

An Assessment of Environmental Health Needs

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Environmental health fundamentally addresses the physical, chemical, and biological risks external to the human body that can impact the health of a person by assessing and controlling these risks in order to generate and maintain a health-supportive environment. In manned spacecraft, environmental health risks are mitigated by a multi-disciplinary effort, employing several measures including active and passive controls, by establishing environmental standards (SMACs, SWEGs, microbial and acoustics limits), and through environmental monitoring. Human Health and Performance (HHP) scientists and Environmental Control and Life Support (ECLS) engineers consider environmental monitoring a vital component to an environmental health management strategy for maintaining a healthy crew and achieving mission success. ECLS engineers use environmental monitoring data to monitor and confirm the health of ECLS systems, whereas HHP scientists use the data to manage the health of the human system. Because risks can vary between missions and change over time, environmental monitoring is critical. Crew health risks associated with the environment were reviewed by agency experts with the goal of determining risk-based environmental monitoring needs for future NASA manned missions. Once determined, gaps in environmental health knowledge and technology, required to address those risks, were identified for various types of exploration missions. This agency-wide assessment of environmental health needs will help guide the activities/hardware development efforts to close those gaps and advance the knowledge required to meet NASA manned space exploration objectives. Details of the roadmap development and findings are presented in this paper.

Nomenclature

AQM	=	air quality monitor
CDM	=	carbon dioxide monitor
CDRA	=	carbon dioxide removal assembly
CSA-CP	=	compound specific analyzer - combustion products
CWC	=	contingency water container
DRM	=	design reference mission
ECLS	=	environmental control and life support
EHS	=	environmental health system
EVA	=	extravehicular activity
FCS	=	flight crew systems
FGB	=	Functional Cargo Block
HHP	=	Human Health and Performance
HMS	=	health maintenance system
ISS	=	International Space Station
IMV	=	intra-module ventilation
LEO	=	low-Earth orbit
LSAH	=	lifetime survey of astronaut health
MCA	=	major constituent analyzer
NIEH	=	National Institute for Environmental Health
NTP	=	National Toxicology Program
OGA	=	oxygen generating assembly

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PEL	=	permissible exposure limit
POM	=	portable oxygen monitor
PWD	=	potable water dispenser
SLM	=	sound level meter
SM	=	Russian Service Module
SME	=	subject matter expert
SMACs	=	spacecraft maximum allowable concentration
SOA	=	state of the art
SSK	=	surface sampler kit
SVO-ZK	=	stored potable water system
SWEGs	=	spacecraft water exposure guidelines
TOC	=	total organic carbon
UPA	=	urine processing assembly
WAFAL	=	water and food analysis laboratory
WRS	=	water recovery system

I. Introduction

A primary requirement for manned spaceflight is the generation and maintenance of a safe environmental in the habitable volume of the vehicle. To meet such a requirement, a multi-disciplinary effort involving scientists, engineers, and medical personnel is needed to assess and manage the risks to environmental health. In manned spaceflight, risks can arise from the degradation or loss of active controls, combustion events, leaks from system or payload equipment, visiting vehicles and cargo transfers, and even crew activities/crew actions such as extravehicular activities (EVAs), personal hygiene, housekeeping, and payload operations. As such, these risks not only affect crew health, but they can also affect the environmental control and life support systems (ECLSS) within the vehicle which were designed to generate an environment suitable for sustaining human life.

Active and passive controls are routinely employed to manage environmental health risks associated with manned spaceflight. Active controls such as the ECLS systems are designed and built to ensure that a proper environment can be generated and maintained to the standards set by environmental health experts. Passive controls include these standards which define acceptable limits for manned spaceflight, the materials selection process, ground procedures such as off-gas testing, crew isolation, proper ground preparation of the vehicle, in-flight procedures, and comprehensive hazard analyses. Employing active and passive controls in conjunction with monitoring the health of the environment and the health of active controls translates into a healthy crew and a high probability for mission success.

Human Health and Performance (HHP) scientists and Environmental Control and Life Support (ECLS) engineers consider environmental monitoring a key component their overall environmental health management strategy. ECLS engineers use environmental monitoring data to monitor and confirm the performance of ECLS systems, whereas HHP scientists use the data to manage potential crew health risks. Different disciplines using the same data for a common goal: crew health and mission success. From the perspective of Human Health and Performance scientists, there are many risks to crew health associated with the cabin environment that need to be managed during missions. Because crew health risks can vary between missions and change over time, environmental monitoring is critical component of spacecraft environmental health systems. HHP clinical and scientific personnel use environmental monitoring data to manage acute crew health problems associated with contamination events that result in exposures, to make smarter assessments of crew-reported symptoms and potential links to contaminant exposure and/or cabin environmental observations, to guide crew actions and success of recovery during off-nominal environmental problems, to contribute exposure data to the Lifetime Survey of Astronaut Health (LSAH), and to aid in post-flight monitoring of the health status of crew. In addition, environmental monitoring provides early warning of off-nominal situations where controls degrade or fail, provides necessary data to assist in correcting failures and determining root cause, and provides data on a variety of toxicological compounds and environmental factors that may have specific crew health impacts.

