and pressure sensors, were not assessed.

## 7.3 Crew Health Care System

The ISS CHeCS is a suite of hardware with the medical and environmental capabilities necessary to ensure the health and safety of crew members during missions. CHeCS is divided into four subsystems:

1. The Countermeasures System (CMS) is composed of equipment and protocols for daily exercise regiments required to mitigate the deconditioning effects of living in a microgravity environment.
2. The Environmental Health System (EHS) monitors chemical and microbial species in the air, water, and surfaces of the habitable volume of the ISS. In addition, the acoustic environment is monitored not only to mitigate potential hearing loss, but also to monitor potential changes in fan performance.
3. The Health Maintenance System (HMS) provides in-flight life support and resuscitation, medical care, and other health monitoring capabilities.
4. The Radiation System (RAD) monitors the radiation environment on board the ISS and continuously monitors the accumulated radiation dosage for each crew member during every mission.

ISS hardware is certified to operate safely at nominal conditions, which is typically 14.7 psia with 21% $O_2$. For hardware used during EVA prebreathe operations, certification to operate safely at a minimum pressure of 9.5 psia and a maximum $O_2$ concentration of 100% is required. The Portable Oxygen Monitor (POM) in EHS is the only CHeCS hardware used during prebreathe operations. It should be noted that requirements levied by an ISS mission and the ISS vehicle are different from those levied on Exploration-class missions and vehicles. Key factors (e.g., size, operational concept, and maintenance logistics) and operating pressure and $O_2$ concentration will change, making some ISS CHeCS hardware unusable even if compatible with an Exploration atmosphere.

Other considerations in assessing CHeCS hardware include:

- ISS CHeCS hardware with identified obsolescence issues was not included in this assessment.
- Consumables (e.g., syringes, sample hardware, pipettes, pipette tips) were not part of this assessment since they are likely to change in Exploration-class missions, requiring recertification.
- Since the required diagnostic hardware for missions beyond low-Earth orbit has not been determined, the medical diagnostic hardware in the ISS HMS was not assessed. Contributing to this decision was the age of existing hardware and degree of obsolescence. It is likely that alternate hardware will be used in future missions when diagnostic needs are determined.

- Due to the size, logistics issues, and degree of obsolescence, the current exercise hardware maintained by ISS CMS was not assessed. However, an attempt was made to assess exercise hardware (i.e., flywheel exercise device) in development for future missions based on the available information.
- The assessment of ISS radiation monitoring hardware was limited to the CAD, because of its planned use in missions beyond low-Earth orbit, and to the HERA. An attempt was made to assess CAD and HERA, despite their development status, based on the information available.

Most of the hardware in CHeCS can be considered as analytical instruments used to measure particular physical properties. These properties may be the concentration of a gas in the cabin atmosphere, the concentration of microbes on a waste management system panel surface, a crew member's heartbeat and blood pressure, or interocular pressure impinging on a crew member's optic nerve. Regardless of the physical property measured, instrumentation requires calibration to translate electrical signals into a measured physical property used by flight surgeons and subject matter experts for diagnosis and assessments. It should be noted that the accepted best practice for the calibration of analytical instrumentation is to use operating conditions to account for differences between the laboratory (i.e., in-shop/bench calibration) and where the instrument will be used (i.e., field calibration) [ref. 53]. As such, it is assumed that all analytical instruments used for Exploration will be calibrated under the conditions of their intended operation.

Alternatively, instruments calibrated at nominal atmospheric pressure and $O_2$ concentration, 14.7 psia and 21% $O_2$, respectively, can apply correction factors to account for any differences when operations are at lower pressures and high $O_2$ concentrations. However, the challenges of calibrating at lower pressures and higher $O_2$ concentrations must be accurately weighed against the challenges of generating correction factors. Field calibration is not practical during missions due to the added crew time, materials and hardware, and complexity of performing the task. In-shop/bench calibration is the most viable option, whether calibrating under operating conditions or generating correction factors [refs. 54, 55].

### 7.3.1 Acoustic Monitor

***Description***

The ISS AM is a COTS unit manufactured by Svantek, P/N SV102A+, and used without modifications (shown in Figure 14). Its primary purpose is to measure ambient sound levels and crew noise exposure, characterize the internal acoustic environment, ensure hardware acoustic levels are being met, and assist in the implementation of effective countermeasures to reduce or eliminate crew exposure to high noise levels. The AM is part of a kit containing the monitor hardware, mini-USB cable, microphone/pre-amp cable, windscreen, and belt pouch.

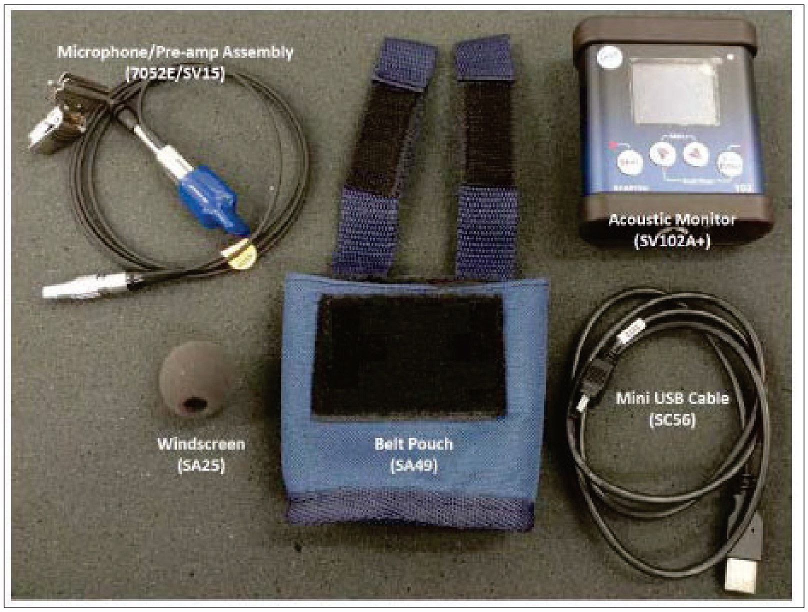


***Figure 14. ISS COTS AM, made by Svantek***

***Performance***

The AM was not certified to pressures and $O_2$ concentrations beyond the nominal ISS levels of 14.7 psia and 21% $O_2$, respectively [ref. 56]. However, the same hardware is planned for use in future Artemis missions and delta certification testing is planned. It is expected, however, that the acoustic environment will become quieter at lower pressures. The intensity of sound drops with decreasing pressure [ref. 57], and the lower pressures and higher $O_2$ concentration of an Exploration atmosphere is expected to have minimal impacts on hardware performance. Initial microphone response testing has shown that reduced ambient pressure (i.e., 14.7 psia) results in higher microphone output voltage and higher recorded sound pressure levels. These initial results suggest that the correction would be negative in terms of sensitivity. Performance testing at 8.2 psia/34% $O_2$ and 10.2 psia/26.5% $O_2$ will be performed as part of the delta certification for Artemis missions to determine the magnitude of all the impacts.

***Thermal***

No information was available for the COTS acoustic monitors to assess thermal impacts of an Exploration atmosphere.

***Qualitative M&P Evaluation***

The AM has an aluminum case, which suggests it would be acceptable for Exploration environment flammability concerns. The cables, including the microphone/preamp cable and the mini USB cable, are flammable. A more robust cable wrap (wrapping with Nomex and then overwrapping with Nitto P-212 glass cloth tape exists that will work for atmospheres up to 30% $O_2$ at 10.2 psia, but probably not for higher $O_2$ concentrations. The belt pouch is flammable in Exploration atmospheres, but is acceptable to 30% $O_2$ at 10.2 psia. A custom pouch would be needed for higher $O_2$ concentrations. Offgassing testing was not required for the ISS, but is probably necessary for Exploration vehicle volumes *(O-3c)*.

***Components not assessed***

All parts of the kit were assessed for flammability concerns.

### 7.3.2 Anomaly Gas Analyzer

***Description***

The AGA, shown in Figure 15, is a portable, battery-powered device that measures and displays the concentration of specific atmospheric constituents. The AGA integrates two forms of spectroscopy into a single unit to measure gases. A Teflon integrating sphere is employed as a multi-pass, optical cell to measure the concentration of $CO_2$, $O_2$, hydrochloric acid (HCl), hydrofluoric acid (HF), and ammonia ($NH_3$) in the cabin atmosphere by absorption spectroscopy. In addition, a photo-acoustic cell is employed to measure the concentrations of CO, hydrogen cyanide (HCN), and hydrazine ($N_2H_4$) by photoacoustic spectroscopy. The AGA will monitor cabin pressure, temperature, and water vapor concentration.

The AGA has two crew selectable modes of operation: post-landing mode and on-orbit mode. In post-landing mode, the AGA will monitor and display $CO_2$, $NH_3$, and $N_2H_4$ for a minimum of 10 hours without changing batteries. In on-orbit mode, the AGA will monitor and display CO, HCl, HCN, HF, $CO_2$, $O_2$, and $NH_3$ for a minimum of 10 hours without changing batteries.

Tunable Diode Lasers (TDLs) will be used to detect specific gases in the cabin atmosphere. Each gas preferentially absorbs light of a particular wavelength unique to the gas of interest, and each TDL was chosen to match these unique wavelengths to detect a specific gas. Interactions between molecules of each gas and the appropriate laser results in a decrease in light intensity as it traverses the integrating sphere. This decrease is measured by detectors in the integrating sphere and related to concentration by a Beer's Law relationship. The photoacoustic cell also uses TDLs to measure specific gases, but in a different manner. As a consequence of the interaction of the laser light with the gas molecules, a pressure wave is created. In a temperature-regulated, vibrationally isolated cell, this pressure wave can be measured with a transducer and the magnitude of the pressure is related to the concentration of the gas in the photoacoustic cell.

***Figure 15. Anomaly Gas Analyzer Mounted in MPCV CM***

TDL spectroscopy is extremely stable regarding calibration. Periodic recalibration of the AGA for the currently planned mission durations will not be required, greatly improving its maintenance logistics. This is based on the robustness of the solid-state optical components and the design and build of the optical platform. In addition, operational experience with the ISS POM, which employs TDL spectroscopy with a multi-pass optical cell, has shown calibration to be stable for at least 3 years based on current maintenance logistics. The lasers will be contained within the photoacoustic cell or the integrating sphere, which are contained within the AGA structure [ref. 58].

***Performance***

The end-item specification of the AGA requires an operating pressure range of 10.2-15.2 psia. This specification does not require AGA to operate in $O_2$ concentrations other than nominal ISS levels of 21% [ref. 59].

Key components of the AGA (e.g., TDLs, photodetectors, pressure transducers, and photoacoustic cell) are not expected to be significantly impacted by operating in an Exploration atmosphere. Preliminary testing [ref. 97] of the AGA at lower pressures (i.e., 10.2 psia) and elevated $O_2$ concentrations (i.e., ~28% $O_2$), suggested that higher $O_2$ concentrations may cause the system to under-report contaminants due to effects to the photoacoustic signal (*F-26*). It has been postulated that this observation is the result of a change in the pressure wave velocity across the photoacoustic cell due to the greater number of $O_2$ molecules [ref. 60]. Lower pressures are expected to affect the pressure wave and acoustic monitor in the same way. Nevertheless, the initial calibration of the AGA under the conditions in which it will be used should account for the lower pressures and greater $O_2$ concentrations of an Exploration atmosphere.

***Thermal***

Internal fans are used to maintain operating temperatures inside the AGA. TDLs and the photoacoustic cell use thermo-electric plates (i.e., conductive heat transfer) to maintain operating temperatures, while lower pressures and higher $O_2$ concentration are assumed not to significantly impact the fan cooling.

***Qualitative M&P Evaluation***

The AGA is housed in a metallic box, so will probably be acceptable for flammability. However, the internal electronics will be flammable and the AGA does have fan cooling, which makes the ability of the box to contain a fire in Exploration atmospheres somewhat uncertain. The AGA is not yet certified for M&P, but is currently planned for use in the ISS and MPCV, so the final design will have to meet flammability and toxic offgassing requirements in the MPCV 30% $O_2$ at 10.2 psia worst-case atmosphere *(O-3d)*.

***Components not assessed***

For ISS operations, the AGA will interface with one pump/probe (i.e., ISS Support Equipment P/N SEZ33125604) that will be used for sampling the atmosphere behind a rack face via the ISS fire ports. The AGA pump will be battery-powered and used in conjunction with the AGA probe. The AGA and pump are powered by batteries, specifically BP975s. None of these components were assessed.

### 7.3.3 Air Quality Monitor

***Description***

The AQM, shown in Figure 16, is a gas chromatograph-differential mobility spectrometer (GC-DMS) used for analysis of trace volatile organic compounds (VOCs) in the cabin atmosphere.

The GC separates the trace contaminant mixture present in the air sample via a temperature-programmed, two-phase separation (gas/solid) mechanism. As the individual contaminant exits the GC, it is ionized with a Ni-63 source (beta-emitter) and fed into the DMS cell comprised of two sets of orthogonal plates. Each set in the DMS cell generates a unique compensation and radio frequency (RF) voltage combination for each contaminant. When calibrated, the ionized contaminant can traverse the DMS cell without impinging on the plates, making contact only with the detector and generating a signal proportional to concentration [refs. 61, 62].

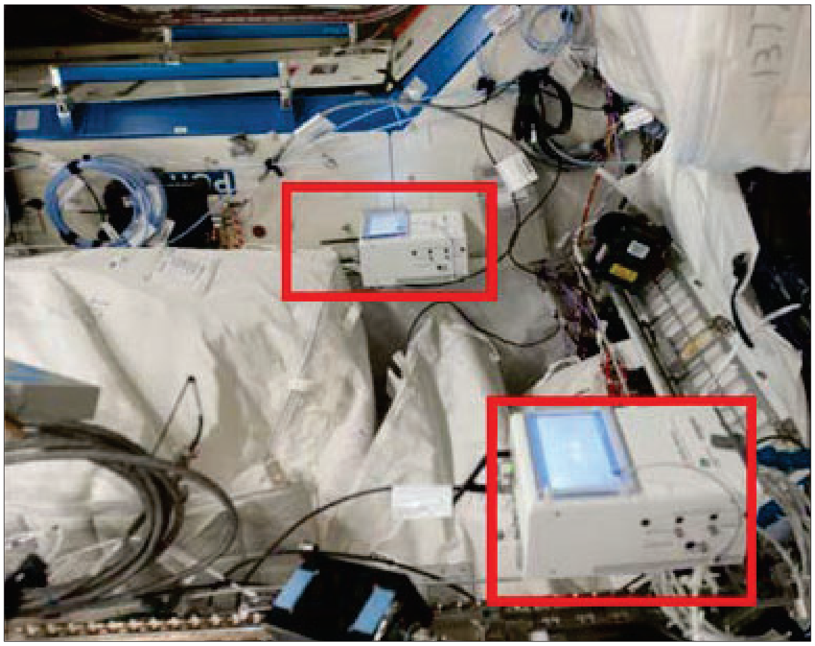

***Figure 16. Air Quality Monitors in ISS Node 2***

### *Performance*

The AQM requirement and verification document [ref. 63] requires an operational pressure range of 10.2-15.2 psia. This document does not require AQM to operate in $O_2$ concentrations other than nominal levels of 21%.

Because the AQM uses filtered cabin air as the mobile phase in the GC separation process, the higher $O_2$ levels may affect the solid phase separating capability efficiency as compared to nominal $O_2$ levels. While this may be mitigated by a modified ground calibration process, it may result in different solid phase material (i.e., a different GC column), and/or a longer GC column to achieve the needed separation for a reliable analysis.

Higher $O_2$ levels potentially may impact the ionization process required for DMS analysis. Ionization of each contaminant occurs by a charge-transfer process with atmospheric species (i.e., typically water and $O_2$) ionized with the Ni-63 source. Higher $O_2$ levels may change the concentration of these reactant ion species in an Exploration atmosphere. Lower pressures may impact the trajectory of the ionized analyte through the DMS cell, thereby altering the compensation and RF voltages unique to each ionized contaminant as compared to nominal ISS atmospheres at 14.7 psia and 21% $O_2$ [ref. 64] *(F-27a)*.

