Evaluation of Heritage Hardware for Use in Cabin Environments with Reduced Pressure and Increased Oxygen Concentration

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On the International Space Station (ISS), the crew perform pre-breathe procedures prior to Extravehicular Activity (EVA) to prevent decompression sickness as their bodies transition from the ISS ambient environment of ~14.7 psia and ~21% oxygen (O_2), to the ~4.3 psia and 100% oxygen environment of the suits. To reduce or eliminate the time required for this transition, exploration missions with high-frequency EVA, such as Lunar surface or Martian surface missions, are considering cabin environments of 10.2 psia and 26.5% O_2 and 8.3 psia and 34% O_2. Although beneficial to EVA operations, these new environments will have consequences on cabin hardware including the environmental control and life support systems (ECLSS), the crew health care system (CHeCS), and crew habitation systems. Given the agency focus on crewed exploration missions within the next decade and incentives to utilize flight-proven cabin hardware, a comprehensive assessment of hardware suitability is needed to begin retrofit and development of exploration cabin hardware. Here we report the results of a study to evaluate the effects of reduced pressure and increased cabin oxygen concentration on the operational performance, the thermal performance, and the material flammability of ISS heritage systems. A discussion of possible mitigations for negative effects and their relative impact on mission planning is provided.

Nomenclature

AAA	=	Avionics Air Assembly
AGA	=	Air Quality Monitor
AM	=	Acoustic Monitor
BPA	=	Brine Processor Assembly
CAD	=	Crew Active Dosimeter
CCAA	=	Common Cabin Air Assembly
CDRA	=	Carbon Dioxide Removal Assembly
Cp	=	specific heat of fluid
CRA	=	Carbon Dioxide Reduction Assembly
CWQMK	=	Colorimetric Water Quality Monitoring Kit
DA	=	Distillation Assembly
DMS	=	Differential Mobility Spectrometer
EVA	=	Extravehicular Activity
GC	=	Gas Chromatograph
GLS	=	Gas Liquid Separator
HERA	=	Hybrid Electronic Radiation Assessor
HX	=	Heat Exchanger
IMV	=	Intermodule Ventilation Fan
ISS	=	International Space Station
lbm	=	pounds mass
MAPTIS	=	Materials and Processing Technical Information System
MCV	=	Multipurpose Crew Vehicle
MUA	=	Material Usage Agreement
N_2	=	Nitrogen
O_2	=	Oxygen

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OGA	=	Oxygen Generation Assembly			pressure (14.7 psia)
OSEF	=	Orion Smoke-eater Filter	SPA	=	Separator Plumbing Assembly
PCA	=	Pressure Control Assembly	*T1*	=	fluid inlet temperature
PFE	=	Portable Fire Extinguisher	*T2*	=	fluid outlet temperature
P_{Nom}	=	Nominal cabin pressure (14.7 psia)	TCCS	=	Trace Contaminant Control System
P_{Exp}	=	Exploration cabin pressure	UPA	=	Urine Processing Assembly
psia	=	pounds per square inch	UWMS	=	Universal Waste Management System
Q	=	heat rejected from fluid	V	=	velocity of fluid through internal duct
Q_{Exp}	=	Heat rejected from air for Exploration cabin pressure	V_{dot}	=	volumetric flow rate
			WPA	=	Water Processing Assembly
Q_{Nom}	=	Heat rejected from air for nominal cabin	ρ	=	density of fluid

I. Introduction

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 atmospheric conditions that will best enable safe and efficient mission execution. Although human physiology presents limits beyond which atmospheric 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, particularly the nominal total pressure and oxygen (O_2) content of the habitat. 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.[1]

One of the attractive benefits of a relatively low cabin pressure is its effect on Extravehicular Activity (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.

Lunar and Martian surface missions 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.[1] 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. As such, potential atmospheric conditions considered for future Exploration missions include 10.2 psia/26.5% O_2[2] and 8.2 psia/34% O_2.[3] Accordingly, the ability of available hardware to control within these limits dictate that Exploration systems be designed and certified at higher O_2 concentrations.

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 also 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 sub-ambient chemical reactors).

The long and successful operation of systems aboard the International Space Station (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[4], 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 Environmenal Control and Life Support Systems (ECLSS), Crew Health Care Systems (CHeCS), and crew habitation systems.