Some environmental health monitoring requirements were captured in the ECLS assessment.¹ However, it was not a comprehensive review of all the areas of environmental health and the requirements were only reviewed from an ECLS perspective. This effort addresses environmental monitoring from a crew health perspective. Crew-health risks associated with the environment were determined by agency experts with the goal of determining risk-based, environmental monitoring needs. Once the risks were defined, how these risks are currently addressed was assessed,

knowledge and technology gaps were identified, and activities/hardware development efforts required to close those gaps and enable NASA crewed space exploration objectives were developed.

II. Environmental Health System

The Environmental Health System (EHS) consists of a suite of hardware and instruments that monitor the ISS habitable environment in order to protect crew health. Currently there are four discipline areas that comprise the EHS:

- Air Quality - assesses potential contaminant exposures during spaceflight and establishes Spacecraft Maximum Allowable Concentrations (SMACs) that will protect crew while living and working in space;
- Water Quality - assesses and characterizes the quality of water sources and verifies these systems meet potability requirements; Water Quality also establishes Spacecraft Water Exposure Guidelines (SWEGs);
- Microbiology - assesses bacterial and fungal contamination levels in the air, water, and surfaces and addresses issues related to infectious disease and microbial ecology of spacecraft; Microbiology also establishes pre-flight and in-flight acceptability levels;
- Acoustics Management- assesses the spacecraft environment and ensures noise levels are within acceptable limits so the crew can comfortably and safely live, communicate, and work; Acoustics also establishes noise exposure levels.

The functional decomposition of EHS is shown in Figure 1. Below each primary function are the elements of the habitable environment that are monitored in order to meet the requirements in the Medical Operation Requirements Document (MORD). For ISS, each element is managed and integrated to maintain EHS Flight Readiness, pre-flight, in-flight, and post-flight. Even though the primary function of EHS elements/hardware is Environmental Health, dependencies with other ISS systems exists, as illustrated in the following list, .

- *All hardware owners can potentially impact acoustics or include acoustic mitigations*
- *ECLSS: Portable Oxygen Monitor (POM) is the ECLSS Major Constituent Analyzer (MCA) back-up*
- *FCS (Flight Crew Systems): Potable Water Dispenser (PWD) accuracy affects sample volumes, contamination remediation flushes and bags*
- *EVA (Extravehicular Activity): Portable Oxygen Monitor (POM) for pre-breathe activity*
- *Ops LAN: Air Quality Monitor (AQM) SSC connection; Acoustic Dosimeter/Sound Level Meters (AD/SLM), Total Organic Carbon Analyzer (TOCA), and Colorimetric Water Quality Monitor Kit (CWQMK) data transfers*
- *HMS (Health Maintenance System): On-orbit Hearing Assessments relate to Acoustic Noise Exposure Levels and Hearing Protection relates to Acoustic Levels*

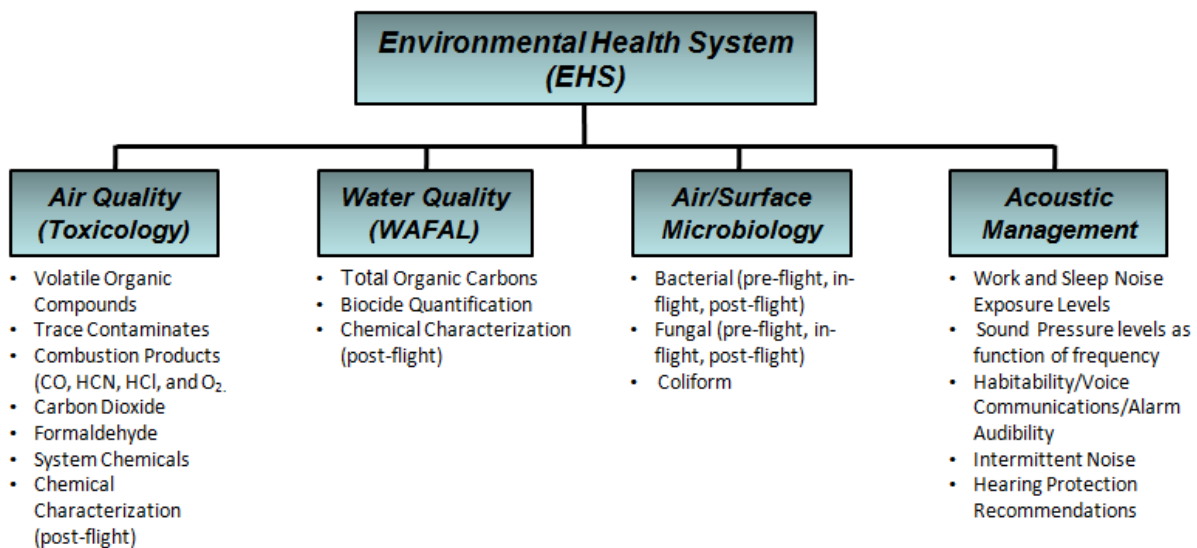


Figure 1. Functional decomposition of the Environmental Health System.