*Thermal*

Lower pressures and higher $O_2$ values will impact GC temperature-programmed separation due to changes in thermal conductivity. Typically, GC column temperature is ramped up using a heater wrapped around the coiled GC column to induce gas mixture separation. Heat removal efficiency during the cooling process at the end of the temperature program will impact how long the GC run will take, affecting the total time required per analysis. A decrease in internal cooling efficiency due to dust-clogged vents has resulted in missed analyses of the ISS cabin atmosphere [ref. 98].[2] The clogged vents prevented the GC column from cooling to a set starting temperature in an allotted time, thus preventing the AQM from starting subsequent analyses. Vent cleaning by the crew, typically by vacuum, restored full functionality by restoring the AQM's full thermal regulating capability. In summary, AQM GC column cooling will be less efficient in reduced-pressure Exploration environments, requiring increased sample times for cabin gas composition analysis *(F-27b)*.

*Qualitative M&P Evaluation*

The AQM has an aluminum housing that should be acceptable for flammability concerns. The polycarbonate display window will be acceptable for flammability in Exploration atmospheres to 30% $O_2$ at 10.2 psia, but will be flammable at higher $O_2$ concentrations. The display exposed surface area is about 24 square in., so it does not meet the JSC 29353 exemption for small quantities of flammable materials. However, it may be acceptable with a MUA based on separation from credible ignition sources. The power cables are Teflon-insulated and acceptable for flammability in Exploration atmospheres, but the polyimide flag labels are flammable and need to be replaced.

Based on the existing toxic offgassing data, a single AQM is acceptable for vehicles with a volume greater than 20 $m^3$, but offgassing would have to be reassessed for vehicles and habitable structures with smaller volumes *(O-3e)*.

*Components not assessed*

Components key to AQM operation that were not assessed include the external power supply, the sieve cartridges used to filter recirculating cabin air used in GC mobile phase, and associated cables.

### 7.3.4 Crew Active Dosimeter

*Description*

CADs are COTS direct ion dosimeters [ref. 65] that measure radiation exposure, convert data to digital format, and transmit the data via Bluetooth low energy to a powered laptop. CADs measure the local radiation environment and store absorbed dose internally and provide time-resolved data and crew feedback in near-real-time. They are designed to be carried in a crew member's pocket or worn clipped to their clothing. A visual display provides crew feedback. The primary advantages of the CAD, shown in Figure 17, include good sensitivity; low power use;

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[2] A change in cleaning frequency was requested due to dust buildup inside AQM. Prior to this request, additional cleaning of AQMs handled in real time using chits to request crew-time for the non-scheduled task. Because of the frequency of this incident, the team decided to formally change the frequency of the AQM cleaning task to address the blocked vents and resulting thermal issue.

and a simple, rugged design. Overall, the CAD is not expected to be impacted by low pressure and increased $O_2$ environments *(F-1b)*.

***Figure 17. Lab Unit CAD***

***Performance***

CAD is based on COTS technology and was accepted for the ISS using a simplified certification process [ref. 66]. No certification testing was performed for operation outside ISS nominal pressure and $O_2$ concentration of 14.7 psia and 21%, respectively.

However, the reduced pressure and increased $O_2$ concentrations are not expected to change the performance of the CADs due to the enclosed and hermetically sealed chamber where the measurement occurs. CADs are planned for future Artemis missions, and are expected to undergo delta certification to confirm prior to flight.

***Thermal***

No information was available for the COTS radiation monitors to assess thermal impacts of an Exploration atmosphere. Thermal impacts are expected to be assessed as part of the delta certification planned for future Artemis missions.

***Qualitative M&P Evaluation***

The CAD body is made of Ultem 1000, which is not flammable in 30% $O_2$ at 10.2 psia, but flammable in 34-40% $O_2$ at 8.2 psia. However, flammability is not expected to be a concern as the dimensions of 0.67 x 1.46 x 0.33 in., with no propagation path or ignition source, and below the threshold for flammability control for IVA items per NASA-STD-6016.

Because of the CAD size, toxic offgassing will not likely be a concern for Exploration vehicles.

***Components not assessed***

The USB dongle was not assessed.

### 7.3.5 Colorimetric Water Quality Monitoring Kit

***Description***

The CWQMK is a diffuse reflectance spectrophotometer used to determine iodine concentrations in the water dispensed from the potable water dispenser (PWD) on board the ISS. Water on board the ISS is iodinated to prevent microbial growth. Prior to dispensing for crew use, the iodine is removed to limit the amount the crew consumes. Excessive iodine is a crew-health issue. Water from the PWD is applied to a reagent-impregnated membrane. The reagent reacts with any iodine in the water, and a color change occurs proportional to the iodine concentration. The intensity of the color change is measured by diffuse reflectance spectroscopy, which is a form of absorption spectroscopy. The CWQMK, shown in Figure 18, is a COTS device, and the reagent-impregnated membranes are procured from the manufacturer [refs. 67-69]. Overall, the CWQMK hardware is not expected to have performance, thermal, or materials impacts due to decreased pressure or increased $O_2$ concentrations *(F-1c)*.


***Figure 18. CWQMK Spectrophotometer for Biocide Analysis***

### *Performance*

While the CWQMK was certified not to generate a hazard at low pressures during depressurization, no certification testing was performed for operations outside nominal pressure of 14.7 psia and there is no requirement to operate outside the nominal 21% $O_2$ concentration [ref. 70].

An Exploration atmosphere is not expected to affect CWQMK operation. Materials re-certification will be needed for the elevated $O_2$ levels. There are membranes specifically for iodine, used in the ISS U.S. segment, and silver, used in the ISS Russian segment. The iodine membranes are coated with PVP (polyvinylpyrrolidone), and the silver membranes are coated with DMABR/Brij-30 (i.e., 5-(p-dimethylaminobenzylidene) rhodanine and polyoxyethylene (4) lauryl ether). The chemistry of the reagent/iodine reaction have not been investigated to evaluate the effects of elevated $O_2$ levels and lower pressures on reaction rates. $O_2$ permeability of the packaging material may accelerate oxidative degradation of the membranes required for the analysis, but testing would be necessary to quantify impacts on shelf life.

Exploration atmosphere pressures and $O_2$ concentrations are not expected to impact the operation of CWQMK. However, it is undetermined of the Exploration pressure and/or $O_2$ concentration will affect the CWQMK chemical reactions or the packaged reagent shelf life *(F-28)*.

### *Thermal*

Since CWQMK was not required to operate outside of 14.7 psia and 21% $O_2$, thermal impacts to its performance is unknown. Nevertheless, impacts to the operations of the diffuse reflectance spectrometer are unlikely. The key components of the spectrophotometer (i.e., light source and detector) are solid-state with negligible performance impacts anticipated at lower pressures and higher $O_2$ concentrations.

*Qualitative M&P Evaluation*

The CWQMK is contained in a pouch, the outer surface of which is Durette fabric, acceptable for flammability at $O_2$ concentrations up to 30% at 10.2 psia, but not for higher concentrations. Most of the items inside the pouch are flammable, even in the ISS environment. However, use of the hardware inside the pouch is limited (i.e., 75 minutes a day, four times per year), the hardware is crew-tended while in use, and the kit contains no credible ignition sources (the spectrophotometer is powered by alkaline batteries, which have insufficient power to ignite solid materials). The flammable materials inside the pouch are assumed to be acceptable for all Exploration atmospheres through operational controls. The outer fabric of the pouch would need to be changed for $O_2$ concentrations above 30%, but standard textiles that meet flammability requirements in Exploration atmospheres are expected to be available.

Based on the existing toxic offgassing data for this hardware [ref. 99], there are no known Exploration vehicles where offgassing is assumed to be a potential issue.

*Components not assessed*

Components key to the analysis of potable water with the CWQMK that were not assessed include sample collection and transfer hardware (e.g., syringes and adapters).

### 7.3.6 Flywheel Exercise Device

*Description*

Human System Integration Requirements (HSIR) specify that any mission longer than 8 days needs to provide each crew member with aerobic and resistive exercise for 30 continuous minutes per day. Exercise should be available to crew as soon as possible and continue throughout all mission phases, except during launch/landing days. This requirement is intended to maintain crew cardiovascular health, maintain muscle mass, and minimize fatigue.

The flywheel device is used by a single crew member at a time, suited or unsuited. It provides rowing capabilities for aerobic exercise and squats, deadlifts, deadlift high-pulls, and bentover row for resistive exercise. To provide this functionality, a system of pulleys and a flywheel, shown in Figure 19 [ref. 71], provides the necessary loads. Straps and harnesses and an exercise bar allow crew members to accomplish the needed exercise. No vehicle power is required for exercise operations. Power is required only for the device sensors that measure displacement, load, and power of exercise. Sensor failure will not prevent operation. A crew-adjustable footplate tailors the device to various crew size.

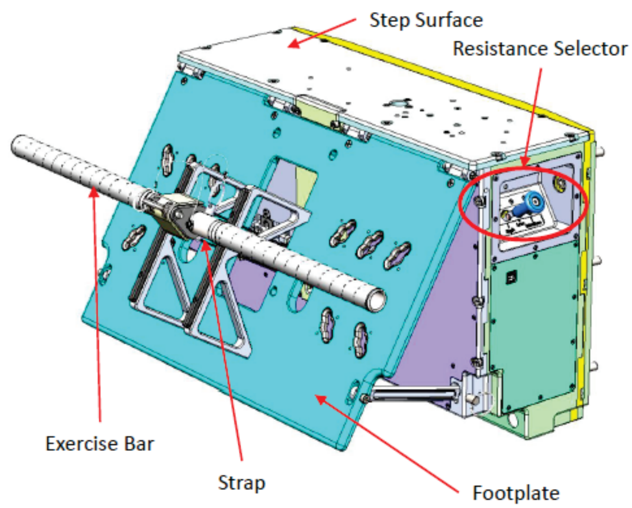


*Figure 19. MPCV Flywheel Device*

***Performance***

Per requirements documentation, the flywheel device is required to operate in pressures from 9.5-15.6 psia. Operation in an elevated $O_2$ atmosphere is not required [ref. 72]. However, it is anticipated that operating the device in an Exploration atmosphere should have no impacts to its function. Aerobic and resistive exercise are provided by the mechanical loads created with straps and a system of pulleys and a flywheel.

***Thermal***

The thermal load of the flywheel device and impacts to its thermal properties are unknown. As such, thermal impacts to the hardware are uncertain *(F-29)*.

***Qualitative M&P Evaluation***

As the flywheel device is in development, a full assessment could not be performed. Its exterior is mainly metallic, so it will likely be acceptable for flammability in Exploration atmospheres. The device strap used by the crew is nylon, which is flammable, but acceptable for MPCV 30% $O_2$ at 10.2 psia because it is crew-tended when in use and, when not in use, contained in the flywheel housing and exposed to the environment for only about 2 in. at the handle connection point. This rationale may be acceptable for higher Exploration atmosphere $O_2$ concentrations. The other straps are also flammable, but contained within the aluminum housing. Toxic offgassing is unknown for Exploration vehicles and habitats.

***Components not assessed***

Neither the straps nor sensors in the flywheel device were assessed.

### 7.3.7 Hybrid Electronic Radiation Assessor

***Description***

The HERA system is an active ionizing radiation area monitoring system for the habitable volume of crewed vehicles. It will provide radiation data and caution and warning capability without the immediate need for ground communication. Additionally, the data are used in risk assessments to estimate physiological consequences to the crew from radiation exposure during spaceflight.

HERA measures the time-resolved absorbed dose rate and flux resulting from the radiation environment. This data, in conjunction with appropriate models of vehicular and body shielding and the radiation environment, will characterize the risk of radiation exposure. Risk characterized during the mission is in the form of acute responses, and after the mission, in the form of risk of exposure-induced death (REID). The radiation environment beyond low-Earth orbit are typically comprised of low intensity and slowly varying galactic cosmic rays (GCR) and sporadic solar particle events (SPEs), for which the probability of occurrence, energy spectrum, and intensity are difficult to characterize. The sporadic nature of SPE necessitates active radiation monitoring so the crew is notified of dangerous conditions. For crewed flights, HERA notifies the vehicle caution and warning when radiation conditions exceed predefined thresholds. This would alert crew members to initiate in-flight procedures directing them to shelter in appropriate locations within the vehicle and notify the mission operations team.

The HERA system is a distributed radiation detection system composed of HERA sensor units (HSUs) and HERA processing units (HPUs). Each HSU contains a radiation detection assembly, a power converter, power supply, and associated electronics for transmitting data to a connected HPU. Each HPU consists of control and data processors, electronic non-volatile memory, RS-422 data hardware, a power converter, and power supply. The system also includes the hardware required to encase and mount the HSUs and HPUs and the cabling necessary to interface with the MPCV power and data units.

The initial flight of the HERA system will be on Artemis I. The same system, coupled to the vehicle caution and warning, will be flown on Artemis II missions and beyond. Overall, no impacts to performance, thermal, or materials due to reduced pressure and increased $O_2$ environments are expected.

***Performance***

Per project requirements, HERA is required to operate from space vacuum to 17.2 psia and an $O_2$ concentration range of 0-40% and cannot be accepted or flight qualified without meeting these requirements. Impacts of an Exploration atmosphere to performance are not expected [ref. 73].

***Thermal***

Per RDWK-10108 Project Technical Requirements Specifications, HERA is required to operate from space vacuum to 17.2 psia and within an $O_2$ concentration range of 0-40%. Impacts of an Exploration atmosphere to thermal properties are not expected.

***Qualitative M&P Evaluation***

HERA is certified for flammability in 40% $O_2$ for use in an MPCV avionics bay with no fire detection or suppression system. Therefore, the HERA would be acceptable for flammability in Exploration atmospheres at this or lower $O_2$ concentrations.

The materials certification assessment of HERA toxic offgassing shows substantial margin for the MPCV vehicle, so toxic offgassing will be acceptable for Exploration vehicles.

***Components not assessed***

RDWK 10108 Project Technical Requirements Specifications for HERA covers requirements for the system encompassing the HSUs and HPUs.

### 7.3.8 MinION

***Description***

MinION is a COTS genetic sequencer developed and manufactured by Oxford Nanopore Technologies that uses functionalized nanopores to determine the sequence of genetic material. Genetic sequencing provides the ability to identify microbes sampled from air and surfaces [refs. 74-76].

MinION is one of the several components in the Biomole Kit, shown in Figure 20 [ref. 77]. The additional pieces of hardware include flow-cells, calibration cells, a mini-polymerase chain reaction (PCR) device, magnetic beads and stands, pipettes and pipette tips, which are used to extract, isolate, and amplify genetic material from microbial samples obtained in the vehicle cabin. Reagents needed to perform the sample preparation and analysis are also included in the kit.


***Figure 20. Components of Biomole Kit Containing MinION Device***
***Components include the device (top left), magnetic stands for sample prep (top right), USB cable , calibration cell, and pipettes and tips (center from left to right), PCR device, USB cable, and power supply for PCR (bottom left to right).***

***Performance***

The MinION/Biomole Kit was not tested to pressures and $O_2$ concentrations beyond the nominal ISS levels of 14.7 psia and 21% $O_2$, respectively [ref. 78]. However, this hardware will be used in future Artemis missions, and delta certification testing will be required. Per the requirements and verifications documents [ref. 79], MinION is required to be functional in atmospheres up to

30% $O_2$. While an operating pressure is not specified, MinION is required to be functional after exposure to 0 psia. No testing has been performed, but the lower pressures and higher $O_2$ concentration of an Exploration atmosphere are not expected to impact hardware performance.

As noted, reagents are also part of the kit. Depending on the permeability of the packaging materials used, higher $O_2$ concentrations may accelerate oxidative degradation of these reagents *(F-28b)*.