II. Assessment Approach

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. A total of 33 subsystems and components (Table 1) were assessed based on their use or demonstration on ISS.

Table 1. List of Assessed Hardware.

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

Specific, quantitative impacts 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 identified the specific hardware that would be impacted, described how and to what extent, and offered qualitative suggestions for potential mitigations. This provides the basis by which developers of Exploration systems can determine the best mitigation approach for their intended application.

A. Assessment Depth and Confidence

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. In some cases, development and certification information of a given system was available only at the original vendor and not available for review by the team. In these cases, an assessment was made based on what was available in the ISS Program records or subsystem manager's records. 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 (SME) insight 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 or previous analysis were available to the team.
- Confidence in assessment (i.e., how thorough was the assessment?)
  -  Green: Assessment complete or nearly so. Additional 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; future or more in-depth analysis expected. Result backed by conceptual analysis and assessment.
  -  Red: Little to no assessment completed. Assessment results based on minimal available information. Likely to contain high uncertainty and error.

B. Performance, Thermal, and Materials Impact Assessment

Each subsystem was evaluated for impacts to subsystem or component performance, impacts to thermal performance, and material flammability and toxicity impacts based on hardware materials as implemented on ISS. Impacts were categorized and color-coded for ease of review as shown in Table 2.

Table 2. 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

Content coded as purple indicated an impact with insufficient data to evaluate or when there were two or more pieces of data with conflicting data. In these cases, additional efforts were made to locate new information or speak with SMEs, but no additional data could be obtained. Green content were determined to have sufficient data available to make an evaluation and no negative impacts were identified. In these cases the hardware would be expected to be usable in the current design. Blue content indicated that full information was not available, but enough was available such that a determination of no anticipated impacts could be made. A grey designation was used when the data suggested that impacts would occur, but that the impacts were either sufficiently small, or were unlikely to warrant redesign of the system in future missions. Yellow, orange, and light red designations were used when the data suggested impacts would occur and design modifications would be required for use in Exploration missions. In these cases, they were qualitatively ranked based on engineering judgement of the level of effort expected to make the hardware usable for Exploration missions. Finally, dark red indicated a system for which no engineering documentation was available, but changes were expected based on general knowledge of the system or component.

III. Assessment Results

A total of 33 subsystems and components were evaluated to identify impacts of low pressure and high O_2 on functional performance, thermal performance, and materials based on their implementation on ISS. Due to incomplete data on some of the subsystems evaluated, the team attempted to communicate the depth of the review and their confidence in the results as described in Section III-C. Several multisystem impacts were identified as described in Section III-D with a summary of the results of each subsystem and component discussed in Section III-E below.

C. Depth and Confidence of Assessment Results

An overview of the depth of and team confidence in the assessment of each evaluated subsystem is provided in Table 3. 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. As such, more information will be required before a complete assessment may be conducted for these subsystems.

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

Subsystem	Depth	Confidence	Subsystem	Depth	Confidence
ECLSS			**CHeCS**		
AAA			AGA		
BPA			AQM		
CCAA			CAD		
CDRA			CWQMK		
ISS PFE			HERA		
MPCV PFE			MinION		
Emergency Mask			Acoustic Monitor		
TCCS			Flywheel Exercise Device		
CRA			**Crew Habitation Systems**		
OSEF			Cordless Vacuum Cleaner		
IMV			Crew Quarters		
OGA			Galley Rack PWD		
PCA			Galley Rack FRIDGE		
Fire and Ammonia Cartridges			Galley Rack Food Warmer		
UPA			ISS Food Warmer		
UWMS			U.S. Sleeping Bag		
WPA			MPCV Sleeping Bag		

D. Multisystem Impacts

During the assessment, several common observations were made across multiple subsystems for functional performance, thermal performance, and materials. Each is summarized below.

1. Functional Performance Impacts

Four types of multisystem impacts were identified in the area of functional performance including a) fans, blowers, and air movers, b) packed beds and particulate filters, c) ambient-referenced valves, regulators, sensors, and bellows, d) acoustics, and e) gas-liquid microgravity separators.

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 lbm/ft3 (1.2 kg/m3), 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).

