Updates to the Risk of Toxic Substance Exposure
Revision B.1

Human System Risk Board

HSRB CR SA-07566
Approved: 2/13/2025

Risk Custodian Team
SK/V. Ryder
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Risk Record

- This package
  - provides continued operational evidence (since 2021) of the release of toxic substances, including their relative frequency and impact to the crewmembers.
  - recommends change to the risk posture based on increased risk acceptance combined with lack of monitoring.
  - includes new concerns related to lack of Program level integration for Artemis missions.

This information was previously reviewed/dispositioned at:

Meeting	Date	Outcome/Direction
Joint BRESCB/SMOCB	10/02/2023	Proceed to HSRB

Contents

1. Risk Title and Risk Statement

- **Risk Title:**

Risk of Toxic Substance Exposure Leading to In-Mission Health Effects or Performance Decrements and Long-term Health Outcomes

- **Risk Statement:**

Given that there are numerous sources of toxic substances that cannot be eliminated during space missions, a possibility exists that the crew will be exposed to toxic substances, which may impact the crew's performance, and lead to loss of mission objectives (LOMO), loss of crew (LOC), loss of mission (LOM), or long-term health (LTH) conditions.

2. Risk History

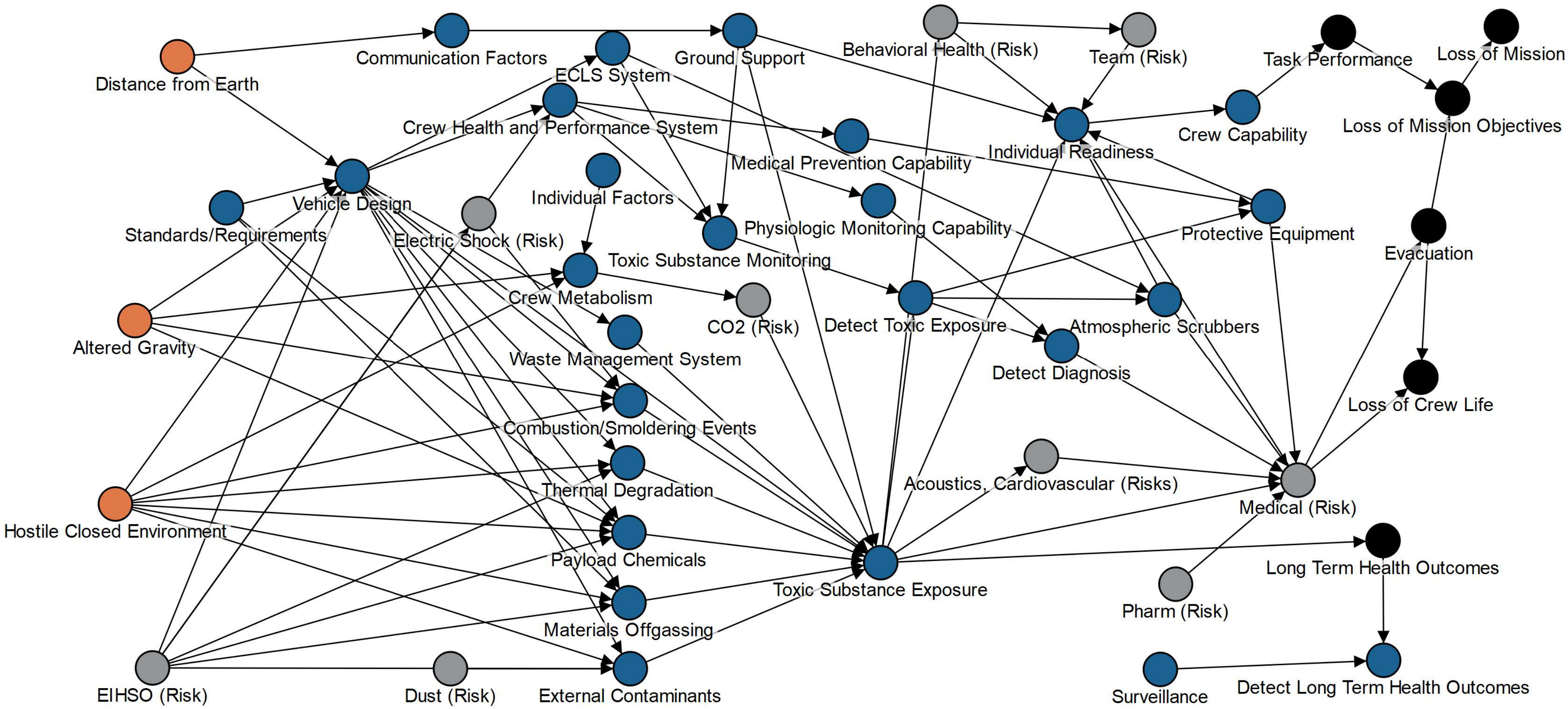
Item	Date	Outcome/Status
Change Request Closure	02/13/25	**Decisional** – CR SA-07566 HSRB DAGtionary Updates and DAG Corrections; CR approved with modifications. Rev B.1
Change Request Closure	12/04/23	**Decisional** - CR SA-06529, Rev B approved out-of-board (Evals unanimous concurs)
HSRB Risk Presentation	10/05/23	**Informational** – Request to Update Risk, Rev B
HSRB Risk Presentation	02/11/21	**Decisional** – CR SA-03269 Approved, Rev A
Risk Evaluated via CR	12/17/20	Evaluation period ends January 8, 2021
HSRB Risk Presentation	12/17/20	**Informational** – present preview of Risk Updates for Rev A
Action Item Closures	05/19/15	**Decisional** – Deliverables Required table content: Approved out-of-board
HSRB Risk Presentation	12/17/14	**Decisional** – CR Approved with Mods; Approved risk baseline
Risk Evaluated via CR	12/02/14	**Decisional** – Review of integrated risk based on new risk process (JSC 66705)
HSRB Risk Presentation	10/27/14	**Informational** – Provide evidence for re-scoped risk; Approved to release CR
Risk Evaluated via CR	11/30/12	**Decisional** – **Withdrawn** – Unable to Invalidate Risk of Toxic Exposure in RMAT Database
Risk Evaluated via CR	10/23/12	**Decisional** – **Withdrawn** – Differences in management philosophy and the need for risk custodian from SK and not SD
HSRB-CR (Out-Of-Board)	12/08/08	**Decisional** – Approved as written. This risk pertained only to CEV design (hydrazine and ammonia) for CxP. "Baseline Toxic Gas RMAT