***Qualitative M&P Evaluation***

The MinION hardware is flammable in the ISS environment, but was accepted based on its being stowed when not in use, lacking a credible internal ignition source, and having all flammable cables wrapped [ref. 100]. The MinION has a clear PMMA (i.e., acrylic) case, which will not be acceptable for Exploration environments due to flammability concerns. Replacing the PMMA case with a polycarbonate case, wrapping the flammable cables with an existing overwrap design demonstrated to prevent fire propagation in 30% $O_2$ at 10.2 psia or replacing with Teflon cables, and eliminating flag labels may be sufficient to make the hardware configuration acceptable for 30% $O_2$ at 10.2 psia. However, for higher $O_2$ concentrations the MinION would require redesign (*F-30*).

The MinION contains over 20 pounds of polymeric materials, and while it was accepted for toxic offgassing for the ISS, the final configuration would need to be tested for offgassing (with heaters powered) for smaller Exploration vehicles.

***Components not assessed***

All components were assessed.

## 7.4 Crew Systems

### 7.4.1 Cordless Vacuum Cleaner

***Description***

The cordless vacuum certified for ISS operations is the COTS Makita 18V LXT Lithium-Ion (36V) Brushless Cordless Half-Gallon HEPA Filter Backpack Vacuum (P/N XCV09Z). This is a ISS crew requested hardware item that will allow for easier movement throughout the open volume of the station when doing daily housekeeping and other operational tasks across multiple modules without cord interference or the need for power planning and coordination. It is certified to fly on CCP vehicles if soft-stowed in a nonflammable cargo transfer bag [ref. 101]. The batteries are charged using an adapter cup fitted for use in the ISS Universal Battery Charger.

An extensive list of components are certified for use with the Makita cordless vacuum, as detailed in Table 8 and Figure 21.

*Table 8. Makita Vacuum Components*

| P/N | Part Name | OpNom | Mass lbs (kg) | Dimensions L x W x H in (cm) |
|---|---|---|---|---|
| CordlessVac-001 | XCV09Z Makita 18V X2 LXT Li-Ion (36V) Brushless Cordless 1/2 Gal HEPA Filter Backpack Dry Vac | Cordless Vacuum Cleaner | 12.39 (5.63) | 7.25 x 9 x 14.75 (18.42 x 22.86 x 37.47) |
| VacFlexHose-001 | XCV09Z Makita Flex Hose (1" x 39") | Cordless Vacuum Hose | 0.5 (0.23) | 1 x 39 (2.54 x 99.06) |
| BentPipe-001 | XCV097 Makita Bent Pipe | Cordless Vacuum Hose Handle | 0.25 (0.11) | 15 x 1.75 x 1.75 (38.1 x 4.45 x 4.45) |
| HEPAfilter-001 | XCV09Z Makita HEPA Filter | Cordless Vacuum HEPA Filter | 0.14 (0.06) | 6.5 x 4.375 x 0.875 (16.5 x 11.11 x 2.22) |
| DustBag-001 | XCV09Z Makita Filter Dust Bag | Cordless Vacuum Cleaner Bag | 0.08 (0.04) | 10.75 x 13.5 (27.31 x 34.29) |
| LithiumBat-001 | Makita 18V LXT Li-Ion 2.0 AH Battery | 2.0 Ahr Makita Battery Pack | 0.8 (0.36) | 4.24 x 2 x 2.87 (10.77 x 5.08 x 7.29) |
| CreviceTool-001 | 6" Makita Black Crevice Tool | Cordless Vacuum Cleaner Crevice Tool | 0.05 (0.02) | 6.25 x 1.25 x 1.25 (15.875 x 3.175 x 3.175) |
| RoundBrush-001 | 2-3/8" Makita Black Round Brush | Cordless Vacuum Round Brush | 0.1 (0.05) | 4.75 x 2.25 x 1.25 (12.07 x 5.72 x 3.175) |
| ShelfBrush-001 | 3-3/4" Makita Shelf Brush | Cordless Vacuum Shelf Brush | 0.09 (0.04) | 7 x 1.125 x 1.125 (17.78 x 2.86 x 2.86) |
| UBC-SP-200 | Makita Vac UBC Battery Adapter | Makita Battery Pack Universal Battery Charger Adapter | 1 (0.45) | 2.7 x 2.4 x 1.6 (6.86 x 6.1 x 4.06) |
| VacFlexTool Adapter-001 | Makita Vac Flex Tool Adapter | Cordless Vacuum Flexible Tool Adapter | 0.1 (0.05) | 4.25 x 1.75 x TBD (10.8 x 4.45 x TBD) |
| VacHoseCap-001 | Makita Vac Hose Tethered Cap | Cordless Vacuum Hose Cap | 0.1 (0.05) | 2.5 x 1.8 x TBD (6.35 x 4.57 x TBD) |
| DC18RD | MAKITA 18V LXT Li-Ion Dual Port Rapid Optimum Charger | Not Applicable – Ground Units | 4.95 (2.25) | 8 x 14 x 4.25 (20.32 x 35.56 x 10.8) |
| DC18RC | Makita 18V LXT Li-Ion Rapid Optimum Charger | Not Applicable – Ground Units | 2.5 (1.14) | 11 x 5 x 10 (27.94 x 12.7 x 25.4) |


***Figure 21. Makita Vacuum Components***

### *Performance*

Acoustics testing shows that the time of use in low, medium, and high motor speed settings within a 24-hour period is 12.5, 3.5 and 2 minutes, respectively [ref. 101]. Hearing protection is required for medium and high settings, per NCR UHR51740. While it is expected that acoustic impacts will be favorable (i.e., less noise in decreased pressure environment due to decreased air density), the vacuum may require increased fan speeds to adequately clean in reduced pressure environment, thereby further increasing the acoustic risk. Additional performance concerns may exist, but no data is available.

### *Thermal*

During Makita battery testing at JSC/ESTA (WO 1908028), it was shown that the 4-ampere hour (AH) battery failed thermal runaway testing. Thus, only the 2.0 AH Makita Battery

(PN BL1820B) was approved for use with the cordless vacuum. In addition, the vacuum is not stowed with the battery installed.

Touch temperature testing was performed under WO-2001004 for the 0% and 100% blockage scenarios, to establish the worst-case thermal extremes in the medium- and high-power modes of operation on the ISS. Testing showed the temperatures were below the 113 °F worst-case metal surface allowable.

***Qualitative M&P Evaluation***

The various polymeric materials used in construction of the Makita vacuum, associated attachments (i.e., flex hose, bent pipe, crevice tool, round brush, shelf brush, flex tool adapter, and vac hose tethered cap), filter bags, HEPA filters, and batteries were assumed to be flammable in 24.1% $O_2$ at 14.7 psia when the hardware was certified for use on the ISS. The hardware was required to be stowed in a nonflammable locker/container when not in use, in accordance with the ISS Operational Control Agreement Database (OCAD), Fire Event on Board ISS. When in use, the hardware is crew-tended and therefore acceptable. The battery is required to be removed when the vacuum is stowed.

This kind of control of flammable materials (i.e., battery removal during storage and crew monitoring when in use) is reasonable for the relatively low $O_2$ concentration on the ISS, but its acceptability for this relatively large hardware item is uncertain for 30% $O_2$ at 10.2 psia and modifications would almost certainly be required for 34-40% $O_2$ at 8.2 psia (*F-31*).

The vacuum (including accessories) was acceptably tested for toxic offgassing in the ISS volume. It is acceptable in Exploration vehicle and habitat volumes.

***Components not assessed***

None.

### 7.4.2 Crew Quarters

***Description***

The CQ is a permanent personal space for sleep, personal recreation, and communication as well as on-orbit stowage of personal belongings. Each CQ provides acoustic, light, and visual isolation as well as laptop connectivity and radiation protection. The CQ is made of a 6061 aluminum rack exoskeleton with a composite substructure, which is primarily ultra-high MW polyethylene (UHMWPE). The CQ is located in Node 2, rack Bay 5, and interfaces to Node 2 using the standard Node 2 rack attachment points. It was launched in the Mini-Pressurized Logistics Module (MPLM) and transferred to the Node 2 element on-orbit. Electrical power and other utilities required to support CQ illumination, laptop use, fans, command and data handling (C&DH), and Audio Terminal Unit (ATU) voice communications are supplied by the Node 2 element at the rack locations via six interface cables. Passive ventilation is accomplished via cabin air exchange with the node aisle. Two redundant fans provide controllable ventilation and $CO_2$ removal. The fan speed and diffuser orientation are used for heat removal. The General Luminaire Assembly (GLA) provides the ambient and task lighting inside the CQ, and audio annunciation devices (AADs) annunciate Class 1 alarms. The ATU speaker provides audio and Class I, II, and III alarms. Finally, the CQ is covered with removable and replaceable acoustic blankets. Figure 22 shows the CQ Flight unit (SEG32109500-301) in the rack handling adapter during acoustic testing.

***Figure 22. CQ Flight Unit (SEG32109500-301)***

The interfaces between ISS and CQ include cabin air, electrical, caution and warning (C&W), data management, access for a PFE, and structural interfaces.

### *Performance*

Key functions of the CQ include acoustic isolation, light and visual isolation, and radiation protection. The CQ is also equipped with lights and a ventilation system.

Acoustic, light, visual isolation, and radiation protection capabilities are not expected to change due to a change in cabin environmental conditions. However, if material changes are required due to flammability or offgassing concerns, CQ performance may be impacted. The Solid State Lighting Assembly (SSLA) provides light in the CQ. These lights are certified for operation after exposure to hard vacuum and are not expected to be impacted by reduced pressures. Ventilation is provided passively through the door of the CQ and actively through fans. Each CQ has an intake and exhaust fan that provides a combined maximum airflow of 95 CFM and minimum airflow of 58 CFM. Failure of one fan drops the minimum air flow to 44 CFM, which is above the 30 CFM minimum flow rating for air flow in the CQ [ref. 102]. Fans will provide the same volumetric air exchange in the reduced pressure environment, and will be acceptable for the purposes of providing $CO_2$ washout.

***Thermal***

The maximum temperature delta between the ISS Node 2 and the CQs while the crew is awake is required to be less than 9 °F. When the crew is asleep, the temperature delta is required to be less than 5 °F.

The CQ fans will require a design change to increase air movement to maintain temperatures necessary for crew comfort. This redesign may result in a specialty design.

***Qualitative M&P Evaluation***

The CQ side walls and kick panels are constructed of 1-in.-thick sandwich composite panels with a Nomex honeycomb core. This design is acceptable for flammability in 30% $O_2$, 10.2 psia [ref. 103]. The composite showed no signs of burning in this environment, so there is a good chance that it will be acceptable in 34-40% $O_2$ at 8.2 psia. Alternate composite constructions exist that would meet flammability requirements for all Exploration atmospheres. The radiation shielding back wall is constructed of 2-in.-thick polyethylene covered with aluminum foil tape. The tape will protect the flammable polyethylene from burning for $O_2$ levels up to 30% $O_2$, 10.2 psia; there is potential for acceptable operation for 34-40% $O_2$ *(F-12g),* but no empirical data are currently available. The internal and external acoustic and padding blankets with Nomex HT90 fabric and Gore-Tex expanded PTFE fabric as the outermost layers will be acceptable for flammability to 30% $O_2$, 10.2 psia, but are unlikely to be acceptable for 34-40% $O_2$ at 8.2 psia. A fire retardant treatment of the Nomex may be sufficient to make it acceptable. The ventilation system internal acoustic abatements, primarily Soundcoat HT polyimide foam, may be acceptable for $O_2$ levels to 30% at 10.2 psia, but not for 34-40% $O_2$ at 8.2 psia (*F-12c*).

The composite sandwich panels were baked out to meet toxic offgassing requirements in the ISS volume, which suggests that toxic offgassing may be a problem for Exploration vehicles and habitats smaller than the standard ISS volume used for offgassing assessment of 118 $m^3$ *(O-3f)*.

### 7.4.3 Galley Rack

***Description***

The Galley rack is a modified Express Transportation Rack designed to consolidate ICC crew member food preparation and storage in one location. The galley contains the PWD, two refrigerated/frozen stowage volumes for crew food (shown as Microgravity Express Rack Locker/INcubator (MERLIN) units in Figure 23, but replaced in 2020 by Freezer/Refrigerator/ Incubator Device for Galley and Experimentation (FRIDGE) units, and two rack-mounted food warmers.

***Figure 23. ISS Galley Rack Prior to Late 2020***
***Contains two cold-stowage MERLIN lockers (stacked top left), the PWD (top right), two Galley food warmers (side-by-side below MERLIN and PWD), and storage (bottom).***

***Performance***

The Galley rack is cooled via the U.S. Laboratory MTLs, and smoke detection is provided by air exchange with Node 1. The Galley rack was designed to have a minimum operating pressure of 13.9 psia and is automatically deactivated in the event internal cabin pressure falls below this pressure.

On ISS, MERLIN cold stowage was replaced with FRIDGE in 2020. FRIDGE is capable of maintaining internal temperatures from -4 to +118 °F (-20 to +48 °C) [ref. 80]. The system does not require air flow for operation and is isolated from the ambient atmosphere except when opened by the crew. Internal to FRIDGE, the temperature is maintained at the walls through the use of a thermoelectric cooler and the contents are convectively cooled within the compartment volume. The internal bulk volume and content cooling rates may be reduced due to decreased air density, though the absolute cooling capability will likely be unaffected *(F-32)*.

The Galley Food Warmer (GFW) target temperature is 180 °F (82 °C), but is not settable, and internal temperatures can range from 145 to 190 °F (63 to 88 °C) during the warm-up process. With reduced pressure environments, while the ultimate target temperature may be reached, contents may take longer to warm to the desired temperature, affecting meal planning, preparation, and shared meal times.

*Thermal*

The PWD pulls air from the Node 1 aisleway for cooling and discharges the warmed air in the Galley rack. Thermal design considerations in-work for use of the Galley rack in Exploration missions include uprating the PWD fan to move more air and maintain temperatures within the PWD. Similarly, the food warmers discharge heat into the Galley rack. However, there is currently no AAA fan in the rack to dissipate the heat beyond the rack structure. To maintain temperatures within a similarly designed ISS Galley rack for Exploration vehicles and habitats, forced convective cooling or water loop cooling will be required *(F-33)*.

*Qualitative M&P Evaluation*

The PWD front panel, locker, and chassis are aluminum, and most of the internal hardware is also metallic. The internal heater assembly contains Kapton heaters, an Aerogel blanket, and melamine foam insulation, but would be acceptable for flammability in Exploration atmospheres because the flammable materials are enclosed by nonflammable Aerogel blanket and anodized aluminum housing. Even if it were capable of propagating fire, the aluminum body would contain an internal fire. Items on the front panel (e.g., polycarbonate window) would be flammable in 34-40% $O_2$ at 8.2 psia, but they are relatively small and there is no credible ignition source. The PWD is acceptable for flammability in Exploration environments.

The PWD would need to be tested for offgassing if used in small Exploration vehicle volumes (e.g., MPCV CM with 15 $m^3$*)*. Although melamine foam is a concern for formaldehyde release, the quantity used is small enough that it is assumed not to be a toxicity problem. The Aerogel blanket may be a problem based on the data in the materials certification *(O-3g)* [ref. 104].

The ISS Gallery Rack food warmer is mostly aluminum. The primary flammability issue for reuse in Exploration missions is the melamine foam used for thermal insulation inserts. This insulation is acceptable for flammability in 30% $O_2$, 10.2 psia, but will be flammable in 34-40% $O_2$ at 8.2 psia. Solimide HT-340 might be an acceptable replacement for the melamine foam in Exploration applications. The MIUL also mentions a “polyimide enclosure” associated with the heater element, which may be acceptable for 30% $O_2$ at 10.2 psia, but will likely be unacceptable for 34-40% $O_2$ at 8.2 psia. Nitto P-213 tape is identified as flammable, but on an aluminum heat sink for flammability. A potential alternative for Nitto P-213 tape is P-212 tape, which is nonflammable in 30% $O_2$, 10.2 psia. Other flammable materials are used in acceptably small quantities or surrounded by nonflammable materials.