Fixed beds (canisters loaded/packed with sorbents, catalysts, and/or exchange-resins) 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 gases. 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). 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 the same way. 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. 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. 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.[5] 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.[6] 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. Ultimately, 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, non-linear effect on heat and mass transfer, such that conclusions on the net difference in efficiency for packed sorbent and catalyst beds and cannot be deduced directly. 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.[7] 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.

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. As an example, 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 such as 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.

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.[8] Further complicating any prediction about whether a lower cabin pressure will be "better" or "worse" acoustically is the possibility 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 modeling of the specific vehicle and systems.

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. As the pressure and temperature are considered in the design of gas-liquid separators, a change in pressure from the design point/range may cause a decrease in separation performance. 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.

2. *Thermal Performance Impacts*

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 that 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:

$$Q = A * V * \rho * Cp * (T1–T2) \qquad Eq.\ 1$$

Where Q = heat rejected from fluid, A = cross-sectional area of internal duct, V = velocity of fluid through internal duct, ρ = density of fluid, Cp = specific heat of fluid, $T1$ = fluid inlet temperature, and $T2$ = fluid outlet temperature.

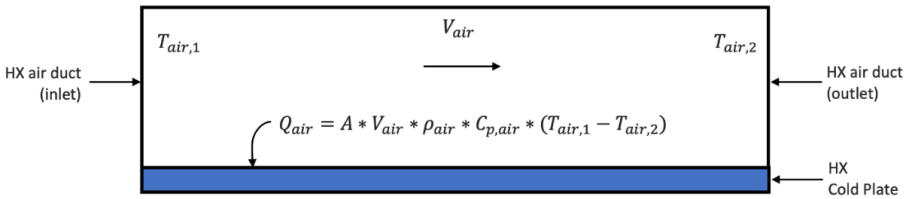


Figure 1. One-dimensional Steady-state Heat Equation

Table 4. 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
ρ = 0.0743 lbm/ft^3 (1.191 kg/m^3)	ρ = 0.0515 lbm/ft^3 (0.825 kg/m^3)	ρ = 0.0418 lbm/ft^3 (0.67 kg/m^3)
C_p = 0.2396 Btu/lb/°R (1.0025 kJ/kg/°K)	C_p =0.2395 Btu/lb/°R (1.0022 kJ/kg/°K)	C_p = 0.2395 Btu/lb/°R (1.0020 kJ/kg/°K)

As illustrated in Figure 1, Equation 1 can be used to simulate the heat transfer associated with cabin air flowing through a generic air/water Heat eXchanger (HX). As shown in Table 4**Error! Reference source not found.**, air density varies linearly with pressure, while specific heat remains relatively constant. Combining Equation 1 with the data in Table 4, we can derive the following relationship:

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

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), and 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 5 for ISS and Exploration cabin pressures. 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. This will manifest as a decrease in the ability of equipment to reject heat via convection. 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:

Table 5. 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}	$Q_{Exp} = 0.694 * Q_{Nom}$	$Q_{Exp} = 0.565 * Q_{Nom}$

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.

3. Materials and Processes

Two types of multisystem impacts were identified in the area of materials included offgassing and flammability. 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 ISS may not be acceptable for smaller vehicles. As an example, concentrations in a vehicle with an internal free volume of 530 ft^3 (15 m^3) would be a factor of 8 higher than in ISS (i.e., free volume for offgassing calculation uses 4167ft^3/118 m^3). Materials offgassing test data in the NASA Materials and Processing Technical Information System (MAPTIS) database are reported in terms of maximum limit weights for the ISS and vehicle-specific 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 ISS or alternative vehicle. These values can be converted to maximum limit weights or number of units for the volume of Exploration vehicles. Toxic offgassing rates are expected to have little dependence on pressure until molecular flow starts to occur (e.g., <1 E-3 torr). Therefore, pressure should not have a significant effect on toxic offgassing for the range of pressures that will be seen in Exploration atmospheres. However, there is a lack of empirical data on the effect of pressure on toxic offgassing rates (F-11). Acceptable quantities of offgassing contaminants on 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.

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[9] 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. 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.[10,11,12,13] Additional work is being conducted to better understand these differences, but definitive data will not be available to affect the nearest-term programs. 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 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. Similarly, 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.

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 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 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.