CEV - Crew Exploration Vehicle; CR - Change Request; CxP - Constellation Program; SD- Space Medicine Operations Division; SK - Biomedical Research and Environmental Sciences Division

3. Executive Summary

- The likelihood and consequence (LxC) of exposure to toxic substances depends on the toxicity of the substance (i.e., low, moderate, or high toxicity), mission duration, vehicle age, duration of exposure, and ability to treat and/or return crew to Earth.
  - Exposures to low toxicity substances occur much more frequently but the consequences of these exposures are much less significant.
  - The likelihood that a toxic substance will be released during a mission increases with mission duration and vehicle age.
  - The consequences of a toxic release may range from mild irritation to loss of crew (death).
- The Risk of Toxic Substance Exposure is managed through prevention (selection of fluids and materials with low toxicity, proper containment, etc.), monitoring, and mitigation (protective equipment, operational procedures, treatment protocols, etc.).
- No changes have been made to the directed acyclic graph (DAG) since the May 2022 acceptance of the DAG updates; minor modifications are recommended for the DAG narrative.
- Risk posture level has been reduced due to preventative and mitigating countermeasures and monitoring for future vehicles and design reference missions (DRMs).

4. Directed Acyclic Graph – DAG



Directed Acyclic Graph – DAG (Narrative)

- Numerous sources of toxic substances on board spacecraft are impacted by the following hazards:
  - **Altered Gravity** increases the risk of exposure to floating particles and liquids, reduces dispersion of gases in areas that are not well ventilated, and results in greater difficulty capturing and removing a release.
  - A **Hostile Closed Environment** limits removal capabilities and increases exposure likelihood (small volume for gases and volatiles to fill).
- **Toxic Substance Exposure** depends on the release of toxic substances into the interior of the spacecraft or spacesuit, which can affect the health and performance of the astronauts. Exposure to toxic substances can be caused by the following:
  - **Crew Metabolism** results in the exhalation of carbon dioxide (**CO_2 Risk)**, which can reach toxic levels. Biovariability is determined by **Individual Factors.**
  - **Waste Management System** includes the above as well as chemicals used for neutralizing and cleaning waste from bodily functions.
  - **Combustion and Smoldering Events** have happened during spaceflight and can result in the release of carbon monoxide, weak acids, and other toxic substances. This is dependent, in part, on the **Electric Shock (Risk)**.
  - **Thermal Degradation** of heated materials such as non-combustible plastics that release toxic vapors into the local atmosphere.
  - **Payload Chemicals** that may be brought on board by a visiting spacecraft or payload that is not always present in the vehicle systems.
  - **Materials Off-Gassing** occurs for plastics, rubbers, and other substances that are not thermally dependent.
  - **External Contaminants** such as lunar or **Martian Dust (Risk)** may be brought into the vehicle or habitat.
- All of these except Crew Metabolism are dependent on **Vehicle Design** and the **EIHSO (Risk).**
- If a **Toxic Substance Exposure** occurs, several pathways affect **Individual Readiness** and **Crew Capability**, including the following:
  - Some toxicants have cardiovascular toxicities—**Cardiovascular (Risk)**— that can lead to dysrhythmias and myocardial tissue damage.
  - Some toxicants are ototoxicants and can affect the **Acoustics (Risk)**.
  - Several toxicants can cause **Environmental Injuries** such as carbon monoxide poisoning or ammonia inhalation, which can occur from coolant release, and other **Medical (Risk)** issues that can lead to consequences such as **Evacuation**, **Loss of Crew Life** or **LTH Outcomes**.
  - Toxicants can also lead to decrements in **Behavioral Health (Risk)**, including altered mental status, and can affect **Cognitive Function** and **Psychological Status**, which can affect the **Team (Risk)**.
- If a **Toxic Substance Exposure** occurs, then the ability of the crew to mitigate the problem depends on the **Vehicle Design**, including the **Crew Health Care System/Crew Health and Performance System** and the Environmental Control Life Support **(ECLS)** System.
- **Toxic Substance Monitoring** enables **Detect Toxic Exposure**, which can drive countermeasure use such as using **Atmospheric Scrubbers** or donning **Protective Equipment**. **Protective Equipment** is part of the **Medical Prevention Capabilities** designed into the **Crew Health Care System/Crew Health and Performance**