The melamine foam is an issue for toxic offgassing in smaller volumes than ISS *(O-3h)*. Melamine foams tend to release formaldehyde, especially when heated to 185 °F (85 °C). This foam was tested for offgassing at 190 °F (88 °C) and found acceptable, but in 1995 [ref. 105], before the standard offgassing test reliably detected and quantified formaldehyde. It could be replaced by an alternate melamine foam (e.g., Basotect-W coated with Viton, which is being used in the MPCV food warmer). Other polymeric materials are assumed not to be an offgassing concern.

The food warmer DC power cable assembly has Teflon insulation and is assumed to be acceptable for flammability and toxic offgassing in Exploration environments.

***Components not assessed***

ORUs within the Galley rack are not addressed. The GFW internal components were not assessed due to the complexity of the design and changes identified for Exploration environments. Flammability and offgassing of FRIDGE components were not assessed due to lack of data.

### 7.4.4 ISS Food Warmer

***Description***

The purpose of the suitcase-style ISSFW, shown in Figure 24, is to heat crew meals. Its aluminum case, with two latches and a transportation handle, contains four heater assemblies between two aluminum plates and two foam inserts used to restrain the food packages while being heated. The inserts, one in the enclosure lid and the other in the enclosure base, are constructed of Melamine foam with a Mosites coating to inhibit moisture absorption.

The heating assembly consists of four heating elements with four thermal sensors placed between two aluminum plates with a sensor in the center of each heating element. Rivets along the perimeter connect the two plates to each other. On one of the plates, under two separate protective white Teflon shields, four thermostats (i.e., two in each shield) are located along the side of the plate. A hinge between the base and the lid attaches the heating assembly. On the lid side, an insulation border underneath the hinge and near the handle provides thermal protection. Both sides of the heating assembly have restraint springs, four on each side, to hold food packages in place.

***Figure 24. ISS Food Warmer (Suitcase Style)***

***Performance***

As a minimum design requirement, the ISSFW heats food packages up to a minimum temperature of 145° F (63 °C) within approximately 45 minutes. Operation was certified for a minimum operating pressure of 13.9 psia. Thermal and pressure deltas would impact performance requiring  longer heating times for food palatability.

***Thermal***

No thermal impacts are anticipated beyond the heating performance of the food warmer.

*Qualitative M&P Evaluation*

The ISSFW shell is aluminum, which is acceptable for flammability in Exploration environments. Inside the suitcase, the Mosites 10298-coated melamine foam is a concern for flammability in 34-40% $O_2$, 8.2 psia, but not in 30% $O_2$, 10.2 psia. It is a concern for toxic offgassing in both environments. Replacing the foam with Basotect W would not change the flammability performance, but would make it acceptable for offgassing in both environments.

The melamine foam in the suitcase food warmer is an issue for toxic offgassing in smaller volumes than ISS *(O-3i)*. Other polymeric materials are assumed not to be an offgassing concern.

*Components not assessed*

None.

#### 7.4.5 ISS and MPCV Sleeping Bag Assemblies

*Description*

The ISS Sleeping Bag Assembly was developed for use in the CCP and was first used during the SpaceX Demonstration-2 mission. The assembly contains a sleeping bag with a replaceable liner and eight ties to tether the bag in place. The bag is 84 in. long x 27 in. wide x 1 in. thick, and with a liner weighs about 6.6 pounds. It will be used primarily inside the CQ, but may be used elsewhere throughout Exploration vehicles and habitats. The sleeping bag has an outer shell of royal blue Nomex, an internal insulation layer of Thinsulate FR-120, an inner layer of elastic Nomex (i.e., Interlock Nomex), and a replaceable liner made of white cotton batiste #128. The liner is located inside the sleeping bag and held in place using Velcro fasteners and toggle-style buttons. The liner is intended to be replaced on a monthly basis. Other design features include gussets (i.e., blue Nomex panels on the sides and bottom of the sleeping bag) that make the bag expandable, a head pocket, pillow accommodation in the liner, arm openings, foot openings, a nylon zipper with cotton liner strip (i.e., 0.2 in. wide x 45 in. long), internal body restraints (i.e., nylon webbing), vents/blue Nomex vent covers, external pockets to accommodate a notebook or iPad Air, and 22 Nomex webbing attachment loops around the bag perimeter. Accessories include the eight sleeping bag ties, which are 24 in. long x 0.15 in. diameter Vectran cords provided for each bag. The accessories could also include a debris screen (27 x 24 in.), which is used at crew discretion to cover the face during sleep. The sleeping bags, liners, ties, and debris screens are be soft-stowed for launch.

*Performance*

Performance of the sleeping bag will not be affected by reduced pressure or increased $O_2$ environment.

*Thermal*

The thermal performance of the sleeping bag will not be affected by reduced pressure or increased $O_2$ environment.

*Qualitative M&P Evaluation*

The ISS sleeping bag is likely too bulky to be used in Exploration vehicles and contains materials that would require special operational controls for use at 30% $O_2$, 10.2 psia due to flammability. The lighter MPCV sleeping bag is certified for use at 30% $O_2$, 10.2 psia, but is required to be stowed in a nonflammable container when not in use. The ISS and MPCV sleeping bag designs would not be acceptable for flammability in 34-40% $O_2$ at 8.2 psia, as the major exposed material is royal blue Nomex *(F-12f, F-34)*.

The ISS and MPCV sleeping bags were baked out at 195 °F (91 °C) for 5-6 days to reduce toxic offgassing to a level where up to six sleeping bags could be used in the MPCV volume (530 $ft^3$/ 15 $m^3$) and CCP volume (388 $ft^3$/11 $m^3$). A similar bakeout would be required for use in Exploration vehicles.

***Components not assessed***

None.

## 7.5 Consequences of Reduced Pressure Environments for Exploration Design

As discussed in Section 6.4, definitive quantitative determinations of the "best" mitigation strategies for each of the performance, thermal, and materials impacts observed in this assessment (see *summary chart, Table 9*) have not been identified. Selecting strategies is left to the developers of Exploration systems and vehicles, who can trade them most effectively within their unique architectures and mission priorities. However, some common themes that point to mass, volume, power, and/or schedule impacts can be deduced from this assessment and provide program managers some perspective as they assess risk.

No substantial mass impacts to any particular subsystem or piece of equipment were uncovered in this assessment, with the possible exception of the Sabatier CRA (if an enclosing dome is selected for hazard control). Although many mechanical parts within components (e.g., fans/ blowers, relief valves, and bellows tanks) will likely require modification or replacement, those parts typically represent a small fraction of system mass and the changes that would be needed can, with reasonable confidence, be regarded as a low risk to system mass. Many items, however, were identified that contain acoustic and/or thermal insulating materials that will likely require replacement to meet flammability requirements at high $O_2$ concentrations. Although insulation by nature is generally lightweight, the current absence of materials suitable for $O_2$ concentrations approaching 40% in 8.2 psia environments, combined with the widespread usage of insulations throughout a vehicle or habitat, makes the possibility of an integrated and substantial mass impact something that deserves continued management awareness and attention.

Like mass, no substantial volume impacts were uncovered for any particular subsystem or piece of equipment, with the exception of the Sabatier CRA if a dome is adopted. Fans and blowers that are required to deliver a defined mass flowrate, like many used for convective cooling, may be at risk for notable impacts to their external envelope if the mitigation strategy selected is to increase the diameter of internal fan blade assemblies. Insulation changes may have noteworthy impacts to volume, which may be more consequential than mass, given their ubiquitous use in vehicles and habitats. Mechanical part changes within components can be expected to have little if any discernable impact to subsystem envelopes.

Potential power consumption impacts are mostly associated with fans and blowers if higher operating speeds are selected as the mitigation strategy to preserve mass flowrate at lower cabin pressures (i.e., air densities). Given the widespread usage of fans and blowers that are depended on to deliver defined mass flowrates for equipment and environmental cooling, the potential for a substantial integrated power impact for a vehicle or habitat should be considered by managers.

Potential schedule impacts are varied. The development of human space systems has multiple examples where a perceived “simple” design change resulted in serious program schedule effects. Assembly and integration schedules can be controlled by delivery of a single item. Because of these considerations, identified or proposed changes to ISS ECLS equipment for use in Exploration vehicles and habitats should be given constant and diligent attention by managers and designers. Substantial schedule risks are present in the many situations in which testing is required to:

- Provide the necessary data to make mitigation selections (e.g., how lower-pressure operating conditions would impact Sabatier CRA performance).
- Understand performance (e.g., how CDRA performance would be impacted by the collective impacts to blower efficiency, bed heating and cooling, and adsorption/desorption kinetics), or in the case of the PFE, AGA, and AQM, how effectiveness is impacted by higher $O_2$ concentration.
- Identify and certify alternate materials, and recertify equipment by test and/or analysis for its intended Exploration operating conditions).

## *Table 9. Summary of Impacts and Specific Concerns per Subsystem*

| Subsystem | Performance @ 10.2 psia | Performance @ 8.2 psia | Thermal | Flammability @ 10.2 psia | Flammability @ 8.2 psia | Offgassing @ 10.2 psia | Offgassing @ 8.2 psia | Specific Concerns |
|---|---|---|---|---|---|---|---|---|
| **AAA** | | | | | | | | Redesign vs power draw to maintain performance. |
| **BPA** | | | | | | | | Bladder weeping risk, steady state touch temperature, bladder flammability |
| **CCAA** | | | | | | | | Reduced sensible heat exchange, reduced condensate collection, silicone foam and general material flammability |
| **CDRA** | * | * | | | | | | Competing effects on performance, insulation flammability |
| **CRA** | | | | | | | | Operational hazards, competing effects on performance, acoustic covering and ducting flammability |
| **ISS Water-Mist PFE** | | | | | | | | Reduced performance, covering flammability |
| **MPCV Water-Spray PFE** | | | | | | | | Reduced performance |
| **Emergency Mask** | | | | ** | ** | | | Kinetic changes at lowest pressure |
| **Fire/Ammonia Cartridges** | | | | ** | ** | | | Kinetic changes at lowest pressure |
| **Orion Smoke Eater Filter** | | | | | | | | Kinetic changes at lowest pressure and increased steady-state temperature |
| **IMV** | | | | | | | | Increased operational temperature vs cooling design change |
| **OGA** | | | | | | | | Increased hazard for rack venting, sensor robustness, combustion hazard |
| **PCA** | | | | | | | | |
| **TCCS** | | | | | | | | Competing effects on performance |
| **UPA** | | | | | | | | Decreased gas separator efficiency, increased operating temperature, insulation flammability |
| **UWMS** | | | | | | | | Decreased efficiency of waste transport, reduced gas/liquid separation efficiency, pretreat injection, increased touch temperatures, hose and insulation flammability |
| **WPA** | | | | | | | | Competing effects on performance, level sensor performance, insulation flammability |
| **Acoustic Monitor** | | | | | | | | Component flammability |
| **AGA** | | | | | | | | Inaccurate readings for variable pressures, flammability of components |
| **AQM** | | | | | | | | Reduced accuracy for readings, labels and display flammability |
| **CAD** | | | | | | | | |
| **CWQMK** | | | | *** | *** | | | Reagent oxidation, component flammability |
| **Flywheel** | | | | | | | | |
| **HERA** | | | | | | | | |
| **MinION** | | | | *** | *** | | | Reagent oxidation, component flammability |
| **Cordless Vacuum Cleaner** | | | | | | | | Thermal performance, component flammability |
| **Crew Quarters** | | | | | | | | Design change vs increased power for fan, acoustic material flammability |
| **Galley Rack PWD** | | | | | | | | Reduced cooling capability |
| **Galley Rack FRIDGE** | | | | | | | | Reduced cooling capability |
| **Galley Rack Food Warmer** | | | | | | | | Reduced cooling capability, insulation flammability |
| **ISS Suitcase Food Warmer** | | | | | | | | Insulation flammability |
| **US Sleeping Bag** | | | | | | | | Material flammability |
| **MPCV Sleeping Bag** | | | | | | | | Material flammability |

***CDRA Blower will require redesign for Exploration environments**

****Materials are all flammable but acceptable due to usage. Storage bags will need to be replaced.**

*****Reagents may have reduced shelf life due to increased oxidation rates.**

# 8.0 Findings, Observations, and NESC Recommendations

## 8.1 Findings

The NESC assessment team identified the following findings:

***Multisystem***

**F-1.** No performance, thermal, or material impacts were identified for three subsystems:

a. Pressure Control Assembly (PCA)
b. Crew Active Dosimeter (CAD)
c. Hybrid Electronic Radiation Assessor (HERA)

**F-2.** Operation of ISS fans and blowers outside their certification parameters (e.g., Exploration atmospheres) will likely cause performance impacts (e.g., excess noise, increased power consumption, and/or decreased lifecycle).

**F-3.** At reduced pressures, packed beds in ECLSS will require redesign to achieve the required performance due to reduced interstitial velocity in sorbent beds and reduced gas hour space velocity in catalytic reactors.

**F-4.** Reduced pressure has a complex, nonlinear effect on heat and mass transfer, such that conclusions on the net difference in efficiency for packed sorbent and catalyst beds cannot be deduced directly.

**F-5.** With no changes to a filter's fibrous structure and porosity, it will have the same or slightly improved filtration efficiency at Exploration pressures.

**F-6.** Mechanical devices that reference the cabin atmosphere for operation (e.g., valves, regulators, sensors, bellows, and gas-liquid separators) will not perform as expected in an environment outside their designed, calibrated, and qualified pressure.

**F-7.** The net effect(s) of a reduced pressure environment on cabin acoustics cannot be predicted with certainty without accurate modeling of the specific vehicle and systems.

**F-8.** When a microgravity gas-liquid separator is operated at a lower pressure than its original design, performance may be reduced.

**F-9.** Exploration environment atmospheres have a decreased per-unit volume heat capacity due to decreased air density.

**F-10.** Exploration environment atmospheres will decrease the ability of equipment to reject heat via convection.

**F-11.** Additional empirical data on the effect of pressure on toxic offgassing rates are needed to establish whether a correction factor can be applied to existing data for 8.2 psia environments.

**F-12.** NASA has limited empirical material flammability data at $O_2$ concentrations higher than 30%, but many ISS materials are unlikely to meet the requirements at higher (32-40%) $O_2$ concentrations based on analysis of material characteristics, including:

a. Polymeric materials.
b. Foam thermal insulations, such as Armaflex and Solimide AC-550 polyimide.

c. Bisco HT-200 sound block silicone and Soundcoat HT polyimide foam.
d. Black KB 10 tape, blue duct tape, and silicone-fiberglass insulations.
e. Flammable paint on metallic substrates.
f. Nomex.
g. Polyethylene covered in aluminum foil tape.

**F-13.** Although some closed-cell foams exist that would meet flammability requirements in habitable Exploration elements, with the exception of Solimide HT-340, no open-cell foams with suitable performance exist at this time.

***ECLSS***

**F-14.** The AAA fan will not meet thermal performance requirements in Exploration environments.

a. For 10.2 psia, upwards of 40% increased volume flow through the racks will be required for the same heat load and temperature limits.
b. For 8.2 psia, upwards of 80% increased volume flow through the racks will be required for the same heat load and temperature limits.

**F-15.** Cabin pressures below that for which the ISS BPA was certified may induce weeping of brine fluid through the device's bladder.

**F-16.** The CCAA will not meet performance, thermal, or material flammability requirements for Exploration atmospheres.

a. The efficiency of the CCAA slurper bars may be decreased due to the decrease in airflow drag force at decreased atmospheric density.
b. The CCAA CHX ORU has foam completely exposed on the rear side of the hardware and is unlikely to be acceptable for Exploration due to the flammability and surface area of the material.

**F-17.** Net performance impacts to CDRA due to reduced cabin pressure are uncertain due to the difficulty in predicting the combined and competing effects of improved adsorption kinetics, reduced blower mass flowrate, and internal convective heat transfer impacting bed heating and cooling.

**F-18.** The CRA may not meet performance requirements and components will not meet material flammability requirements in Exploration atmospheres.

a. If the same hazard mitigation approach of sub-ambient pressure operation is chosen for Exploration Sabatier hardware, the Sabatier reactor pressure would need to be decreased below 10.2 or 8.3 psia, resulting in a reduction in the reaction rate of the Sabatier reactor and a decrease in the performance of life support gas-liquid separators.
b. The CRA compressor has a high risk for flammability because of the nonmetallic acoustic cover and the large number of polymeric materials inside the cover.