A. Crew Health and Environmental Health

Crew health is dependent on the health of the environment and gravity. One of the difficulties in setting exposure limits for manned spaceflight arises from the changes in human physiology that occur in micro-gravity.² Significant changes have been documented in the cardiovascular system, immunological system, skeletal (bone) system, muscular system, nutritional and pharmacological metabolics, and neurovestibular (sensory-motor) system. Upon entering micro-gravity, body fluids, including blood, shifts from the legs to the head and upper body. On Earth, the body is accustomed to having gravity force fluid downward. When this force is removed, fluids begin to pool in the upper part of the body and diminish in the lower portion. This leads to swollen facial features, often referred to as “puffy heads”, and a reduction in leg mass. Unfortunately, as a result of this fluid shift, an overall fluid loss is also observed, i.e., crew members become dehydrated. U.S. astronauts and Russian cosmonauts have been reported to lose from 10 to 23 percent of their total fluid volume.³ One concern associated with fluid loss is during instances of extreme G-loading like re-entry, when possibility of stroke or hemorrhage increases. As such, it is common for both astronauts and cosmonauts to load up with fluids prior to re-entry to reduce the risks associated with fluid loss. The cardiovascular changes experienced while in micro-gravity can potentially increase the health risks of performing surface operations on Mars, or the Moon, or even an asteroid.

Changes in the immune system also occur. Viral infections acquired on the ground and have been cured still remain in the human system in an inactive state. Evidence suggests that in micro-gravity, these viral infections can reactivate making crew members in long duration mission much more susceptible to illness.⁴

Perhaps the most well know effects of long-term exposure to micro-gravity is the reduction in bone density and change in bone composition, and the reduction in muscle mass and strength. Exercise protocols used in long-duration missions such as ISS help mitigate these effects. Upon return to Earth and a 1-g environment, crew enters a regiment of physical therapy to help regain what was lost. Synergistic effects can also occur. During a mission in micro-gravity, a reduction in bone density is manifested as a loss of calcium in the bone and a concomitant increase of calcium in the blood stream. Higher than normal calcium levels in the blood stream exacerbate the fluid loss issue mentioned above and increase the potential for kidney stones during long-duration micro-gravity missions.

Nutritional studies suggest that the human body absorbs and processes foods differently in micro-gravity than in 1-g. The consequences of nutritional imbalance include performance degradation and a decrease in immunological functions. Changes in the absorption process within the human body will also affect the metabolism and absorption of medication which, in turn, will greatly affect the effective dose provided to the crew during missions. Neurovestibular (sensory-motor) changes, typically experienced as dizziness and disorientation, have been documented to occur upon introduction to micro-gravity, and can persist throughout the mission, and sometimes continue after return to 1-g (Earth). This can have consequences while trying to perform difficult tasks, such as landing the vehicle or conducting activities that require fine motor skills. Although this can be treated on the ground with medication, metabolic changes and changes in absorption during a mission make it difficult to determine the effective dosage to ensure treatment while minimizing potential side-effects.

Documented links between susceptibility upon exposure to environmental contaminants, microbial growth, and noise and observed physiological changes in microgravity are extremely limited. Although qualitatively, they cannot be overlooked. Links between chronic exposure to higher than normal carbon dioxide levels and visual impairment due to increased intracranial pressure has been suggested.⁵ On the ground, carbon dioxide is considered a potent vasodilator and rapidly increases blood flow to the brain. Symptoms of excessive carbon dioxide exposure are typically observed at 10-15 mmHg CO₂ on the ground. The same symptoms are typically observed in micro-gravity at 1.3 - 6 mmHg CO₂.⁶

In 2010, the European Agency for Safety and Health at Work (EU-OSHA) released a report on chemical exposure and its effect on hearing.⁷ Acoustic SMEs manage risks to hearing through acoustic insulation, quiet fan/quiet pump technology, personal protection equipment, as needed, such as noise-cancelling headsets and ear plugs, and acoustic monitoring. The study determined that exposure to chemical substances can also impair hearing by affecting the structures and/or function of the inner ear and possibly even the connected neural pathways. Although ototoxicity is a well known potential side affect of certain medications, the potential ototoxicity of chemicals that can be found in manned vehicles was not taken into consideration when setting SMACs until recently.