System.

- **Physiologic Monitoring Capability** can include biomarkers that identify the physiologic response of an astronaut who has been exposed to a toxic substance and can help **Detect Diagnosis** to tailor medical care, which is part of the **Medical (Risk)**.
- The effectiveness of medical interventions will, in part, depend on the **Pharm (Risk)** for **Pharmaceutical Effectiveness**.
- Historically the detection of vehicle system issues that can lead to **Release of Toxic Substances** has, in large part, depended on **Ground Support** from **Mission Control**. This support is available in low Earth orbit (LEO), but **Communication Factors** must be considered for DRMs that are more **Distance from Earth**. The need for increased crew autonomy during these missions may require increased monitoring capability to reduce the risk of toxic exposures.
- Some **Toxic Substance Exposures** can lead to **LTH Outcomes** such as cardiovascular, pulmonary, renal, and other medical conditions. **Surveillance**, such as occupational health surveillance after flight and post career, is critical to **Detect LTH Outcomes** and better characterize the magnitude of the LTH risks.

5. Risk Summary

Primary Hazard:

Hostile <u>Closed</u> Environment

Secondary Hazard(s):

Altered Gravity

Countermeasures in use:

<u>Prevention</u>
Human system integration processes (implementation of standards, materials selection, development of a hazardous materials summary table, proper containment, etc.) and crew selection
<u>Monitoring</u>
Smoke particulate, volatile organics, and targets of specific concern (e.g., ammonia on the International Space Station [ISS])
<u>Intervention</u>
Vehicle scrubbing, protective equipment, treatment protocols, operational procedures and response

Contributing Factors

Sources of potential toxic substances (combustion and smoldering events, thermal degradation, vehicle systems, payload chemicals, materials off gassing, crew metabolism, and external contaminants) combined with individual factors (age, body weight, genetics, prior exposures, etc.)

State of Knowledge

Astronauts can be exposed to toxic substances in the air and water on the spacecraft. Based on historical data, the likelihood and frequency of toxic exposure is inversely related to the toxic hazard. The risk of exposure to toxic substances is mitigated by preventive measures aimed at reducing or eliminating toxic exposure events, and by monitoring and intervening after a release to minimize impacts to the crew and to reduce the risk of LOMO, LOM, LOC, and LTH consequences. The lack of in-flight monitoring of volatile organic compounds (VOC) during Artemis missions results in a lack of insight into toxic exposure events and the effectiveness of mitigations and interventions.

General Assumptions

All LxC assessments:

- Assume that NASA Standards 3001 have been met
- Based on the Human System Risk Board (HSRB) LxC matrix and the HSRB DRM categories

DRM-Specific Assumptions

DRM Categories	Mission Type and Duration	Prior Assumptions (2021)	Current Assumptions (2023)
Low Earth Orbit (LEO)	Short (<30 days)	Appropriate personal protective equipment (PPE) and clean-up materials and procedures are in place	Appropriate PPE and clean-up materials and procedures are in place
	Long (30 d-1 yr)	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available
Lunar Orbital	Short (<30 days)	30 sec communication delay Appropriate PPE and clean-up materials and procedures are in place	30 sec communication delay Appropriate PPE and clean-up materials and procedures are in place
	Long (30 d-1 yr)	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available	30 sec communication delay Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is not present in all mission phases
Lunar Orbital + Surface	Short (<30 days)	Appropriate PPE and clean-up materials and procedures are in place	30 sec communication delay Appropriate PPE and clean-up materials and procedures are in place
	Long (30 d-1 yr)	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available	30 sec communication delay Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is not present in all mission phases
Mars	Preparatory (<1 year)	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available
	Planetary (1 – 3 years)	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available	Appropriate PPE and clean-up materials and procedures are in place In-flight VOC monitoring is available