**F-19.** Low-pressure atmospheres could impact water-spray PFE characteristics, including changes to plume dispersal, water flow rate, required water quantity, and corresponding tank size.

**F-20.** Increased $O_2$ concentrations could reduce all PFE abilities to extinguish fire.

**F-21.** The designs of ISS emergency systems are not well-documented in the internal or external NASA literature, resulting in minimal data from which to assess existing hardware.

**F-22.** The OGA may experience significant impacts to performance and safety in Exploration atmospheres:

a. It is possible that the increased pressure drop across OGA cells will overcome the protonic drag within the cell stack and allow liquid water to be released into the $O_2$ product stream.

b. For Exploration atmospheres where $O_2$ is already elevated, an $O_2$ leakage from OGA could result in an unacceptable hazard within a rack; an alternative hazard mitigation would be required.

c. If the recirculation loop pressure is decreased, possible impacts include dissolved $H_2$ coming out of solution in the recirculation loop, required changes to the rotary separator accumulator high/low setpoints, and out-of-range sensors.

d. Decreased cabin pressure may reduce the performance of the OGA $H_2$ sensors and/or cause premature failure due to increased water content in the product $O_2$.

e. Ambient $O_2$ within the OGA recirculation loop could accumulate in the separator during start-up and combine with residual product $H_2$ to create a hazardous scenario for flammability and/or explosion.

**F-23.** The gas separation efficiency of the UPA's SPA may be decreased due to a lower shell-side pressure (reduced driving force) if the SPA is vented to a reduced pressure cabin.

**F-24.** For constant fluid velocities, the drag force exerted by airflow to move liquid and solid waste in the UWMS will be decreased in Exploration environments, thus decreasing the effective capture of UWMS.

**F-25.** The WPA MLS low- and high-level sensors will be exposed to a change in gas-core volume that may affect performance

***CHeCS***

**F-26.** Preliminary testing has shown the AGA's photoacoustic response to be impacted at $O_2$ concentrations greater than 21%, causing contaminants to be under-reported.

**F-27.** The AQM may experience impacts to functional and thermal performance in Exploration environments including:

a. Elevated $O_2$ concentrations may impact the chromatographic separations and ionization processes that together determine AQM performance.

b. AQM GC column cooling will be less efficient in reduced-pressure environments, requiring increased sample times for cabin gas composition analysis.

**F-28.** Lower atmosphere pressure and/or elevated $O_2$ concentration may negatively affect reagents used in the CWQMK and MinION, including:

a. Interfere with the chemical reactions upon which the CWQMK functions.

b. Reducing the shelf-life of CWQMK and MinION packaged reagents due to increased rates of oxidation.

**F-29.** Although performance is not expected to be affected, thermal impacts to the flywheel in reduced pressure atmosphere are uncertain.

**F-30.** The MinION case, cabling, and labels are not suitable for use at the elevated Exploration $O_2$ concentrations.

**F-31.** ISS risk acceptance rationale for the flammable vacuum cleaner may not be acceptable for 30% $O_2$ and 10.2 psia, and almost certainly will be unacceptable at 34-40% $O_2$ and 8.2 psia due to the relatively large size of the hardware item.

**F-32.** Galley cold food storage and food warmer hardware will be operational in Exploration environments, but will require additional time to cool and heat, respectively.

**F-33.** To maintain temperatures within a similarly designed Galley rack for Exploration, forced convective cooling or water loop cooling will be required.

**F-34.** Neither the ISS nor Orion sleeping bags are acceptable for flammability at 8.2 psia and 34%+ $O_2$.

## 8.2 Observations

The NESC assessment team identified the following observations:

**O-1.** There is some limited data to suggest improved adsorption kinetics of $CO_2$ on ISS CDRA zeolite at <5 psia versus nominal ISS environments.

**O-2.** Existing MAPTIS offgassing data older than 10 years, and especially from the 1980s and 1990s, may not reflect current material characteristics because of developments in analytical instrument sensitivity and materials manufacturing changes.

**O-3.** Toxic offgassing of hardware may be too high when used in smaller vehicles (11-18 $m^3$) due to the reduced volume for dilution and will also be higher for 8.2 psia environments than at standard test pressures. This is of particular concern for:

a. Emergency masks
b. UWMS hardware
c. Acoustic monitor
d. AGA hardware
e. AQM hardware
f. CQ composite sandwich panels containing Nomex honeycomb core
g. Galley Rack PWD Aerogel blanket
h. Galley Rack Food Warmer Melamine foam
i. ISS Suitcase Food Warmer Melamine foam

**O-4.** Minimal flammability data exists at varying $O_2$ concentrations in partial-gravity environments.

**O-5.** Gas streams that vent to cabin and contain trace contaminants will increase the risk of odor accumulation in Exploration-sized vehicles.

## 8.3 NESC Recommendations

The following NESC recommendations are directed to Program Managers for missions anticipating high-frequency EVA, which include HLS and Foundation Surface Habitat.

**R-1.** Conduct performance, thermal, and material testing and/or analysis of hardware at Exploration environments to inform mitigation strategy decisions for the following systems:

- Components
  - Fans, blowers, and air movers *(F-2, F-9, F-10, F-14)*
  - Mechanical devices (e.g., valves, regulators, sensors, and bellows) *(F-6)*
  - Gas-liquid separators *(F-6, F-8)*
- Systems
  - BPA *(F-15, O-5)*
  - CCAA *(F-9, F-10, F-16)*
  - CDRA *(F-3, F-4, F-17)*
  - TCCS *(F-3, F-4)*
  - Sabatier CRA *(F-3, F-4, F-8, F-9, F-10, F-18)*
  - ISS water-mist and MPCV water-spray PFEs *(F-19, F-20)*
  - Emergency mask, fire and NH3 cartridges, and the OSEF *(F-3, F-21)*
  - OGA *(F-8, F-22)*
  - UPA *(F-23, O-5)*
  - UWMS *(F-8, F-24)*
  - WPA *(F-25)*
  - AGA *(F-26)*
  - AQM *(F-27)*
  - CWQMK *(F-28)*
  - Flywheel exercise device *(F-29)*
  - MinION *(F-28, F-30)*
  - Vacuum Cleaner *(F-31)*
  - Galley Rack *(F-32, F-33)*
  - Sleeping Bags *(F-34)*

**R-2.** Utilize a multiphysics simulation tool with pressure-dependent coefficients simultaneously solved for momentum, mass, and thermal coupled balance equations to resolve the impacts of Exploration environment pressure on sorbent- and catalysis-based ECLS functions. *(F-4)*

**R-3.** Perform acoustic modeling of Exploration vehicles to characterize and quantify the effects of atmosphere pressure. *(F-7)*

**R-4.** Conduct testing of material offgassing rates at reduced pressures. *(F-11, O-3)*

**R-5.** Evaluate the explosion risk from ambient $O_2$ leakage into OGA with leak rates and material balances for Exploration environments. (*F-22 e*)

**R-6.** Conduct material development where gaps in available materials exist to meet flammability requirements in high $O_2$ environments. *(F-12, F-13, O-4)*

## 9.0 Alternate Technical Opinion(s)

No alternate technical opinions were identified during the course of this assessment.

## 10.0 Other Deliverables

No unique hardware, software, or data packages, other than those contained in this report, were disseminated to other parties outside this assessment.

## 11.0 Recommendations for the NASA Lessons Learned Database

No recommendations for NASA lessons learned were identified as a result of this assessment.

## 12.0 Recommendations for NASA Standards, Specifications, Handbooks, and Procedures

No recommendations for NASA standards, specifications, or procedures were identified as a result of this assessment.

## 13.0 Definition of Terms

| | |
|---|---|
| Exploration Atmosphere | A habitable volume atmosphere maintained nominally at 8.2 psia/26.5% $O_2$ or 10.2 psia/26.5% $O_2$. |
| Exploration Mission(s) | Pertaining to any individual or combination of missions with an assumed temporary or nominal operational cabin environment of 8.2 psia/26.5% $O_2$ or 10.2 psia/26.5% $O_2$. |
| Exploration Vehicle | Any vehicle used in Exploration missions with an assumed nominal or temporary operational cabin environment of 8.2 psia/26.5% $O_2$ or 10.2 psia/26.5% $O_2$. |
| Finding | A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation. |
| Observation | A noteworthy fact, issue, and/or risk, which is not directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support. |
| Recommendation | A proposed measurable stakeholder action directly supported by specific finding(s) and/or observation(s) that will correct or mitigate an identified issue or risk. |

## 14.0 Acronyms and Nomenclature

| | |
|---|---|
| 4B$CO_2$ | 4Bed CO2 Scrubber |
| 4BMS | 4Bed Molecular Sieve |
| AH | Ampere Hour |

| | |
|---|---|
| AM | Acoustic Monitor |
| AAA | Avionics Air Assembly |
| AAD | Audio Annunciation Device |
| AGA | Anomaly Gas Analyzer |
| AQM | Air Quality Monitor |
| ATU | Audio Terminal Unit |
| BPA | Brine Processor Assembly |
| CM | Crew Module |
| C&DH | Command and Data Handling |
| C&W | Caution and Warning |
| CAD | Crew Active Dosimeter |
| CCAA | Common Cabin Air Assembly |
| CCP | Commercial Crew Program |
| CDRA | Carbon Dioxide Removal Assembly |
| cfm | Cubic Feet per Minute |
| CRA | Carbon Dioxide Reduction Assembly |
| CHeCS | Crew Health Care System |
| CHX | Condensing Heat Exchanger |
| CMS | Countermeasures System |
| CO | Carbon Monoxide |
| CO2 | Carbon Dioxide |
| COTS | Commercial Off-the-Shelf |
| CQ | Crew Quarters |
| CRA | Carbon Dioxide Reduction Assembly |
| CWQMK | Colorimetric Water Quality Monitoring Kit |
| DA | Distillation Assembly |
| DMS | Differential Mobility Spectrometer |
| ECLS | Environmental Control and Life Support |
| ECLSS | Environmental Control and Life Support System |
| ECM | Exploration Command Module |
| EHS | Environmental Health System |
| EVA | Extravehicular Activity |
| FCPA | Fluids Control and Pump Assembly |
| FRIDGE | Freezer/Refrigerator/Incubator Device for Galley and Experimentation |
| GAC | Granular Activated Carbon |
| GC-DMS | Gas Chromatograph-Differential Mobility Spectrometer |
| GCR | Galactic Cosmic Rays |
| GFW | Galley Food Warmer |
| GHSV | Gas Hourly Space Velocity |
| GLS | Gas Liquid Separator |
| GLA | General Luminaire Assembly |
| $H_2$ | Hydrogen |
| HCl | Hydrochloric Acid |
| HF | Hydrofluoric Acid |

| | |
|---|---|
| HCN | Hydrogen Cyanide |
| HERA | Hybrid Electronic Radiation Assessor |
| HF | Hydrofluoric Acid |
| HLS | Human Landing System |
| HMS | Health Maintenance System |
| HPU | HERA Processing Unit |
| HSIR | Human System Integration Requirements |
| HSU | HERA Sensor Unit |
| HX | Heat eXchanger |
| IMV | Intermodule Ventilation Fan |
| ISS | International Space Station |
| ISSFW | ISS Food Warmer |
| IVA | Intravehicular Activity |
| IWP | Ionomer-Membrane Water Processor |
| LiOH | Lithium Hydroxide |
| LSH | Lunar Surface Habitat |
| LTL | Low Temperature Loop |
| M&P | Materials and Processes |
| MAPTIS | Materials and Processing Information System |
| MERLIN | Microgravity Express Rack Locker/Incubator |
| MLS | Mostly Liquid Separator |
| MPCV | Multipurpose Crew Vehicle |
| MPLM | Mini-Pressurized Logistics Module |
| MTL | Moderate Temperature Loop |
| MUA | Material Usage Agreement |
| MW | Molecular Weight |
| $N_2$ | Nitrogen |
| $N_2H_4$ | Hydrazine |
| $NH_3$ | Ammonia |
| NextSTEP | Next Space Technologies for Exploration Partnerships |
| $O_2$ | Oxygen |
| OCAD | Operational Control Agreement Database |
| OGA | O2 Generation Assembly |
| ORU | On-orbit Replacement Unit |
| OSEF | Orion Smoke-Eater Filter |
| PCA | Pressure Control Assembly |
| PCP | Pressure Control Panel |
| PCR | Polymerase Chain Reaction |
| PFE | Portable Fire Extinguisher |
| PMMA | Polymethyl Methacrylate |
| POM | Portable Oxygen Monitor |
| psia | Pounds per Square Inch Absolute |
| PTFE | Polytetrafluoroethylene |
| PVP | Polyvinylpyrrolidone |

| | |
|---|---|
| PWD | Potable Water Dispenser |
| RAD | Radiation System |
| REID | Risk of Exposure-Induced Death |
| RF | Radio Frequency |
| RH | Relative Humidity |
| RPM | Rotations Per Minute |
| SOA | State of the Art |
| SPA | Separator Plumbing Assembly |
| SPE | Solar Particle Event |
| SSLA | Solid State Lighting Assembly |
| SSP | Space Shuttle Program |
| USB | Universal Serial Bus |
| TCCS | Trace Contaminant Control System |
| TCCV | Temperature Control Check Valve |
| TDL | Tunable Diode Laser |
| UHMWPE | Ultra-High Molecular Weight Polyethylene |
| UPA | Urine Processor Assembly |
| UWMS | Universal Waste Management System |
| V | Velocity |
| VOC | Volatile Organic Compound |
| WPA | Water Processor Assembly |
| WSTA | Wastewater Storage Tank Assembly |

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# Appendix A. NESC Exploration Environments Assessment

## 1. Cabin air properties

### a. Density

Using IG EOS: $P = \rho RT$

Where $P$ is total pressure, $\rho$ is the molar density (mol/m^3), $R$ is the universal gas constant, and T is the temperature.

Rearranged: $\rho = \frac{P}{RT}$

### b. Vapor pressure

The Antoine equation allows us to estimate the vapor pressure of a liquid as a function of temperature.

$$\log_{10} P = A - \frac{B}{C + T}$$

Where $P$ is the vapor pressure, $T$ is the temperature in degrees $C$, and $A$, $B$, and $C$ are constants empirically defined for liquids. The values of A, B, and C used for water are 8.07131, 1730.63, and 233.426, respectively. They are used for a range of T = [1:100] °C.

### c. Heat capacity

The heat capacity of a fluid can be estimated with empirical correlations. A polynomial correlation for the heat capacity was used, of the form:

$$c_P \left(\frac{J}{mol - K}\right) = A + BT + CT^2 + DT^3$$

The values for empirical constants were taken from Perry's Chemical engineering Handbook and shown below. The heat capacity of the ideal gas mix was assumed to be a molar average of the constituent heat capacities.

| *Species* | *MW* | *A* | *B* | *C* | *D* | *Cp(22C) (J/mol-K)* |
|---|---|---|---|---|---|---|
| $O_2$ | 32 | 28.11 | -3.70E-06 | 1.75E-05 | 1.07E-08 | 2.99E+01 |
| $N_2$ | 28 | 31.15 | -0.01357 | 2.68E-05 | -1.17E-08 | 2.92E+01 |
| $H_2O(g)$ | 18 | 3.22E+01 | 0.001924 | 1.06E-05 | -3.60E-09 | 3.36E+01 |

### d. RH

The saturation temperature of water in the atmosphere (dew point) can be calculated using modified Raoult's Law, which assumes a saturated vapor phase. Where:

$$Py_w = P_w^{sat}(T)\gamma_w x_w$$

Where $P$ is the total pressure, $y_w$ is the mole fraction of water in the gas phase, $P_w^{sat}$ is the saturation pressure of water at $T$ (calculated using above Antoine eq.), $\gamma_w$ is the gamma coefficient for water accounting for non-ideal mixtures. We can further assume that only liquid water is condensable, thus simplifying $\gamma_w = 1 = x_w$. Thus, the saturation partial pressure of water is equal to the vapor pressure calculated by the Antoine equation at that temperature.