The National Institute of Environmental Health (NIEH) and the National Toxicology Program (NTP) recently started to look at why some people are more susceptible to chemicals or even radiation than others. At the NIEH/NTP National Toxicogenomics Center, scientists are developing libraries of patterns of genes that are either turned "on" or "off" when exposed to known toxins. Chemicals can then be tested for toxicity by comparing gene patterns following exposure to the chemical to the gene patterns from exposure to the known toxins. Through the Environmental Genome Project, scientists are studying known "susceptibility" genes in tissue samples from

statistically representative groups of the population. The focus is to match the variations in these genes to the varying susceptibility to chemicals and illnesses.⁸ These types of studies may lead to screening methods that might help choose the best candidates, i.e., those with the least susceptibility to certain chemicals, for the initial long-durations mission beyond LEO.

B. Basis for Risks

With the goal of developing a risk-based, environmental health roadmap outlining technology needs, risks to crew health for the given design reference missions (DRMs) were determined and assessed. Flight experience provides many examples of events which have impacted the environmental health of manned vehicles from the Apollo Program to the current ISS Program, some of which are listed below. These events, to a great extent, provide the basis for the crew-health related risks identified. Despite a robust ECLS system, events affecting environmental health can even occur when ECLS systems are operating nominally. In these cases, ground-based and in-flight monitoring technology helped to detect or characterize the issue, determine its root cause, and ensure the environment was safe for continued manned operations.

➤ ISS Air Quality Events

- Crew sickened in FGB during poor ventilation, probably from rebreath of exhaled air/CO₂ (Flight 2A.1)
- Freon 218 leaks from Service Module air conditioner (Apr 01 to Mar 02)
- Extremely high methanol in a sample of FGB air; exact source never determined (Aug 01)
- METOX canister regeneration caused noxious air with many pollutants (Feb 02)
- Crew complained of odor from UPA when processing urine; Gas-liquid separator evidently does not have odor filter (15Dec08).
- Artificial CO₂ event 9-12 FEB 09: CDRA was turned off to monitor true capacity of Vozdukh to control CO₂ in prep for 6 crew. CO₂ rose to 6 mmHg before test was terminated and CDRA reactivated (flight rule limit is 5.3 mmHg). CO₂ measured by both MCA and CDM.
- HTV-1 hatch open 18 SEP 09 CSA-CP readings taken at first entry: CO at 5 and 7 ppm with one pocket of 10 ppm that dispersed. No acid gases detected.

➤ ISS Water Quality Events

- High cadmium level detected in SVO-ZV traced to a spring in dispenser (Exp 1 [5A] to Exp 2 [5A.1])
- Caprolactam in CWC water stored long-term (Expedition 1)
- Incidents of abnormally high silver in Rodnik water from 10 P (Dec 02) and 11P (Apr 03)
- High turbidity levels in SVO-ZV water (Expeditions 3-7)
- Cadmium issue reappeared in SVO-ZV; dispenser suspected again & replaced (Exp 13/14)
- Incorrect replacement of valve in SM Rodnik potable water Tank 1 caused potential preserved urine contamination (Exp 15, 26 July 2007); corrected by replacement and flushing of lines.
- Summer 2010 Continuously increasing TOC levels eventually determined to be due to dimethylsilanediol, a chemical previously not on monitoring list.

➤ ISS Microbial Events

- Potential fungal contamination on FGB panels 406 & 408 reported by Exp. 9; In-flight sampling with SSK indicated fungal levels at or above acceptability limit
- High bacteria counts noted in archive samples from 2 CWCs from 13A.1; numbers confirmed by in-flight total count
- During Water Recovery System/Potable Water Dispenser (PWD) 90-Day Checkout Dec-2008, elevated bacterial levels were found in the PWD ambient leg.

➤ ISS Acoustic Events

- Intra-Module Ventilation (IMV) noise issues (US LAB, JEM and Node 2) – ongoing problem
- Increased acoustic levels caused by IMV fan clogging/stalling (dust build-up)
- Noise of WRS2 in Node 3 higher than predicted, significant noise exceedance
- High acoustic levels of Urine Processor Assembly (caused by separator bearing failure)
- Oxygen Generation Assembly (OGA) pump inside OGS rack noise exceedance

C. Technology Gap Assessment for Environmental Health

An assessment of technology needs is typically preceded with a well defined mission and mission objectives. Since this determination is ongoing, general DRMs were used to perform this assessment. Pertinent characteristics of the general DRMs are listed in Table 1. These general DRMs were also used in the assessment of ECLS systems⁹, extravehicular activity (EVAs)¹⁰, and other functional aspects of manned spaceflight.