6. LxC Quick Look

2021

DRM Categories	Mission Type and Duration	OPS LxC	OPS Risk Disposition	LTH LxC	LTH Risk Disposition
Low Earth Orbit	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
Lunar Orbital	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
Lunar Orbital + Surface	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
Mars	Preparatory (<1 year)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
	Planetary (1 - 3 years)	4x3 (low) 3x4 (mod) 2x5 (high)	Accepted with Monitoring	3x1 3x2 3x4	Accepted with Monitoring

2023

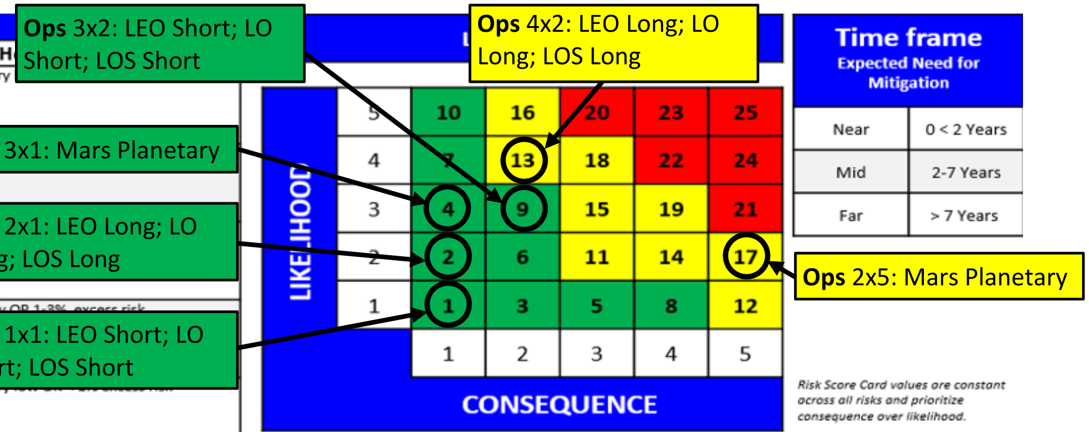
DRM Categories	Mission Type and Duration	OPS LxC	OPS Risk Disposition	LTH LxC	LTH Risk Disposition
Low Earth Orbit	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
Lunar Orbital	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Requires Mitigation	2x1 2x2 2x4	Requires Mitigation
Lunar Orbital + Surface	Short (<30 days)	**3x2 (low)** **2x3 (mod)** **1x5 (high)**	Accepted with Monitoring	1x1 1x2 1x4	Accepted
	Long (30 d-1 yr)	4x2 (low) 3x3 (mod) 1x5 (high)	Requires Mitigation	2x1 2x2 2x4	Requires Mitigation
Mars	Preparatory (<1 year)	4x2 (low) 3x3 (mod) 1x5 (high)	Accepted with Monitoring	2x1 2x2 2x4	Accepted with Monitoring
	Planetary (1 - 3 years)	4x3 (low) 3x4 (mod) 2x5 (high)	Accepted with Monitoring	3x1 3x2 3x4	Accepted with Monitoring

Greater Programmatic risk acceptance and lack of in-flight VOC monitoring in Artemis vehicles lead to reduced insight during an event and eliminates the ability to evaluate LTH consequences

7. HSRB Risk Likelihood x Consequence Matrix

Low Toxicity Events

LIKELIHOOD RATING	In-Mission	Flight Recertification	Long Term Health
5 Very High	More likely to happen than not during the mission or probability (P) >10%	Very likely to happen. Controls are insufficient or P> 10%	Likelihood is very
4 High	Likelihood is during the mission or 1%<P≤10%	Likely to happen. Controls have significant limitations or uncertainties or 1%<P≤ 10%	Likeliho
3 Moderate	May happen during the mission or 0.1%<P≤1%	Not likely to happen. Controls exist with some limitations or uncertainties or 0.1%<P≤1%	Likeliho
2 Low	Unlikely to happen during the mission or .01%<P≤0.1%	Not expected to happen. Controls have minor limitations or uncertainties or 0.01%<P≤0.1%	Likelihood is low OR 1-3% excess risk
1 Very Low	Nearly certain to not occur in-mission or P≤0.01%	Extremely remote possibility that it will happen. Strong controls in place or P≤0.01%	Likeliho



Time frame Expected Need for Mitigation	
Near	0 < 2 Years
Mid	2-7 Years
Far	> 7 Years