RH is calculated with the equation:

$$\%rH = \frac{P_w}{P_w^{sat}(T)}\ x\ 100\%.$$

Thus:

$$y_w(rH,T) = \frac{\%\ rH}{100} * \frac{P_w^{sat}(T)}{P_{total}}$$

**e. Gas composition**

The gas composition and MW is calculated as: The mole fraction for $O_2$ is specified (21% in 14.7 psia, 26.5% in 10.2 psia, 34% in 8.2 psia.). The mole fraction for water is calculated by specifying a temperature and RH. Then, the mole fraction of $N_2$ is calculated as:

$$y_{N2} = 1 - y_{O2} - y_w$$

MW and specific heat are then calculated as a molar average of the components, where:

$$MW^{mix} = \sum_{i=1}^{\#\ of\ componets} y_i * MW_i$$

$$c_P^{mix} = \sum_{i=1}^{\#\ of\ componets} y_i * C_{p,i}$$

**f. Specific humidity**

Specific humidity is the mass of water vapor in the atmosphere per mass of dry air. It is calculated using the above information using a basis of 1 mol:

$$sH = \frac{y_w MW_w}{y_{O2} * MW_{O2} + y_{N2} MW_{N2}}$$

Specific humidity is difficult to compare across atmospheres with different compositions (i.e., less absolute $N_2$ in Exploration atmospheres). Therefore, one may wish to calculate absolute humidity, defined as the total mass of water vapor per-unit volume (the density of water vapor in the atmosphere).

**g. Absolute humidity**

Using the IG EOS, we find the total moles of gas in the cabin assuming a basis of 1m^3:

$n_{total} = \frac{Ptotal}{RT}$

Which means $n_w = n_{total} * y_w$

Thus, with a basis of 1m^3, the absolute humidity is equal to:

$$aH = n_w * MW_w\ [=] \frac{g}{m^3}$$

## h. Psychrometric charts

Humidity diagrams for each cabin pressure and $O_2$ composition were generated using the above equations. The x-axis was taken as temperature, and the y-axis used was specific humidity. Absolute humidity for a specific condition was shown for clarity. We see here, for the same temperature and RH, that although the specific humidity and thus mole fraction of water varies with pressure, the dewpoint temperature and absolute humidity are constant between environments.

***Table A-1. ECLSS Appendix Table 1***

| **Nominal ISS cabin** | | **Exploration Cabin environment** | | **Exploration Cabin environment** | | |
|---|---|---|---|---|---|---|
| 14.7 | psia | 8.3 | psia | 10.2 | psia | |
| 21 | %$O_2$ | 34 | %$O_2$ | 26.5 | %$O_2$ | |
| ***Component*** | ***Mole fraction*** | ***Component*** | ***Mole fraction*** | ***Component*** | ***Mole fraction*** | |
| *$H_2O$* | 0.011 | *$H_2O$* | 0.019 | *$H_2O$* | 0.0150 | |
| *$O_2$* | 0.21 | *$O_2$* | 0.34 | *$O_2$* | 0.265 | |
| *$N_2$* | 0.779 | *$N_2$* | 0.641 | *$N_2$* | 0.720 | * ALL Values calculated at 40% rH and 22 °C |
| ***MW (g/mol):*** | 28.733 | ***MW (g/mol):*** | 29.17 | ***MW (g/mol):*** | 28.90981424 | |
| ***Cp (kJ/kg/K)*** | | ***Cp (kJ/kJ/K)*** | | ***Cp (J/mol/K)*** | | |
| 1.02 | | 1.01 | | 1.02 | | |
| **Nominal ISS cabin** | | **Exploration Cabin environment** | | **Exploration Cabin environment** | | |
| 14.7 | psia | 8.3 | psia | 10.2 | psia | |
| 21 | %$O_2$ | 34 | %$O_2$ | 26.5 | %$O_2$ | |
| **air density (mol/m^3)** | **Rho(kg/m^3)** | **air density (mol/m^3)** | **Rho (kg/m^3)** | **air density (mol/m^3)** | **Rho (kg/m^3)** | |
| 41.29 | 1.186437261 | 23.31 | 0.680081548 | 28.65 | 0.828308166 | |

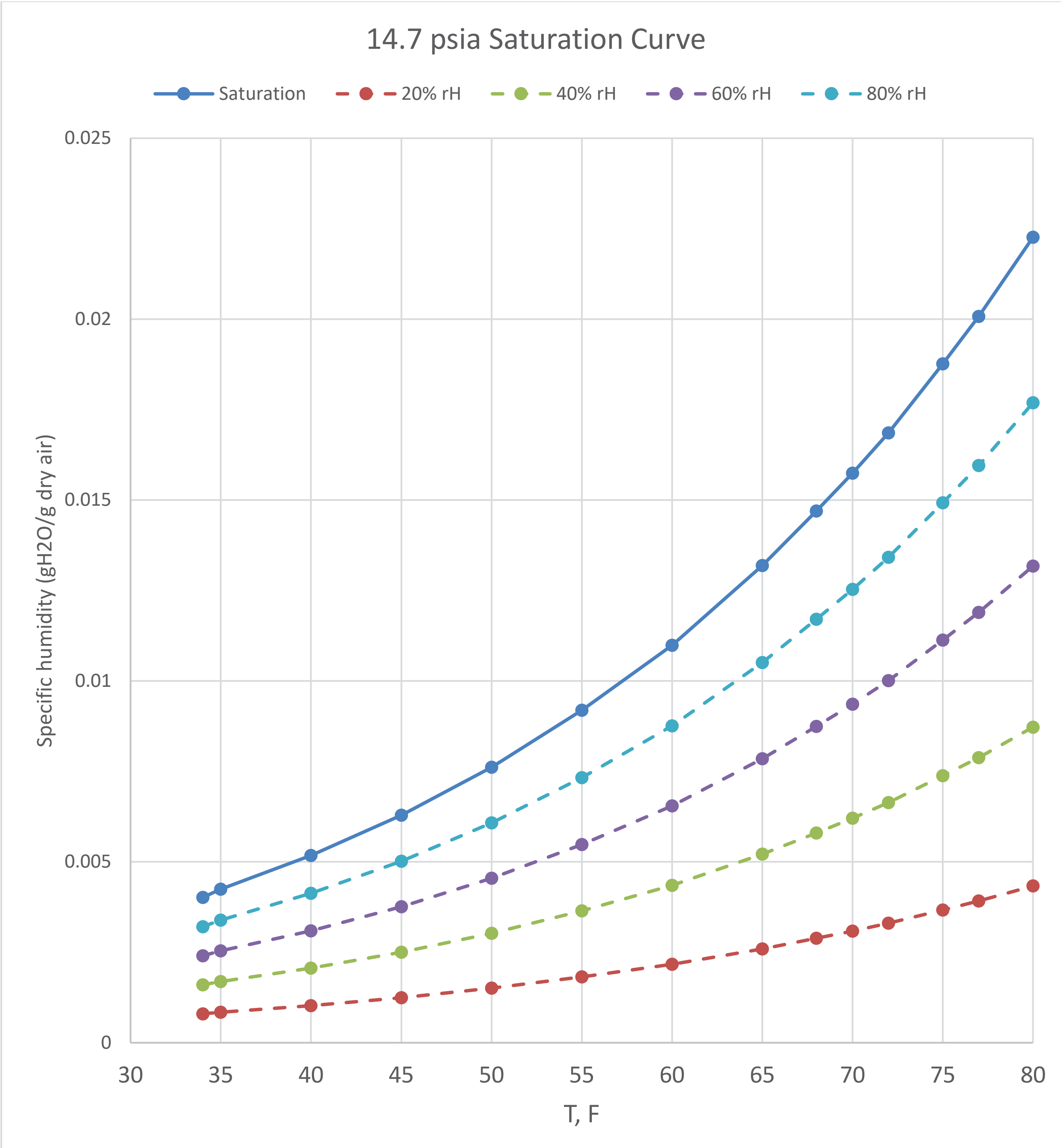


***Figure A-1. 14.7 psia Water Saturation Curves at 20%, 40%, 60%, 80%, and 100% (saturated) Relative Humidity (RH)***

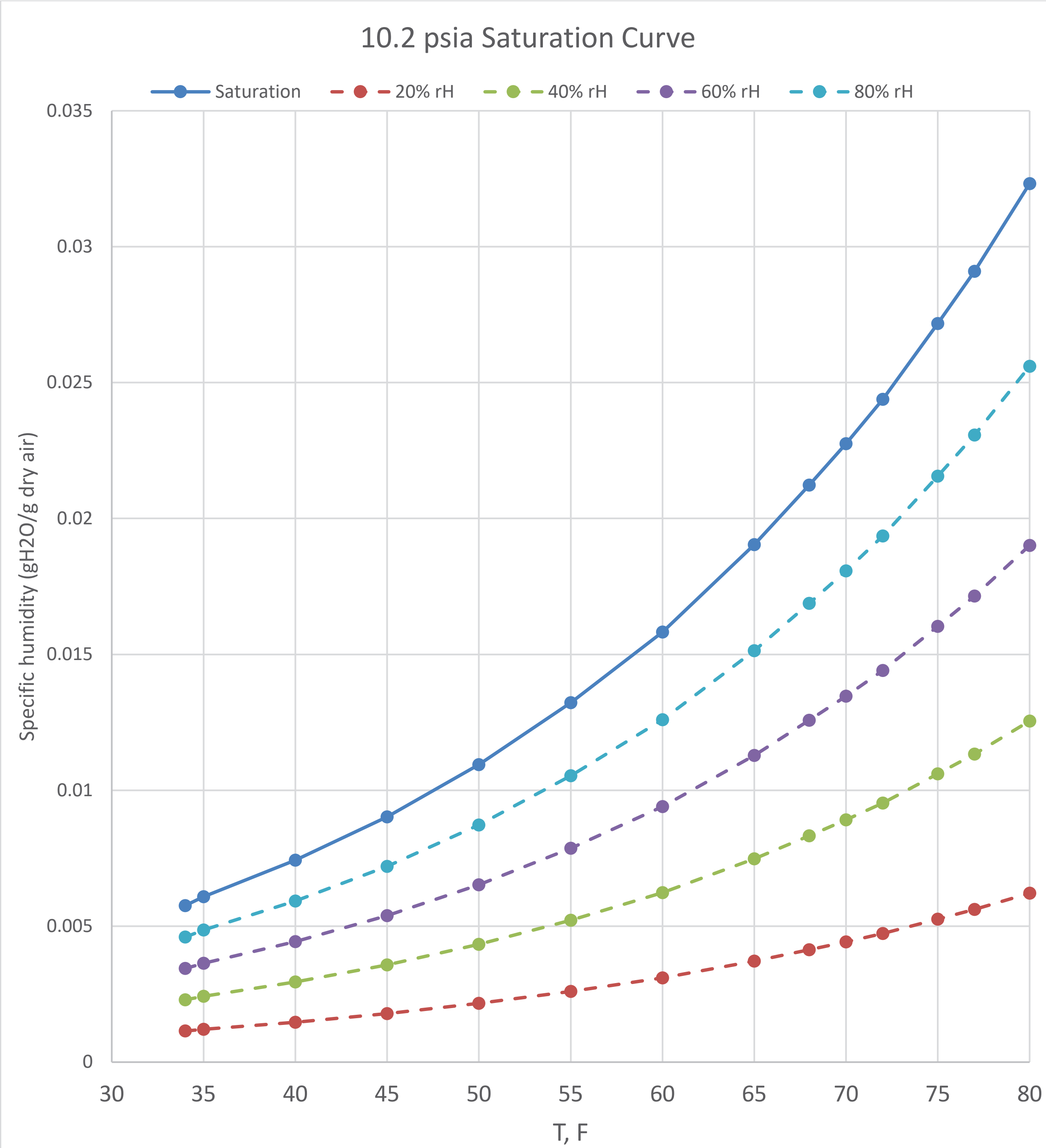


***Figure A-2. 10.2 psia Water Saturation Curves at 20%, 40%, 60%, 80%, and 100% (saturated) RH***

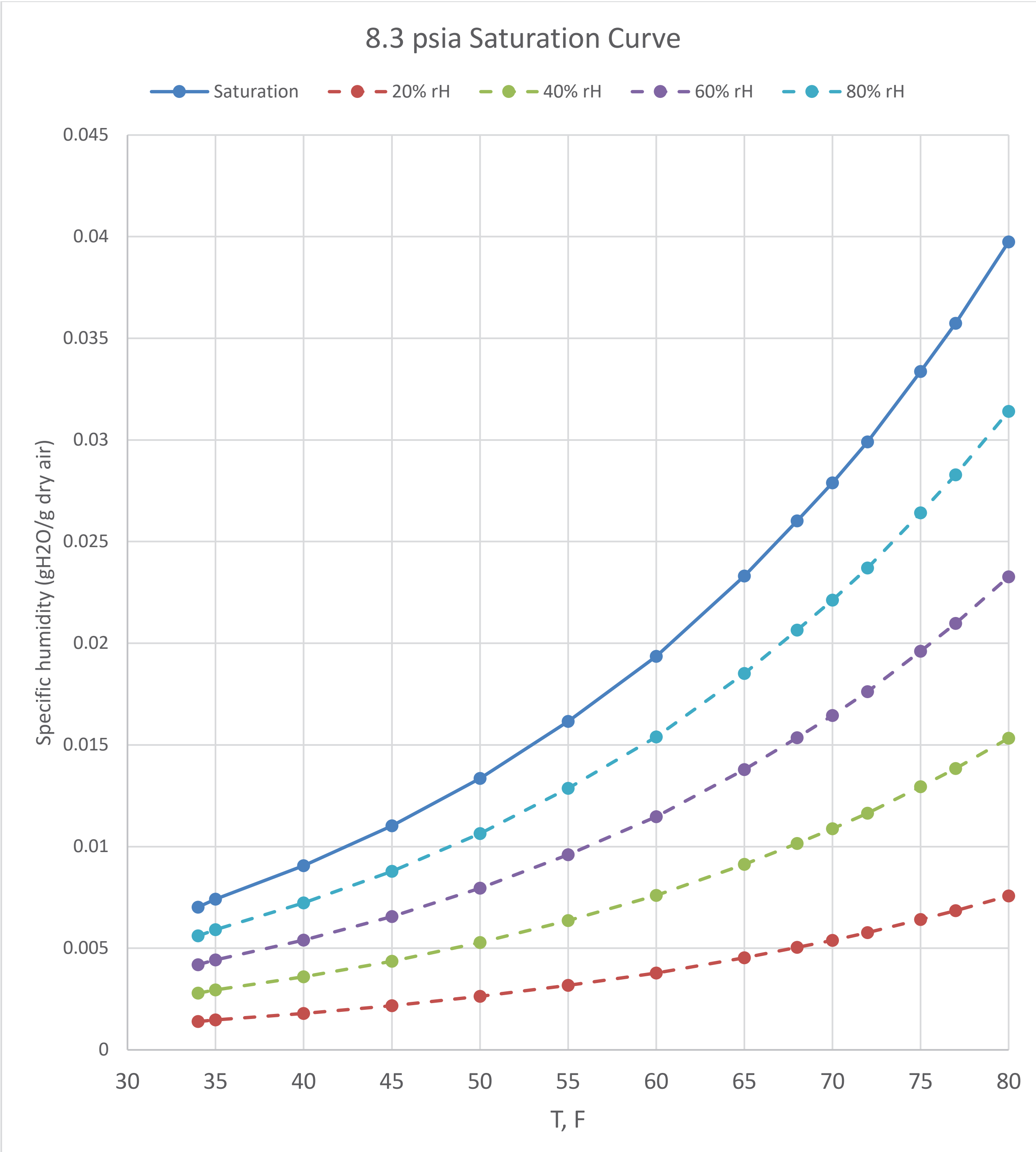


***Figure A-3. 8.3 psia Water Saturation Curves at 20%, 40%, 60%, 80%, and 100% (saturated) RH***

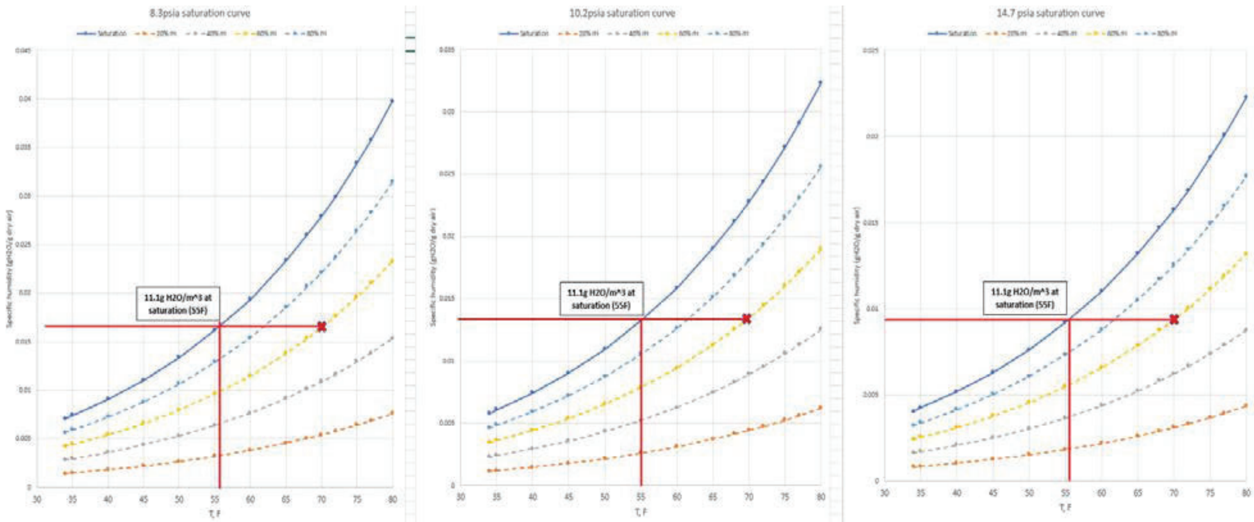


***Figure A-4. Effect of Pressure on Atmospheric Water Content***
***For a given temperature and RH, specific humidity (and mole fraction of water) varies with pressure but dewpoint and absolute humidity are constant.***