Reference Mission 1: Short Duration
< 3 - 4 weeks
<i>Examples: MPCV, MMSEV, SEV, Lander</i>
Other considerations
EVA via an airlock or suitport
8 – 14.7 psia range of cabin pressures depending on specific mission
<i>MPCV ECLSS proposed as the Point of Departure design for this general scenario</i>
Reference Mission 2: Long Duration, Micro-Gravity
> 6 month to years
"Derivative increments" will have some differences
Limited or no resupply available (need for high self sufficiency and reliability)
<i>Examples: ISS, Deep Space Habitat, Long-duration transit vehicle</i>
Other considerations
EVA via an airlock or suitport
8 psia/32% O2 working atmosphere capability is the objective
<i>ISS ECLSS proposed as the Point of Departure design for this general scenario</i>
Reference Mission 2a: Medium Duration, Micro-Gravity
>1 month to ~6 months
Reference Mission 3: Long Duration, Partial Gravity
Similar requirements to the microgravity habitat
Evaluate use of advanced or gravity dependent technologies

Table 1. Characteristics of design reference missions used in the assessment of technology needs for environmental health.

The technology gaps or needs were further characterized in the same manner as ECLS gaps, as enhancing or enabling.⁹ Enhancing needs are desired for the mission but the current state of the art (SOA) would suffice or could suffice with updates. Enabling needs are required for mission and either significant updates to SOA or new technology would be needed for the mission to occur. Trying to match ground-based capability to in-flight capability is currently technically and fiscally unrealistic. With a myriad of commercially available analytical technology, it is easy to inadvertently overlook needs that directly address an actual risk. Technology that does not mitigate actual risks are of little to no value to the mission. Availability of technology should not be a criteria used to determine whether or not risks are pertinent to a given mission scenario.

The objective of this assessment was to obtain an Agency-wide consensus on the technology needs for environmental health. To facilitate this, the assessment was broken down into the four functional areas of environmental health - air quality, water quality, microbial monitoring, and acoustic management. Each area's assessment was performed independently to identify specific risks and perform the gap analysis. The various mission parameters such as duration, operating conditions, e.g., pressures and oxygen concentrations, and distance from Earth, were also factored with crew-health related risks in determining the gaps. The functional area leads were given the freedom to pull in technical personnel in any discipline within the Agency with a vested interest in the functional area, not just subject matter experts (SMEs) in the functional area. To simplify documentation, risks common to the hardware in all the functional areas, such as risk of no resupply, and risk of inaccurate environmental data provided by hardware during missions, were combined into a separate area called Mission-Related Risks to Crew Health. Also, it was assumed that ways to close the gaps identified as Mission-Related Risks are applicable to the hardware in each area. Note that this assessment is based on general DRMs. Once a mission is better defined, this assessment will need to be revised and gaps reassessed with the specific mission scenario and goals in mind.

III. Environmental Health Assessment

The crew-health related risks identified are in Tables 2-6. Also listed are the identified gaps or needs required to address the risk properly. The needs are in generic terms so as not to limit answers to any current hardware developments. The risks for each functional area of environmental health dealt with exposure and the adverse health effects that may result. Generally, enabling needs were driven by distance from low-Earth orbit (LEO) and by mission duration. Needs for Reference Mission 2 and 3, long-duration, micro-gravity and long-duration, partial gravity, respectively, typically required enabling technologies.

A. Risks

The habitable volumes of manned vehicles are very controlled environments given the level of active and passive controls imposed on these volumes, and the level of scrutiny and limitations imposed on visiting vehicles and cargo. Despite this degree of control, habitable volumes are very complicated and contain mixtures of chemicals that represent virtually all functional types, and a microbial presence in the air, water and surfaces. This is primarily due to (1) human presence, and (2) materials off-gasing.¹¹ Publically available data from extensive analyses of grab samples of ISS air show a myriad of compounds, most of which are at or below detection limits, with only 12-15 chemicals accounting for approximately 95% of the total trace contaminant load.¹² Chemicals that are minimally water soluble will be present in the water, in addition to what was already present in the water if it is brought from Earth. Manned spacecraft is a unique, closed system operated in an extremely harsh environment where crew exposure to the spacecraft's environment is continuous. As such, permissible exposure limits (PELs) based on time-averaged 8-hour workdays can only serve as a rudimentary guideline for exposure in spacecraft by crew members. Active and passive controls must maintain the concentrations of chemicals and the number of microbial colony forming units well below terrestrial environmental standards. A concerted effort is made to conservatively set the environmental standards, i.e., exposure limits for chemical contaminants in the air and water (SMACs and SWEGs), the amount of microbial growth in the air, water, and surfaces, and the acoustic levels throughout the vehicle. However, because of the physiological effects of micro-gravity and a statistically small population of humans exposed to microgravity, the degree of conservatism in these standards is very difficult to ascertain. Hence, spacecraft environmental standards are meant to be guidelines. Chemicals, microbial growth, and noise are ubiquitous to manned spaceflight and minimizing exposure is the key. However, the physiological changes in micro-gravity and the potential synergistic effects experienced due to constant exposure to the chemical contaminants, microbial growth, and acoustic environment of the vehicle may very well alter the susceptibilities of crew members during a long-duration missions. Consequently, environmental monitoring from a crew-health perspective is of paramount importance.