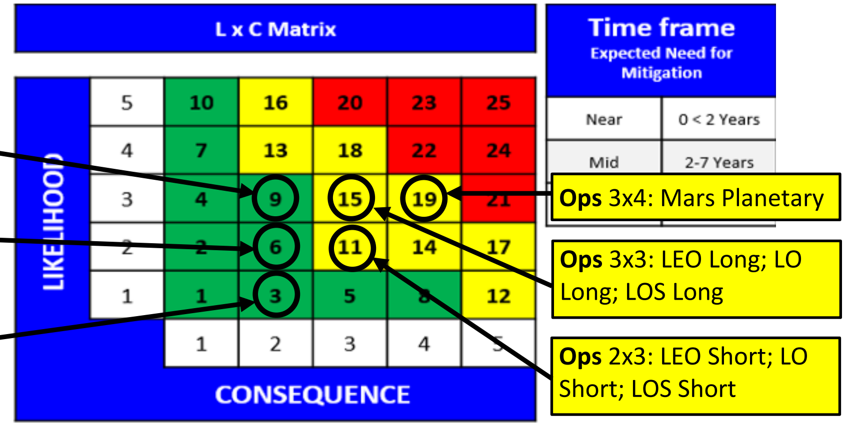
Risk Score Card values are constant across all risks and prioritize consequence over likelihood.

CONSEQUENCES		1	2	3	4	5
IN MISSION	Crew Health Impact OR	Temporary discomfort	Minor injury/illness that can be dealt with by crew without ground support, minor crew discomfort	Significant injury/illness or incapacitation that requires diagnosis and/or treatment support from ground, may affect personal safety	Critical injury/illness of one crew member requiring extended medical intervention and support, may result in temporary disability	Death or permanently disabling injury/illness affecting one or more crewmember (LOCL/LOC)
IN MISSION	Mission Objectives Impact	Insignificant impact to crew performance and operations – no additional resources required	Minor impact to crew performance and operations – requires additional resources (time, consumables)	Significant reduction in crew performance, threatens loss of a mission objective	Severe reduction of crew performance that results in loss of multiple mission objectives	Loss of mission due to crew performance reductions or loss of crew
FLIGHT RECERT	Crew Flight Recertification Status	Immediate flight recertification status	Flight recertification status within 3 months with limited intervention	Flight recertification status within 1 year with nominal intervention or restricted flight status	Flight recertification status requires extended medical intervention and takes > 1 year	Unable to be Recertified for Flight Status, premature career end
LONG TERM HEALTH	Health Outcomes OR	Career related short term self-resolving medical conditions	Career related medical conditions manageable with outpatient medical treatments	Treatable career related medical condition that requires hospitalization for management	Chronic career related medical condition requiring intermittent hospitalization or nursing care	Career related premature death or permanent disability requiring institutionalization
LONG TERM HEALTH	Quality of Life	No impact on quality of life OR independence in activities of daily living	Minor, short-term impact on quality of life OR rare support required for activities of daily living	Moderate long-term impact on quality of life OR may require some time-limited support for activities of daily living	Major long-term impact on quality of life OR requires intermittent support for activities of daily living	Chronic debilitating impact on quality of life OR requires continuous support for activities of daily living

HSRB Likelihood x Consequence Matrix

Medium Toxicity Events

LIKELIHOOD RATING	In-Mission	Flight Recertification	Long Term Health
5 Very High	More likely to happen than not during the mission or probability (P) >10%	Very likely to happen. Controls are insufficient or P> 10%	Likelihood is very high OR >10% excess risk
4 High	Likelihood is during the mission or 1%<P≤10%	Likely to happen. Controls have significant limitations or uncertainties or 1%<P≤ 10%	Likeliho[illegible]
3 Moderate	May happen during the mission or 0.1%<P≤1%	Not likely to happen. Controls exist with some limitations or uncertainties or 0.1%<P≤1%	Likeliho[illegible]
2 Low	Unlikely to happen during the mission or .01%<P≤0.1%	Not expected to happen. Controls have minor limitations or uncertainties or 0.01%<P≤0.1%	Likelihood is low OR 1-3% excess risk
1 Very Low	Nearly certain to not occur in-mission or P≤0.01%	Extremely remote possibility that it will happen. Strong controls in place or P≤0.01%	Likeliho[illegible]