## 2. Thermal Calculations

### a. AAA Max air temperature in Exploration environments

Assumptions:

- Constant heat load from avionics across ISS and Exploration environments.
- The blower delivers the same volume flow rate of air through the racks (decreased mass flow).
- Steady-state heat transfer.
- Nominal operation: inlet air rack temp: 72 °F, max outlet: 109 °F.
- Density calculated w/ ideal gas law at 22 °C. Cp calculated from empirical data. Assumed composition is 40rH at 22 °C.

$$Q_{ISS} = Q_{Exploration}$$

$$\dot{V}\rho_{ISS}c_{p,ISS}\Delta T_{ISS} = \dot{V}\rho_{exp}c_{p,exp}\Delta T_{exp}$$

$$\Delta T_{exp} = \frac{\rho_{ISS}c_{p,ISS}\Delta T_{ISS}}{\rho_{exp}c_{p,exp}}$$

$$T_{max,exploration} = \frac{\rho_{ISS}c_{p,ISS}\Delta T_{ISS}}{\rho_{exp}c_{p,exp}} + T_{min,AAA}$$

$$T_{max,exploration} = \left(\frac{41*29*20}{23*29} + 22\right)*\frac{9}{5} + 32 = 136\ °\mathrm{F}$$

➔ 8.3 psia, 34% $O_2$

$$T_{max,exploration} = \left(\frac{41*29*20}{29*29} + 22\right)*\frac{9}{5} + 32 = 123\ °\mathrm{F}$$

➔ 10.2 psia, 26.5% $O_2$

## b. AAA volume flow increase in Exploration

Assumptions:

- Constant heat load from avionics across ISS Exploration environments.
- Constant temperature change of AAA air across ISS and Exploration environments.
- Steady-state, 1-D heat transfer.
- Incompressible flow, negligible molecular transport effects.
- Cp and density assumed constant with T for simplicity.
- Nominal operation: inlet air rack temp: 72 °F, max outlet: 109 °F.
- Density calculated w/ ideal gas law at 22 °C. Cp calculated from empirical data. Assumed composition is 40rH at 22 °C. See above for more information.

The simplified heat transfer model of AAA air as it moves through the racks can be written from an energy balance as follows:

$$\dot{Q} = \dot{V}\rho C_P (T_{hot} - T_{cold})$$

And to pick up the same heat load in Exploration:

$$\dot{Q}_{ISS} = \dot{Q}_{exploration}$$

Plugging in above equation and rearranging:

$$\dot{V}_{exploration} = \dot{V}_{ISS} \frac{\rho_{ISS}}{\rho_{exploration}} \frac{C_{P,\,ISS}}{C_{P,\,exploration}}$$

$$\dot{V}_{exploration} = 1.77 * \dot{V}_{ISS} \text{ for 8.3 psia}$$

$$\dot{V}_{exploration} = 1.44 * \dot{V}_{ISS} \text{ for 10.2 psia}$$

## c. Adsorbent bed model with mass, heat, and momentum balances

A 1-D simulation has been developed that includes mass, heat, and momentum balances based on work by Knox *et al* 2016 and written in the COMSOL Multiphysics simulation software package. Porous media flow is represented by the Darcy equation. Mixture properties are calculated by the Thermodynamics Properties feature. Adsorption equilibrium capacity for $CO_2$ is represented by the dual site Langmuir equation based on recent literature data (Huang et al, 2017).

Goal: Compare transient bed cooling and $CO_2$ adsorption for different total air pressures to make recommendations for usage in low pressure Exploration environments.

Selected equations from Knox, et al (2016) are shown below to illustrate, in particular, the treatment of the thermal or energy balance.

**Gas-side energy balance**

$$\epsilon a_f \rho_f c_{p,f} \frac{\partial T_f}{\partial t} - \epsilon a_f k_{eff} \frac{\partial^2 T_f}{\partial x^2} = -\epsilon a_f \rho_f v_i c_{P.f} \frac{\partial T_f}{\partial x} + a_f a_s h_s \left(T_s - T_f\right) + P_i h_i (T_w - T_f)$$

**Pellet-side energy balance**

$$(1-\epsilon) a_f \rho_s c_{p,s} \frac{\partial T_s}{\partial t} = a_f a_s h_s (T_f - T_s)$$

Where $T_f$ is the temperature of the fluid(gas), $T_s$ is the temperature of the pellet, $\epsilon$ is the void fraction of the bed, $c_{p,s}$ is the heat capacity of the pellets, $\rho_s$ is the density of the pellets, $a_f$ is the superficial free-flow area, $v_i$ is the interstitial velocity, $c_{p,f}$ is the heat capacity of the fluid, $\rho_f$ is the density of the fluid, $k_{eff}$ is the fluid effective conductivity, $a_s$ is the pellet external surface area per volume, $h_s$ is the gas-pellet heat transfer coefficient, $P_i$ is the inner perimeter of the column, $h_i$ is the heat transfer coefficient between the column wall and the gas phase, and $T_w$ is the column wall temperature.

The equation relating surface area and volume of the bed is:

$a_s = \frac{3(1-\varepsilon)}{R_p}$ , where *Rp* is the radius of the pellet. The density and heat capacity of the pellet is known and assumed to be constant. The dynamic viscosity of the gas can be calculated as a function of the fluid temperature with empirical calculations.

Dimensionless numbers are needed for heat transfer coefficient correlations. The Reynolds number can be expressed as:

$$Re = \frac{2\rho_f \varepsilon v_i R_p}{\mu}$$

where $\mu$ is the dynamic viscosity (Knox et Al). The Schmidt number can be expressed as:

$$Sc = \frac{\mu}{\rho_f D}$$

where *D* is fluid diffusion coefficient and is commonly expressed with the Fuller method . The Sherwood number is expressed as:

$$Sh = 2 + 1.1 Sc^{1/3} Re^{0.6}$$

And the gas-pellet heat transfer coefficient can be estimated as according to Ruthven:

$$h_s = \frac{ShD}{2R_p}$$

We may estimate $k_{eff}$ using the Krupickzka equation along with the correlation of Yagi et al (1960).

### d. Preliminary Simulation Results from Adsorbent Bed Model

A preliminary evaluation was conducted to help understand the influence of reduced pressure on $CO_2$ removal systems. One area of particular concern has been the cooling of the $CO_2$ sorbent bed via process air at reduced pressure. The $CO_2$ sorbent beds are heated for desorption, and this heat must be removed by process air at the start of the subsequent adsorption step. A 4-Bed

Molecular Sieve model using COMSOL Multiphysics previously developed to support the 4-Bed $CO_2$ Scrubber (4B$CO_2$) flight technology demonstration project was used for this analysis (Knox et al. 2016, Giesy 2017).

The COMSOL Thermodynamics module was utilized in this analysis, which includes calculations of gas mixture properties. It has been assumed that those calculations include the full range of pressures and temperatures. However, this should be verified for each property calculation of interest. Also, this model includes only $N_2$ and $CO_2$ presently and thus should be expanded to include $O_2$ at elevated partial pressures as planned for Exploration missions.

Figure A-5 shows the gas mixture properties of heat capacity and thermal conductivity at 5 minutes of simulation time. Variations in bed temperatures along with differences in total pressure drive the observed variations in heat capacity (solid lines). Heat capacity is of primary importance as a term in the gas convection term. Thermal conductivity (dashed lines) vary only due to temperature differences, as evidenced by these lines converging at the bed inlet (flow is right to left) where the temperature for all three pressure conditions is the same. In any case, the magnitude of conductive heat flux is 4 orders less than convective heat flux and so has little influence on overall heat flux.

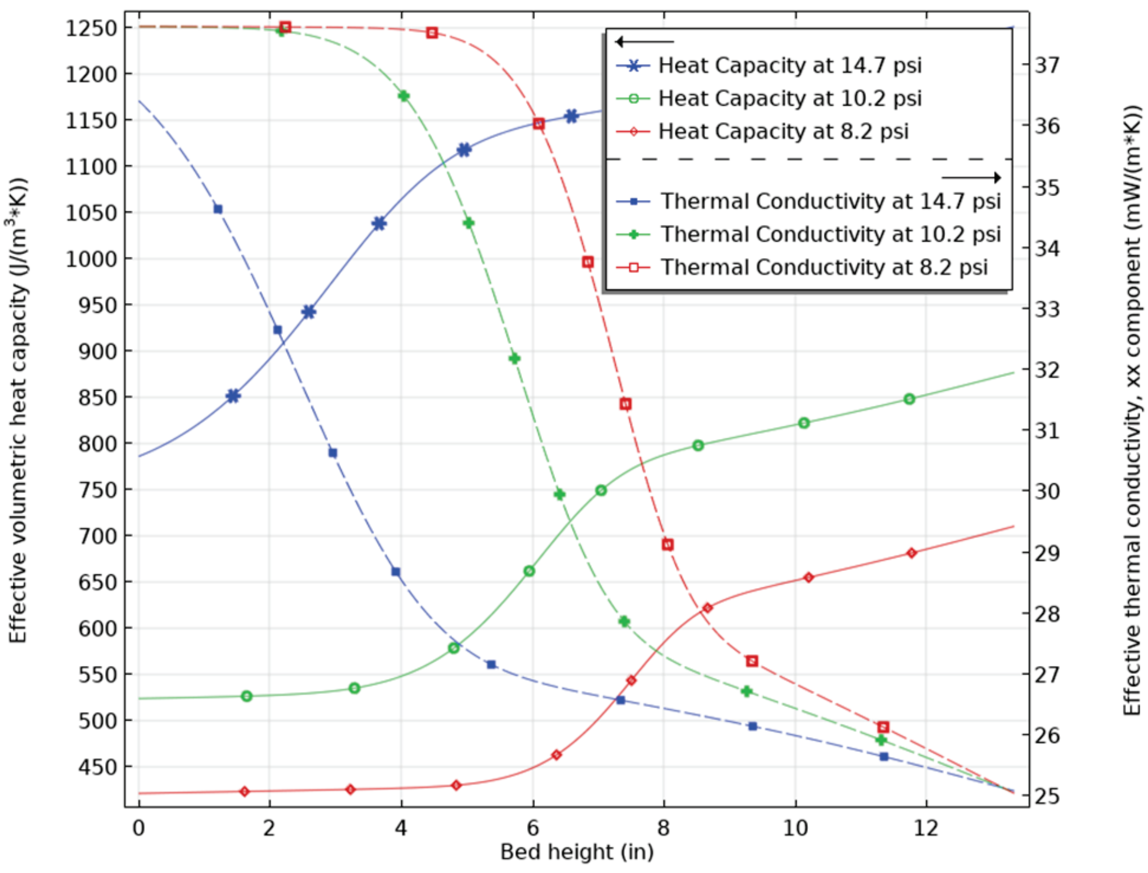


***Figure A-5. Gas Heat Capacity and Conduction Along Sorbent Bed for Total Pressures of 14.7, 10.2, and 8.2 psia at 5 minutes Simulation Time***

Temperatures at three points in the adsorbing sorbent bed are shown in Figure A-6. The bed is uniformly at 400 °F at the start of the simulation, then air at 50-60 °F flows into the inlet. The inlet of the bed cools rapidly and little change of cooling is evident due to total pressure.

However, at the center of the bed, the influence of reduced pressure (and reduced convective heat flux) is evident, with the 14.7 psia case clearly cooling fastest. The same trend is evident at the bed outlet.

However, the temperatures begin to converge by the end of the 80-minute adsorption period. The negative influence of total pressure on the $CO_2$ capacity is thus diminished in this time period, as evident in Figure A-7. Here, the breakthrough curve shows the latest (best) breakthrough for the 14.7 psia case initially as expected for lower temperatures and thus higher $CO_2$ sorbent capacity. However, at about 60 minutes the trend reverses and the 8.2 psia case has the slowest and best breakthrough curve. This was not expected, as the model does not include internal pellet diffusion and thus would not show improve kinetics due to reduced interference of non-active gas molecules.

In conclusion, this preliminary model has demonstrated that, although reduced pressure has an obvious effect on the combined heat and mass transfer in adsorption physics, overall impact to the $CO_2$ removal efficiency may be minor, at least for the specific hardware modeled here. Further studies should be conducted to validate the gas mixture models, include $O_2$ at appropriate partial pressures, and include the diffusion kinetic models that would actually benefit from reduced total pressures.