The risks address exposure to excessive contaminants and potential, viable routes that could lead to an increased probability of exposure. Here, "contaminants" are chemicals, microbial growth, and even noise. Viable routes include combustion, i.e., fires, possible system leaks or failure of mission-specific hardware such as ECLS and thermal systems, and even leaching of contaminants from materials over a long period of time. Also noted were risk of adverse health effects from the destination environment and potential contaminants and particles from an EVA. The toxicity of lunar dust is only now being assessed.¹³ Although the information on Martian soil provided by unmanned missions is extremely valuable, return samples will be required to fully assess its toxicological effects. Unfortunately, return samples for such an assessment may not be possible, thereby requiring an alternative approach to manage such risks. Risks to crew health may also arise indirectly, such as system performance degradation due to excessive microbial growth on surfaces. Risks in one area of the environment also affects other areas of the environment. Excessive water-soluble, airborne contaminants may lead to increase in volatile contaminants in water. Excessive microbial growth in the air and on surfaces may lead to excessive microbial growth in water. Microbial growth on the ventilation fans of various systems coupled with increased particle counts in the air may increase acoustic levels. As mentioned above, these risks were determined for general reference missions. Once specific missions are defined, risks will have to be reassessed using this framework.

Air-related Risks to Crew Health	Enabling Technology Needs	Enabling to DRMs			
		1	2	2a	3
Risk of system leak or contamination due to failure of mission-specific equipment	Automated, crew independent means to detect leaks of specific system fluids, as dictated by vehicle system architecture, that may result in crew exposure to system fluid	X	X	X	X
Exposure to toxic products of combustion	Replacement for current ISS CP monitor and alternative technology for combustion products and particulate monitoring	X	X	X	X
Risk of hypoxia	O2 monitoring with sufficiently high accuracy		X		X
Exposure to accumulated air pollutants	Flight-validated VOC monitor that meets reqmts without relying on ground sample analysis and can properly operate after periods of dormancy.		X		X
Exposure to toxicants during EVA	Airlock VOC and particulate monitor		X		X
Risk of Adverse Health Effects of the Destination Environment, e.g., Lunar Dust, Asteroid, ISRU	Broad-spectrum VOC and particulate monitor		X		X
Excess exposure to carbon dioxide, formaldehyde, other target gases	Air Quality – Major Constituents / Complete development and flight of MCA replacement (ISS/Orion Air Monitor)				
	Portable, optical-based monitor for target gases, e.g., formaldehyde	X	X	X	X
	Knowledge Gap: Better understanding on physiological effects of elevated CO2 for long-term missions				

Table 2. Air quality-related risks to crew health.

Water-related Risks to Crew Health	Enabling Needs	Enabling to DRMs...			
		1	2	2a	3
Risk of crew injury due to elevated biocide concentrations in water	Ability to monitor biocide concentrations in water for duration of mission.		X		X
Risk of crew injury due to ingestion of recovered water that doesn't meet appropriate water quality requirements	On-orbit water quality monitor with species identification (inorganic and organic).		X		X
Risk of crew injury due to exposure to recovered water that contains unanticipated organic contaminants			X	X	X
Risk of having insufficient chemical water quality monitoring data to make informed operational decisions			X	X	X
Risk of crew injury due to release of contaminants from stored water systems		Shelf-life studies on new materials that may be used for water storage and on-orbit water quality monitor with species identification (inorganic and organic).		X	

Table 3. Water quality-related risks to crew health.

General Risks to Crew Health (common to all EHS hardware)	Enabling Needs	Enabling to DRMs...			
		1	2	2a	3
Risk of misinterpretation of environmental Information	Hardware/software which organizes, interprets, and presents environmental health data easily interpreted and correlated to crew health like physiological symptoms		X		X
Risk of no resupply	Environmental Health monitoring technology that uses minimal-to-no consumables		X		X
Risk of incorrect environmental data provided by hardware during mission.	Built-in protocols/hardware to automatically validate proper operation of monitoring technology to ensure data integrity.		X		X
Risk of mismatched standards for various mission	Knowledge Gap: Review environmental health standards for compatibility to missions				X
Risk of misunderstanding effects of integrated risks	Knowledge Gap: Better understanding of long-term, integrated system risks. Long-duration human studies, e.g., ISS one year increment				X

Table 4. General risks to crew health (common to all EHS hardware).