CONSEQUENCES		1	2	3	4	5
IN MISSION	Crew Health Impact	Temporary discomfort	Minor injury/illness that can be dealt with by crew without ground support, minor crew discomfort	Significant injury/illness or incapacitation that requires diagnosis and/or treatment support from ground, may affect personal safety	Critical injury/illness of one crew member requiring extended medical intervention and support, may result in temporary disability	Death or permanently disabling injury/illness affecting one or more crewmember (LOCL/LOC)
	OR					
	Mission Objectives Impact	Insignificant impact to crew performance and operations – no additional resources required	Minor impact to crew performance and operations – requires additional resources (time, consumables)	Significant reduction in crew performance, threatens loss of a mission objective	Severe reduction of crew performance that results in loss of multiple mission objectives	Loss of mission due to crew performance reductions or loss of crew
FLIGHT RECERT	Crew Flight Recertification Status	Immediate flight recertification status	Flight recertification status within 3 months with limited intervention	Flight recertification status within 1 year with nominal intervention or restricted flight status	Flight recertification status requires extended medical intervention and takes > 1 year	Unable to be Recertified for Flight Status, premature career end
LONG TERM HEALTH	Health Outcomes	Career related short term self-resolving medical conditions	Career related medical conditions manageable with outpatient medical treatments	Treatable career related medical condition that requires hospitalization for management	Chronic career related medical condition requiring intermittent hospitalization or nursing care	Career related premature death or permanent disability requiring institutionalization
	OR					
	Quality of Life	No impact on quality of life OR independence in activities of daily living	Minor, short-term impact on quality of life OR rare support required for activities of daily living	Moderate long-term impact on quality of life OR may require some time-limited support for activities of daily living	Major long-term impact on quality of life OR requires intermittent support for activities of daily living	Chronic debilitating impact on quality of life OR requires continuous support for activities of daily living

HSRB Likelihood x Consequence Matrix

High Toxicity Events

LIKELIHOOD RATING	In-Mission	Flight Recertification	Long Term Health
5 Very High	More likely to happen than not during the mission or probability (P) >10%	Very likely to happen. Controls are insufficient or P> 10%	Likelihood is very high OR >10% excess risk
4 High	Likelihood is during the mission or 1%<P≤10%	Likely to happen. Controls have significant limitations or uncertainties or 1%<P≤ 10%	Likeliho
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L x C Matrix

LIKELIHOOD					
5	10	16	20	23	25
4	7	13	18	22	24
3	4	9	15	19	21
2	2	6	11	14	17
1	1	3	5	8	12
CONSEQUENCE	1	2	3	4	5

LTH 3x4: Mars Planetary (19)
LTH 2x4: LEO Long; LO Long; LOS Long; Mars Prep (14)
LTH 1x4: LEO Short; LO Short; LOS Short (8)
Ops 2x5: Mars Planetary (17)
Ops 1x5: All DRM, except Mars Planetary (12)

Time frame
Expected Need for Mitigation

Near	0 < 2 Years
Mid	2-7 Years
Far	> 7 Years

across all risks and prioritize consequence over likelihood.

CONSEQUENCES		1	2	3	4	5
IN MISSION	Crew Health Impact OR	Temporary discomfort	Minor injury/illness that can be dealt with by crew without ground support, minor crew discomfort	Significant injury/illness or incapacitation that requires diagnosis and/or treatment support from ground, may affect personal safety	Critical injury/illness of one crew member requiring extended medical intervention and support, may result in temporary disability	Death or permanently disabling injury/illness affecting one or more crewmember (LOCL/LOC)
	Mission Objectives Impact	Insignificant impact to crew performance and operations – no additional resources required	Minor impact to crew performance and operations – requires additional resources (time, consumables)	Significant reduction in crew performance, threatens loss of a mission objective	Severe reduction of crew performance that results in loss of multiple mission objectives	Loss of mission due to crew performance reductions or loss of crew
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	Quality of Life	No impact on quality of life OR independence in activities of daily living	Minor, short-term impact on quality of life OR rare support required for activities of daily living	Moderate long-term impact on quality of life OR may require some time-limited support for activities of daily living	Major long-term impact on quality of life OR requires intermittent support for activities of daily living	Chronic debilitating impact on quality of life OR requires continuous support for activities of daily living

8. Risk Postures

Low Earth Orbit (< 30 Days)
Operations

3x2 (l) 2x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Moderate for low toxicity event
  Low for moderate toxicity event
  Very low for highly toxic event

- **LxC Drivers for Consequence:**
  Minor injury, illness, and discomfort for low toxicity event
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event

- **Rationale for Risk Disposition:** Although more likely to leak, low and moderate toxicity chemicals are accepted due to limited consequences (off gassing, for example), but highly toxic substances (combustion products or ammonia, for example) **must** be monitored.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Low Earth Orbit (< 30 Days)
Long-Term Health

1x1 (l) 1x2 (m) 1x4 (h)	Accepted

- **LxC Drivers for Likelihood:**
  Very low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:** Accepted

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Low Earth Orbit (30 d–1 yr)
Operations

4x2 (l) 3x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Increase for low and moderate toxicity events only; highly toxic substances remain tightly controlled so the likelihood does NOT increase
  High for low toxicity event
  Moderate for moderate toxicity event
  Very low likelihood of highly toxic event

- **LxC Drivers for Consequence:**
  Does not differ based on duration—impacted by severity of release
  Minor injury, illness, and discomfort for low toxicity event
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event

- **Rationale for Risk Disposition:**
  Due to increased likelihood of low and moderate events occurring over longer durations, VOCs of potential concern for crew health or ECLS systems (not just highly toxic substances) **must** be monitored.