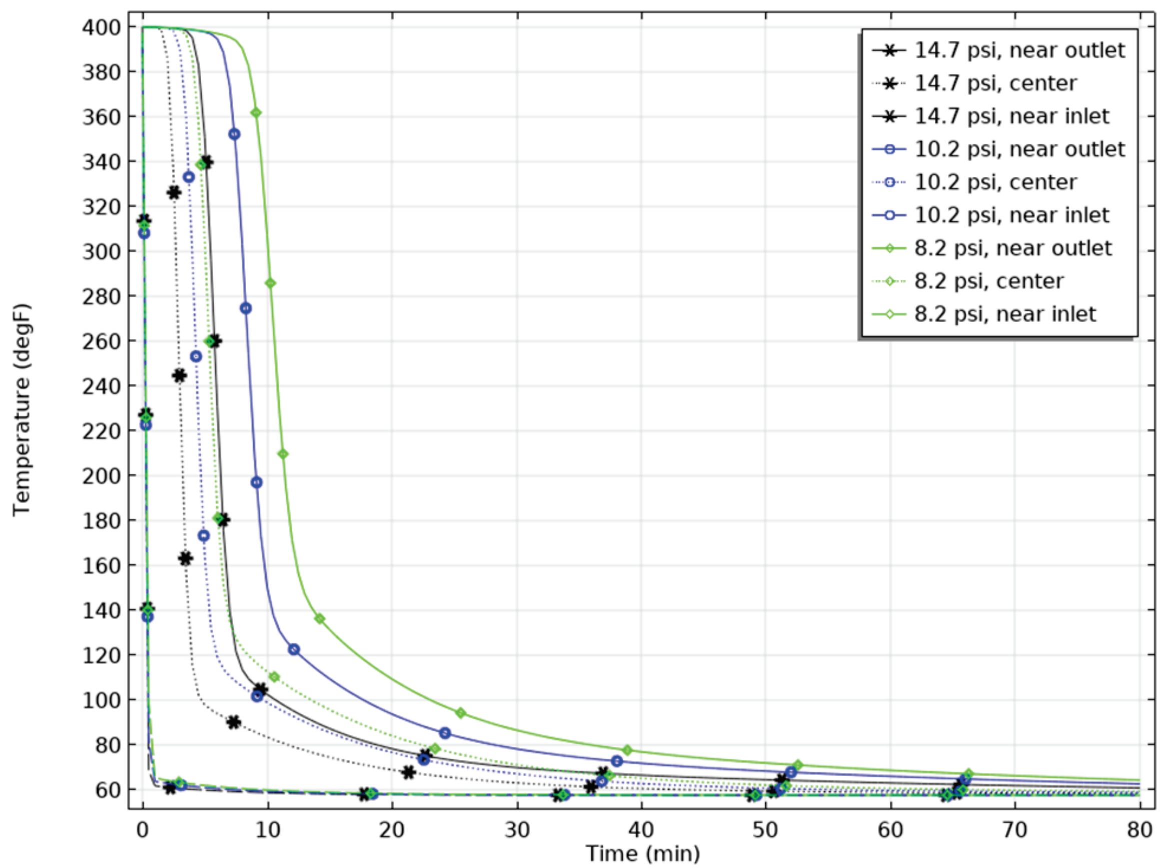


***Figure A-6. Temperature History at Three Points in Adsorbing Sorbent Bed for Total Pressures of 14.7, 10.2, and 8.2 psia***

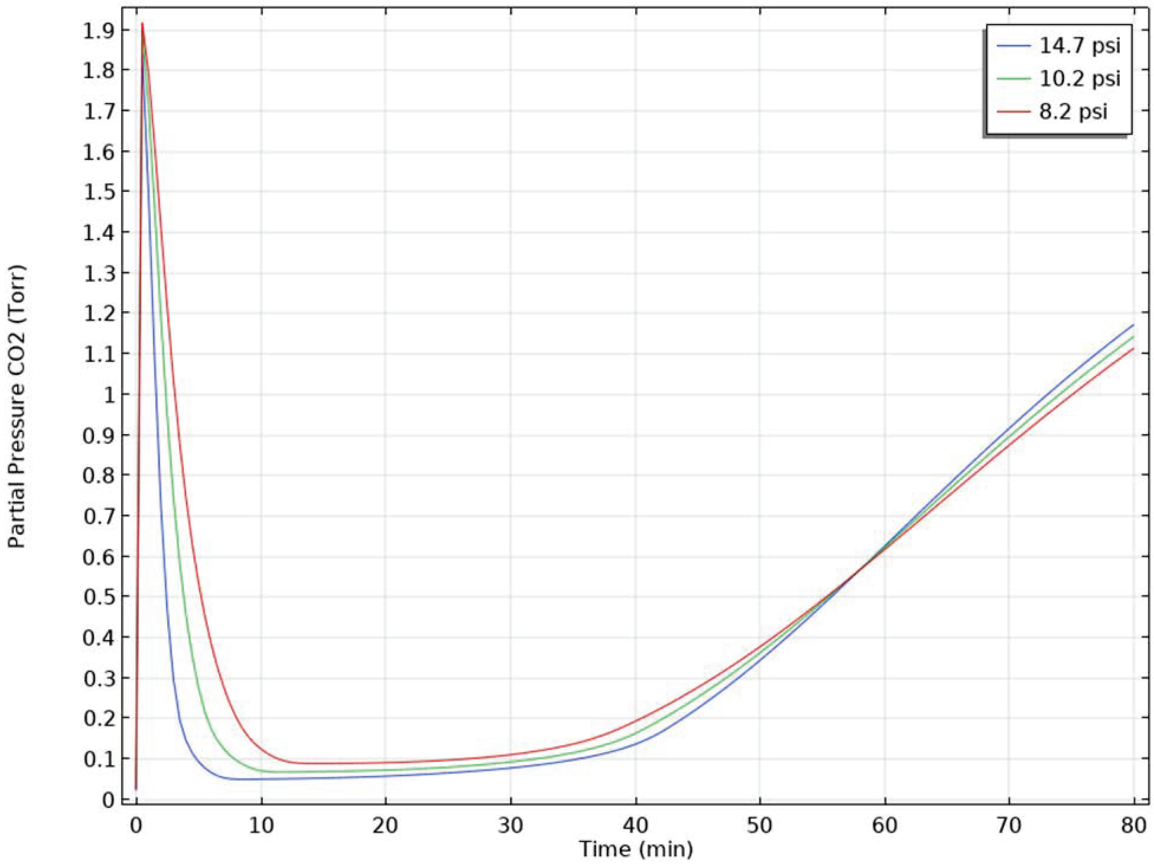


***Figure A-7. Breakthrough of $CO_2$ for Total Pressures of 14.7, 10.2, and 8.2 psia***

## References

Knox, J. C. (2016). "Limitations of Breakthrough Curve Analysis in Fixed-Bed Adsorption." Industrial and Engineering Chemistry Research, 55(16), 4734-4748.

Huang, R., et al. (2017). CO2 Capacity Sorbent Analysis using Volumetric Measurement Approach. 47th International Conference on Environmental Systems. Charleston.

Ruthven, D. M. (1984). Principles of Adsorption and Adsorption Processes.

Yagi, S., et al. (1960). "Studies on Axial Effective Thermal Conductivities in Packed Beds." AIChE Journal 6(4): 543-546.

Giesy, T. J., et al. (2017). Virtual Design of a 4-Bed Molecular Sieve for Exploration. 47th International Conference on Environmental Systems. Charleston.

## 3. Notes/Other

***TCCS Usage in Exploration Atmospheres***

*Meeting between Jay Perry and Chase Hopkins, 05/05/2021 2:30-3:30 PM EST*
*Notes compiled by Chase Hopkins*

**<u>Key points:</u>**

1. Source contamination control is the biggest takeaway from conversation with Mr. Perry. ISS has been seeing issues unpleasant odors as the result of venting from the BPA. These odors occur at concentrations far below levels that present health risks; however, the smells can negatively affect quality of life. This effect will be increased in a smaller cabin environment like those intended for Exploration. As such, to prevent unnecessarily large increases in mass and complexity to the TCCS, source contamination control should be implemented in hardware producing large venting of odorous vapor (BPA). This would be in the form of a carbon bed and/or additional packed beds.
2. Input loads to the TCCS will not be affected by pressure. This includes loads from the crew and equipment offgassing (appreciable increases in offgassing only occur near or at hard-vacuum (out-gassing)).
3. The packed beds will exhibit the same saturation capacity.
4. TCCS uses a variable speed blower to correct for changes in pressure. It uses a flow meter to monitor and ensure a constant mass flow rate. The calibration of this may need to be changed for lower pressures.
5. The blower is variable speed but is not expected to meet performance requirements "as-is" in Exploration environments.
6. The high temperature catalytic oxidizer will require less power to operate at the same set point temperature for the same volume flow rate. For a constant mass flow rate, we may expect a roughly equal power requirement.
7. There is a small risk of carbon bed-fire, particularly in 34% $O_2$ environment. This is a very large risk if using regenerative beds with T, P swing to desorb. There is an example from MIR where Russians beds were being used regeneratively and cabin air was passed over a freshly regenerated bed before it cooled adequately—a bed fire erupted, resulting in a large cloud of smoke and CO poisoning for the crew.

***Discussion with Mr. Kevin Takada***

*Meeting on OGA usage in Exploration environments between Kevin Takada, Bob Bagdigian, and Chase Hopkins on 06/28/2021, 10-11 AM EST*
*Notes compiled by Chase Hopkins*

**<u>Key points:</u>**

- ISS OGA is very similar to AOGA. AOGA uses two separate domes to allow independent servicing of cell stack/RSA. AOGA not anticipated to fly until 2025.
- The cell stack and RSA are in a dome exposed to vacuum for safety.
- $N_2$, feedwater, and recirc loop pressures are all greater than 20 psia.
- Shouldn't expect any impacts from low P—leakage (in/out) could be decreased.
- $O_2$ outlet is exposed to cabin atmosphere—therefore: so is $O_2$ side of cell stack.

- Could see a change in separation across membrane. Could see more $H_2O$ carryover into $O_2$. More analysis would be required to understand the transport mechanism of water and its driving forces. (%Rh in membrane or in cabin?) Diffusion driven.

- This decreased pressure could impact outlet $H_2$ sensors, cell performance (unlikely).
  - $H_2$ sensors use catalytic beads to sense $H_2$ via temp change from $O_2/H_2$ rxn over catalyst. Likely need to re-calibrate for novel thermal environment.
- Simplest solution would be to install a backpressure regulator on $O_2$ vent to maintain 14.7 psia. Could cause un-optimal design.
- Lower $O_2$ vent pressure could decrease MDP determined by initiating detonation pressure.
- Risk of detonation due to ambient $O_2$ leakage-in needs to be understood with leak rates and material balances.
- OGA is cooled via MTL. There is minimum convective cooling via AAA.
- AAA is used to drive air through rack to dilute $O_2$ in a possible loss-of-containment event. Max $O_2$ concentration after dilution in the rack is 29% (would need to be assessed and updated).
- OGA was built at MSFC in conjunction with Collins. Kevin will look for and send $O_2$ concentration certification/assessment to share.
- $H_2$ vent to Sabatier utilizes backpressure reg., so would not be impacted by any changes to Sabatier operating pressure.

***Drag Force Estimation/Calculation Notes***
*Compiled by Chase Hopkins*

The drag force on a body of area A:

$$F_d = \frac{1}{2}\rho u^2 c_d A$$

*Cd* is the drag coefficient which depends on object geometry and Reynolds number + mach number of the fluid (if fluid is a gas)

So for same *Cd*: $F_d \propto \frac{1}{2}\rho u^2$ and we can estimate the reduction in drag force due to density decrease in Exploration environments. But *Cd* should be dependent on cabin pressure and thus impacted. Correlations are available. A lower-bounding case should be such that assumes constant drag coefficient.

***Low Pressure/High $O_2$ Effects on ECLSS Hardware***
*NESC Discussion with Boeing and Collins*
*01/02/2021 11:00 AM – 1:00 PM EST*
*Meeting notes prepared by Bob Bagdigian, Chase Hopkins, Morgan Abney*

**OGA**

- OGA has three barriers from ambient during shutdown: three valves and a shutdown anode purge. So pressure on shutdown in recirculation loop should be higher than ambient in Exploration environments. Needs a review of recovery/reactivation procedures. Needs investigation (**analysis** and **maybe testing**).
- Water permeation due to the increased gradient from cathode to anode in Exploration environments could potentially overcome protonic-dragging of water in the opposite

direction from anode to cathode. Likely will cause increased hydration of the cell stack, potentially flooding the anode side, and additional humidity in the $O_2$ vent stream. Needs investigation to determine the effect of change in pressure gradient across the cell stack (**analysis** and **testing**)
  - This effect may be different for different cell types (i.e., OGA cells vs AOGA cells) specifically due to increased delta pressure from 12 psid to 18 psid (**ask Giner)**
  - Change in pressure of the anode ($O_2$ side of the cell stack) will cause a need to decrease the pressure of the recirculation loop if water permeation to the anode is found to be excessive. Too low of pressure could potentially cause cavitation in recirc loop pump (**analysis)**.
  - This would likely require a large amount of work, including changes to the RSA $H_2$ relief valves and high/low setpoints (**analysis)**

- OGA delivers water to the waste water bus which will be impacted by pressure change through the waste water ORU bellows tank and through a (potential) change to OGA pressure as mentioned above. Could cause back-flow (**analysis)**.
  - Could potentially solve through a back-pressure regulator on $O_2$ vent to increase anode cell pressure to the its nominal ISS pressure. This would not require decreasing the recirculation loop pressure and doing so would violate hazard controls.
  - Controller and some software setpoints would need to be changed.
- Hydrogen sensors in the $O_2$ vent line need to be reassessed and possibly testing for lower pressure, depending on OGA configuration (**analysis** and **possible testing)**.
- May see impacts caused by decreased potable water bus pressure (from reference to ambient through bellows) which delivers feedwater to RSA and sets the OGA RSA pressure (**analysis)**.
- Hazard analyses include assumption of $O_2$ vent/leak dilution in rack maintaining safe environment.  Need to evaluate dilution with lower pressure/higher $O_2$ ambient (**analysis)**

**AAA**

- Handbook states AAA was designed for 9 psia, but testing did not include the same heat load. Operation was successful at decreased capability. Need to evaluate performance at lower pressure (to 8.2 psia) and the same heat loads (**analysis and test)**.
- AAA provides mixing inside OGS rack for control of potential release of $O_2$ below 28% maximum concentration. This would need to be updated for Exploration $O_2$ concentrations (**analysis)**.
- Decreased heat transfer in the racks and cabin will cause decreased efficiency and requiring scaling to be accounted for.
- AAA uses open cell acoustic insulations which only pass flammability for up to ~32% $O_2$. This is also used in numerous other hardware. Development and testing is required for replacement materials (**testing and development)**.
- Filters in AAA will see increased volume throughput and thus foul sooner. Will need increased cleaning/maintenance frequency and potentially design changes.
  - Afterthought from Morgan: Do we expect to generate more particles in the vehicle? If not, wouldn't we see similar loading, regardless of the volume?

**CCAA**

- CCAA can nominally deliver 500 cfm, but only 300 cfm in the airlock at 10.2 psia (not accounting for density-impacts) due to restrictions from the CHiPS filters.
  - Airlock CCAA is currently operating well.
  - Possible test up to 500 cfm at 10.2 psia would require replacement of CHiPS filters with HEPA filters (**test)**
- Expected to see decrease in heat rejection due to density decreases.
- Will see performance decreases in heat rejection requiring increased fan speeds. Analysis and testing are required to better understand this in the desired Exploration pressures. The impacts will be larger for 8.2 psia and possibly requiring development testing **(analysis)**.
- Sizing/flow would need to be scaled for reduced HX efficiency in low pressure (**analysis)**
- The water separator outperforms requirements on air % (v/v) in the condensate by a lot. But lower pressures and their required increased volume throughput for cooling may impact the water separator. Additionally, could see impacts from air velocities down the slurper bars including increased gas to the separator. This will all depend on the application of CCAA and needs analysis and test data (**analysis** and **test)**.

**WPA**

- AAA air is used for supplemental cooling of the controller (which is on a coldplate). Loss of AAA requires shutdown of WPA. This cooling will be decreased as previously mentioned and thermal control of the controller needs to be assessed with analysis (**analysis)**.
- Reactor pressure may be decreased by decrease in ambient pressure. This is referenced to ambient through the waste water tank. (And a regulator?) This needs to be investigated. Likely not a big issue, especially for the new next gen catalyst (**analysis** and **test)**.
- The impact of decreased sweep gas density on separation in the GLS needs to be investigated and tested. This will go through a deltaCert regardless because of the expected change in supplier for future membrane modules **(test).**
- The waste water bellows tank has caused issues before with decreased pressure. It may be worth it to investigate a higher bellows tank pressure. It currently uses 1-3 psig (**test)**.
- The MLS is referenced to ambient and performance needs to be tested for Exploration pressures (**test)**.
- May see some issues with the water delivery ORU through bellows tank reference to ambient. Could see a lower absolute pressure on the potable water bus which could have downstream impacts (i.e., OGA RSA pressure) (**test)**.

**IMV**

- IMV will not require increased speeds because only constant volume flow is required.
- The IMV controller is heat-sinked to the airflow stream for thermal control. As constant volume flow rates across a range of pressure is anticipated, the controller will see decreased cooling in Exploration environments. Needs analysis and potentially development for increased cooling (**analysis** and **development)**.