Microbial-related Risks to Crew Health	Enabling Needs	Enabling to DRMs...			
		1	2	2a	3
Risk of crew illness due to exposure of crew to microorganisms in potable water	On-orbit biocide introduction/re-dosing method (on ECLSS Roadmap)		X		X
	On-orbit microbial monitor for water with speciation		X		X
Risk of crew illness due to exposure of the crew to microorganisms from environmental air and surfaces	On-orbit microbial monitor for water with speciation		X		X
Risk of degraded vehicle system performance due to microbial growth on material surfaces	Microbial-resistant materials to inhibit or minimize microbial growth in vehicle		X		X
Risk of condensate buildup, or other uncontrolled water accumulation during spaceflight missions	Automated, crew-independent means to detect leaks of specific system fluids, as dictated by the vehicle system architecture		X		X
Risk of Adverse Health Effects due to Alterations in Host Microorganism Interaction	Knowledge gap: Comprehensive assessment of microbial hazards and their characteristics; dose-response characteristics of organisms for a better assessment of crew exposure.		X		X
Risk of Crew Adverse Health Event Due to Altered Host Immune Response	Knowledge gap: Better understanding of host susceptibility.		X		X
Risk of crew illness due to exposure of the crew to microorganisms from other crewmembers	Knowledge Gap: Managing medical-related microbial issues				X
Risk that antimicrobial countermeasures may be inappropriate or less effective during spaceflight missions.	Knowledge Gap: Studies in <u>pharmaco</u> -kinetics and dynamics				X
Risk of insufficient spaceflight food requirements for foods with elevated microbial content and complex microbial diversity	Knowledge Gap: Definition of how to microbiologically monitor various foods where high counts do not necessarily disqualify samples, e.g., yogurt				X

Table 5. Microbial-related risks to crew health.

Acoustics-related Risks to Crew Health	Enabling Needs	Applicable to DRMs...			
		1	2	2a	3
Risk of degraded crew-crew (face-to-face) voice communications due to interference from background noise	Quiet fan/pump technology (duplicate of ECLSS roadmap)		X		X
Risk of degraded crew-crew (face-to-face) voice communications due to interference from background noise	Better-performing and lighter flight-certified acoustic materials		X		X
Risk of degraded crew-crew (face-to-face) voice communications due to interference from background noise	Real-time, automated acoustic monitor		X		X
Risk of off nominal situation causing increased noise level					X
Lack of real-time acoustic monitoring may result in crew exposures to high noise levels			X		X
Risk of increased sound levels as vehicle systems age during mission			X		X
Risk of increased sound levels caused by accumulation of dust in hardware systems			X		X
Crew-desensitization to gradual increases in noise may cause exposure to increased noise levels			X		X
Lack of crew-time may cause inadequate acoustic monitoring frequency or spatial coverage to recognize increased noise levels			X		X
Risk of degraded crew-to-ground or EVA communications due to interference from background noise		Better helmet/headset noise attenuation		X	
Risk of sleep disturbance due to high continuous or intermittent noise	Lightweight sleep location noise attenuation		X		X
Increased intracranial pressure, caused by weightlessness, may cause temporary hearing loss which may result in decreased voice communication effectiveness	Monitoring devices to measure intracranial pressure on-orbit		X		X

Table 6. Acoustic-related risks to crew health.

B. Gaps

Technology gaps were determined from these risks and the state of the current ISS SOA. In addition to technology gaps/needs, knowledge gaps were also identified. Knowledge gaps require better understanding of the risk and its cause to properly address the risk. Operational considerations and the effects micro-gravity will have on analytical techniques were also considering in the gap analysis. The primary limitation with the current SOA is reliance on sample return and ground analysis and ground support. This is true across all area of environmental health. Despite the Air Quality Monitor on ISS, environmental health SMEs still rely on grab sample analyses. Currently, in-flight water quality monitoring is based on total organic carbon (TOC) levels and biocide levels. Identification and quantification of aqueous species depend solely on return water samples and ground analysis. The increasing TOC situation in 2010 on-board ISS exemplifies the limitations of current in-flight water quality monitoring technology.¹⁴ In-flight microbial monitoring relies on culture-based microbial assay kits for monitoring microbial counts in air, water, and on surfaces. A coliform kit is also included to detect the presence of coliform in water. For LEO applications with ground return capabilities, this method for monitoring is quite effective. Ground procedures, in-flight crew procedures, and high efficiency particulate air filters in vehicles control microbial growth to manageable levels given the primary source for microbes are the crew members themselves. For longer-duration missions, it is generally accepted that a means to speciate as well as enumerate microbial growth is an enabling technology gap that needs to be filled because of limited or potentially no sample return.

Other gaps identified were reliance on resupply of consumables. Contributing to this were limited calibration life and battery life of current SOA. Monitoring target gases such as combustion products have relied on electrochemical sensors that have limited calibration and battery life. On the ground, electrochemical-based, target gas sensors are cost-effective solutions that are easily calibrated and have unlimited batteries. Limited up-mass and down-mass capability is driving an effort to move to optical-based solutions to monitor target gases. Optical approaches have potentially indefinite calibration life and battery life measured in years, but are highly dependent on the availability of low-power, coherent light sources (lasers) operating in the required wavelength.

The need to reduce crew-time was also identified as a gap. Tasks as simple as checking calibration, changing batteries, sampling surfaces with a cotton swab, are tasks that would take a few minutes when performed on the ground, but may take up to an hour in-flight. There is limited room for error in-flight and as such, maintenance tasks are performed step-wise, in a very meticulous manner resulting in longer task times. Also, limited space has resulted in creative storage solutions on-board the ISS that, at times, require even more creative locating protocols.