  Note: Likelihood of moderate or highly toxic events may increase with increased risk acceptance.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Low Earth Orbit (30 d–1 yr)
Long-Term Health

2x1 (l) 2x2(m) 2x4 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:**

Lunar Orbital (< 30 Days)
Operations

3x2 (l) 2x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Moderate for low toxicity event
  Low for moderate toxicity event
  Very low for highly toxic event

- **LxC Drivers for Consequence:**
  Minor injury, illness, and discomfort for low toxicity event
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- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital (< 30 Days)
Long-Term Health

1x1 (l) 1x2 (m) 1x4 (h)	Accepted

- **LxC Drivers for Likelihood:**
  Very low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Accepted

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital (30 d–1 yr)
Operations

4x2 (l) 3x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
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  Does not differ based on duration—impacted by severity of release
  Minor injury, illness, and discomfort for low toxicity event
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event

- **Rationale for Risk Disposition:**
  Required Mitigation without in-flight VOC monitoring.

  Note: Likelihood of moderate or highly toxic events may increase with increased risk acceptance.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital (30 d–1 yr)
Long-Term Health

2x1 (l) 2x2(m) 2x4 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Requires mitigation without in-flight VOC monitoring.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1- Strong

Lunar Orbital + Surface (< 30 Days) Operations

3x2 (l) 2x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Very low for highly toxic event
  Moderate for low toxicity event
  Low for moderate toxicity event

- **LxC Drivers for Consequence:**
  Severe injury or death for highly toxic event
  Severe injury or death for highly toxic event
  Significant impact that may require treatment for moderate toxicity event

- **Rationale for Risk Disposition:**
  Although more likely to leak, low and moderate toxicity chemicals are accepted due to limited consequences (off gassing, for example), but highly toxic substances (combustion products or ammonia, for example) **must** be monitored.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital + Surface (< 30 Days) Long-Term Health

1x1 (l) 1x2 (m) 1x4 (h)	Accepted

- **LxC Drivers for Likelihood:**
  Very low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Accepted

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital + Surface (30 d–1 yr) Operations

4x2 (l) 3x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Very low likelihood of highly toxic event
  Increase for low and moderate toxicity events only; highly toxic substances remain tightly controlled so likelihood does NOT increase
  High for low toxicity event
  Moderate for moderate toxicity event

- **LxC Drivers for Consequence:**
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event
  Does not differ based on duration—impacted by severity of release
  Minor injury, illness, and discomfort for low toxicity event

- **Rationale for Risk Disposition:**
  Requires mitigation without in-flight VOC monitoring.

  Note: Likelihood of moderate or highly toxic events may increase with increased risk acceptance.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:**

Lunar Orbital + Surface (30 d–1 yr) Long-Term Health

2x1 (l) 2x2(m) 2x4 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Requires mitigation without in-flight VOC monitoring

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Mars Preparatory (<1 yr.)
Operations

4x2 (l) 3x3 (m) 1x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  High for low toxicity event
  Moderate for moderate toxicity event
  Very low for highly toxic event

- **LxC Drivers for Consequence:**
  Does not differ based on duration—impacted by severity of release and availability of medical treatments and response
  Minor injury, illness, and discomfort for low toxicity event
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event

- **Rationale for Risk Disposition:**
  Due to increased likelihood of low and moderate events over longer durations, VOCs of potential concern for crew health or ECLS systems (not just highly toxic substances) **must** be monitored.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Mars Preparatory (<1 yr.)
Long-Term Health

2x1 (l) 2x2(m) 2x4 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Very Low

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Mars Planetary (730–1224 d) Operations

4x3 (l) 3x4 (m) 2x5 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Depends heavily on implementation of requirements and containment
  Very high for low toxicity events
  High for moderate toxicity events
  Low for highly toxic events

- **LxC Drivers for Consequence:**
  Does not differ based on duration—impacted by severity of release and availability of medical treatments and response
  Minor injury, illness, and discomfort for low toxicity event
  Significant impact that may require treatment for moderate toxicity event
  Severe injury or death for highly toxic event

- **Rationale for Risk Disposition:**
  Due to increased likelihood of low and moderate events over longer durations, VOCs of potential concern for crew health or ECLS systems (not just highly toxic substances) **must** be monitored.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 3-Weak

Mars Planetary (730–1224 d) Long-Term Health

3x1 (l) 3x2(m) 3x4 (h)	Accepted with Monitoring

- **LxC Drivers for Likelihood:**
  Moderate

- **LxC Drivers for Consequence:**
  Self-resolving for low toxicity events
  Manageable for moderate toxicity events
  Major impact for highly toxic events

- **Rationale for Risk Disposition:**
  Monitoring provides insight for investigations involving occupational (in-flight) exposures.