E. Summary of Subsystem Impacts

Table 6 provides a summary of the impacts identified for individual subsystems and components. Detailed analysis and discussion of impacts is available on NASA's Technical Reports Server.[14] The color coding is described in Table 2. Identified key impacts to each subsystem are summarized below.

Table 6. Summary of ISS Subsystem Functional Performance, Thermal Performance, 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
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						

AAA: AAA fan performance will be decreased in low pressure environments without aerodynamic optimization of blade angles. 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. Lower density air has a decreased per volume heat capacity. 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. For 10.2 psia, upwards of 40% increased volume flow through the racks is required for the same heat load and temperature limits. For 8.2 psia, upwards of 80% increased volume flow through the racks will be required for the same heat load and temperature limits.

BPA: The bladder used in the BPA is semipermeable, and 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. BPA avionics hardware receives cooling from cold plates, natural convection, and forced convection via process air.[5] 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. The BPA uses materials flammable in ISS environments (i.e., bladder) up to 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. The brine processor bladder was specifically tested for offgassing in ISS, and results show that it is acceptable for offgassing in smaller volume vehicles. The other BPA materials were verified acceptable for 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.

CCAA: Without aerodynamic optimization, CCAA fan performance will be impacted by flow effects in lower pressure requiring increased volumetric flow to maintain the crew within temperature limits. CCAA will see decreased sensible HX performance caused by decreased air density. This could be mitigated by increased air flow rates through the CCAA**.** 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. The CCAA HX 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. 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 ISS.

CDRA: 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. It is likely the CDRA blower or 4BCO_2 blower (mag-lev) under development will not meet the required volumetric flow in Exploration environments. 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.[15] 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.

CRA: Decreased pressure within in the Sabatier reactor will have thermodynamic and potentially kinetic impacts on the process. Thermodynamically, the lower pressure operation will decrease carbon dioxide conversion [refs. 22, 32].[16,17] 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.

PFE: The ISS water-mist and MPCV water-spray PFEs are certified for use in a 10.2 psia and 30% O_2 environment.[18] 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. Increased O_2 concentrations could decrease the ability of water-spray and/or water-mist PFEs to extinguish a fire. The Nomex cover used on the ISS PFE will not meet flammability requirements at the highest Exploration O_2 concentrations. However, Nomex may be acceptable if treated with a fire retardant.

Emergency Mask, Fire, and Ammonia Cartridges: Cartridges may have reduced performance due to kinetic changes of catalytic reactions or the reduced pressure drop impacts. This may necessitate geometric changes to the filters for 8.2 psia. 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. 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.[19] 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. 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).

OSEF: The OSEF may have kinetic impacts related to fluid velocity necessitating sorbent or catalyst bed dimensional change. Decreased heat capacity of process air may result in higher steady state temperatures, which could decrease sorbent capacity or catalyst performance.

IMV: 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, which may necessitate alternative cooling approaches for Exploration. An evaluation of IMV materials was not possible due to lack of data.

OGA: 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 operational and safety 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. 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. Other impacts to the OGA are caused by a possible decrease in pressure of the wastewater bus. If the recirculation loop pressure is decreased, then possible impacts include dissolved H2 coming out of solution in the recirculation loop, required changes to the rotary separator accumulator high/low setpoints, and out-of-range sensors. 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 materials and processes concerns. Specifically, H2 sensors are used in the O_2 vent stream to monitor H2 concentrations and shut down OGA in the event H2 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 H2 sensors and/or cause premature failure due to increased water content in the product O_2. The OGA may be acceptable for flammability for all Exploration environments with changes to the insulation.

PCA: There are no anticipated impacts to the pressure control assembly.

TCCS: A dimensional change to the TCCS carbon bed (i.e., aspect ratio) may be needed to achieve the required residence time for proper kinetics. The fan will have performance impacts due to aerodynamic concerns. The high temperature catalytic reactor may need less heat supplied by the heater to reach the reaction temperature, potentially offering power-saving benefits.

UPA: The gas separation efficiency of the UPA's Separator Plumbing Assembly may be decreased due to a lower shell-side pressure (i.e., reduced driving force) if the assembly is vented to a reduced pressure cabin. Some pressure switches will be impacted (e.g., in the SPA). However, these may be mitigated through set point recalibration. Distillation Assembly (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. 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.