Related to the need to reduce crew time is increasing the degree of autonomy with environmental monitoring hardware. By automating the routine operations and procedures associated with environmental monitoring, a significant impact on the crew time required for environmental health can be made. Ground commanding of systems is already possible. Systems can also be configured to automatically operate at predefined intervals and perform data analysis. However, further developments in automation to lessen an over reliance on ground support to verify in-flight results using sample returns and ground analysis is required. To the non-expert, analytical hardware are “black-boxes” that generate data. Validation of this data relies on a comparison to the ground analysis of return samples by ground-based SMEs. Identification and verification of anomalies are performed by ground support. Proper operation of hardware is verified by ground support. Translating the data generated by the hardware is performed by ground support. In-flight validation protocols to ensure proper instrument functionality and data integrity are quite limited with current environmental monitoring hardware. A limited degree of data validation is usually accomplished through redundancy and/or comparison to ground analyses. Ground support will always be present, albeit in a limited manner. To compensate for the limited ground support that will be available and the loss of return samples, a degree of autonomy from the monitoring hardware is required not only to decrease the amount of crew time required for environmental monitoring, but also to decrease the crew’s reliance on ground support. As missions travel farther from LEO the degree of autonomy will increase.

Ground support is also an invaluable resource for the identification of unknown chemicals that may appear in routine analyses during a mission. Unknown chemicals are unanticipated or unforeseen chemicals. Viable ways to manage the presence of an unknown to the extent possible is needed. Unknown chemicals can be transient contaminants that have the potential to negatively affect routine analyses. Separation of chemicals for analysis is accomplished with chromatographic techniques. Chromatography is a two-phase process relying on prior knowledge of the components in the mixture to achieve effective separation. Factors such as temperature, flow rates, types of chemicals in the mixture, and chromatography material determine separation performance and are set prior to deploying an instrument. An unknown introduces another factor whose effect on separation performance is difficult to determine. On the ground, temperature and flow rates can be adjusted to account for the presence of an unknown. At times, different chromatography material may be required. Assuming that the unknown can be effectively separated from the other chemicals in the mixture, its identify can only be truly confirmed by comparison to a sample of the pure substance. Unknowns are extremely difficult to identify on the ground, typically requiring a combination of several analytical instrumentation, extensive experience, and access to pure compounds for unequivocal comparison. Although the extensively-managed environment of habitable volumes of manned spacecraft is well characterized and controlled, the potential negative effects of unknowns on the analyses required to ensure environmental health demands the development of viable methods to properly manage their presence when they appear.

The typically physical characteristics imposed by any mission beyond LEO apply to all environmental monitoring hardware as well. All hardware must be small in size and volume, have low power requirements, and have little to no consumables. Multi-functional hardware can be desirable, but further assessment may be required since the loss of hardware can potentially translate into the loss of two or more capabilities. An issue not generally addressed with environmental monitoring hardware is the idea of dormancy. It is certainly possible that missions to habitats may only last a few weeks in a given year, with the habitat remaining dormant the rest of the time. In such a case, hardware left in the habitat must be able to either power down or hibernate during the dormant period and power on and be operational within a reasonable amount of time after the dormant period. Since analytical hardware employed for environmental monitoring are usually designed to be continuously powered and operated in regular intervals, the ability to handle dormancy is a gap that needs to be addressed. There is limited precedence for such a need. Several medical technologies are designed with dormancy in mind. Defibrillators are dormant for longs

periods of time but are expected to operate with no problems when needed. Launch delays serve as the closest analog to dormancy. In some cases, several weeks may pass between loading and launch because of unforeseen technical delays with the launch vehicle. In these cases, usually more “clean runs” are needed once the hardware is on-orbit because of the meticulous packaging of the hardware prior to loading. Dormancy will drive crew procedures but it may also drive hardware design.

IV. Conclusions

Environment-derived crew-health risks can vary between missions and during the course of a mission. Monitoring air quality, water quality, microbial growth, and acoustic environment are critical components to spacecraft environmental health. In the effort described here, crew health risks associated with the environment were identified and reviewed by agency experts with the goal of determining *risk-based*, environmental monitoring needs. Once determined, agency experts identified critical technology needs for enabling exploration missions, knowledge and technology gaps in environmental health, and the activities/hardware development efforts that should be invested in over the next several years to close those gaps and enable NASA manned space exploration objectives. As part of a comprehensive environmental health risk management strategy, environmental monitoring technology must provide useful and timely information to the crew and ground support as necessary. It should provide near real-time response, monitor parameters that are useful to the crew, and provide alerts to off-normal situations involving environmental health. Environmental Health monitoring should complement ECLS system design and operation, enable mission autonomy, and provide crew the necessary information to properly manage the Environmental Health of the vehicle throughout the mission.

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