UWMS: 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. 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. 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. 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 decreased pretreat quantities in an Exploration environment. 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. 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 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, and with the possible exception of the urine hose assembly, is acceptable to 30% O_2 at 10.2 psia. 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 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.

WPA: 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 overall WPA system performance. For Exploration, the wastewater bellows tank 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 to compensate for decreased upstream pressure.

AM: No performance impacts are expected due to reduced pressure environment. No information was available for the commercial-off-the-shelf acoustic monitors to assess thermal impacts of an Exploration atmosphere. The AM 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 not for higher O_2 concentrations. The belt pouch is flammable in the highest O_2 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 is necessary for Exploration vehicle volumes.

AGA: Preliminary testing[20] 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. 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. The AGA internal electronics are flammable and combined with the AGA fan cooling reduces the confidence in the ability of the box to contain a fire in Exploration atmospheres. Flammability and offgassing testing will be necessary at Exploration environmental conditions to quantify the risk.

AQM: Because the AQM uses filtered cabin air as the mobile phase in the gas chromatograph (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 differential mobility spectrometer (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 radio-frequency voltages unique to each ionized contaminant as compared to nominal ISS atmospheres at 14.7 psia and 21% O_2.[21] 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. The AGA 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 polyimide flag labels used on power cables are flammable and need to be replaced.

CAD: There are no anticipated impacts to the Crew Active Dosimeter.

CWQMK: O_2 permeability of the CWQMK packaging material may accelerate oxidative degradation of the iodine-specific membranes required for the analysis but testing would be necessary to quantify impacts on shelf life. It is undetermined of the Exploration pressure and/or O_2 concentration will affect the CWQMK chemical reactions or the packaged reagent shelf life.

Flywheel Exercise Device: The thermal load of the flywheel device and impacts to its thermal properties are unknown and could not be assessed. Toxic offgassing is unknown for Exploration vehicles and habitats.

HERA: HERA is designed to operate from space vacuum to 17.2 psia and an O_2 concentration range of 0-40%. Impacts of an Exploration atmosphere to performance are not expected

MinION: Depending on the permeability of the packaging materials used, higher O_2 concentrations may accelerate oxidative degradation of MinION reagents. The MinION has a clear polymethyl methacrylate (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

Cordless Vacuum Cleaner: Hearing protection is required for medium and high settings of the vacuum. 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 increasing the acoustic risk. The final result of these competing effects will require testing to quantify. There are a number of flammable materials on the vacuum. However, control of these materials on ISS is managed through battery removal during storage and crew monitoring when in use. These controls are reasonable for the relatively low O_2 concentration on ISS, but their 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.

Crew Quarters: 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. 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. 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.

Galley Rack PWD: 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. Successful implementation will be required for operation in Exploration environments.

Galley Rack FRIDGE: 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. No data was available on materials of FRIDGE to assess.

Galley Rack Food Warmer: The Galley Food Warmer internal temperatures can range from 145 to 190 °F (63 to 88 °C) during the warm-up process. While the ultimate target temperature may be reached in reduced pressure environments, contents may take longer to warm to the desired temperature, affecting meal planning, preparation, and shared meal times. 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, forced convective or water loop cooling will be required. Melamine foam is used as a thermal insulation and 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 melamine foam is also an issue for toxic offgassing in smaller volumes than ISS.

ISS Suitcase Food Warmer: The ISS suitcase food warmer 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.

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.

US Sleeping Bag: The US sleeping bag contains materials that would require special operational controls for use at 30% O_2, 10.2 psia due to flammability and is unacceptable at higher O_2 concentrations. US 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 MPV cabin volume (530 ft^3/15 m^3). A similar bakeout would be required for use in Exploration vehicles of similar size.

MPCV Sleeping Bag: The MPCV sleeping bag contains materials that are acceptable at 30% O_2, 10.2 psia but will require redesign for 34-40% O_2 at 8.2 psia. Like the US sleeping bags, the 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 cabin volume (530 ft^3/15 m^3). A similar bakeout would be required for use in Exploration vehicles of similar size.

IV. Conclusions

Definitive quantitative determinations of the "best" mitigation strategies for each of the performance, thermal, and materials impacts observed in this assessment 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).

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