- **DRM Specific Assumptions:**

- **DRM Specific Evidence/Level of Evidence:** 3-Weak

9. Overall Assessment of the Evidence

- **Toxic substance releases (suspected and real) can and do occur.**
  - These releases continue to have little impact on crew health.
- **Increased acceptance of this risk may alter frequency and/or likelihood of toxic substance release events.**
- **Reduced monitoring reduces evaluation of and response to an unexpected release of toxic substances.**
- **Vehicle systems are not infallible—Increased reliance on engineering controls rather than mitigation and monitoring increases the risk of release and exposure to toxic substances.**

10. State of Knowledge

Monitoring Smoke Detection and Combustion Products

- Requirements are currently met and implemented via continuous real-time smoke detection, supplemented with real-time (but not continuous) handheld event monitors.
- Current smoke detectors are particulate based and prone to false alarms due to other particle sources (housekeeping, for example).
  - This is associated with a concern for alarm fatigue—alarms go off frequently but are generally declared false.
- Smoke alarms are currently confirmed or declared to be false by the use of hand-held combustion product (carbon monoxide, hydrogen chloride, hydrogen cyanide) monitors.
- Improved fire detection may be achieved for future programs by requiring continuous real-time monitoring of some or all combustion products and/or by improved smoke detectors that distinguish between smoke particulate and other particles (see high value risk mitigation targets).

Lessons Learned from Apollo Missions

- **ECLS Compatibility**
  - When different vendors build different parts of a complex spacecraft (Apollo Command Module and Lunar Lander "square peg in round hole" carbon dioxide removal, for example), issues can arise during failures and/or emergencies if there is no commonality between systems and spares.
  - This is a potential concern for common spacecraft such as Orion, Gateway, and the Human Landing System (HLS) that are build and designed by independent partners. Interface Requirement Documents are essential in these cases.

- **Vehicle Automation**
  - The most notable toxic exposure to date was the ingestion of nitrogen tetroxide into the capsule during re-entry of the Apollo-Soyuz Test Project. The systems performed as

designed but led to ingestion of contaminated external atmosphere.

Take Home Message

- **Releases are not restricted to a particular location or contributing factor type (payloads, vehicle systems, crew metabolism, etc.).**
- **Hardware fails (scrubbing and monitoring hardware), therefor backup equipment is critical.**
- **Suspected and actual releases happen fairly often (several times/year) but generally do not impact crew health.**
  - High likelihood exists of toxic substance releases with minor consequences.
  - Very low likelihood exists of toxic substance releases with major consequences.

Concerns

- **Increased risk acceptance can lead to**
  - Reduced fault tolerance
  - Resistance to use personal protective equipment (PPE)
  - 'Blanket' Non-Compliance Reports and reduced insight regarding adequacy of containment for all scenarios
- **Lack of consequences and safety insight into operational failures**
  - On-orbit operation continues despite failures and issues and/or failures to modify hardware prior to re-flight.
- **Short timelines for vehicle development reduces insight**
  - Inadequate time to evaluate and address the hazard before the system is built and delivered means equipment must be accepted rather than properly designed.
- **Limited adjudicated requirements**
  - This limits the ability to preclude an event and force reliance on response instead
- **Increased reliance on engineering analysis and controls rather than prevention, monitoring, and response**
- **Limited cross-program integration (Artemis)**
  - Exposures to toxic substances across multiple vehicles are not being adequately assessed nor addressed.

11. Metrics

- Evaluation of frequency and severity of toxic releases and exposures via operational reports

12. Risk Mitigation Framework – Color Changes

- **How do we know when we go from red → yellow? NA**
- **How do we know when we go from yellow → green?**
  - **Review implementation of reduced fault tolerance**
  - See high value risk mitigation targets

13. Risk → Standards → Requirements Flow

Risk of Toxic Risk Exposure

Standard

NASA-STD-3001: NASA Space Flight Human-System Standard Vol. 1, Crew Health, Revision C – September 2023

[V1 3001] Selection and Recertification
[V1 3004] In-Mission Medical Care
V1 3015] Certification of Training Plans for Launch/Landing Medical Team
[V1 3018] Post-Mission Long-Term Monitoring [V1 5001] Medical Training
[V1 5002] Crewmember Training
[V1 5003] Crew Medical Officer Medical Training

NASA-STD-3001: NASA Space Flight Human System Standard Vol. 2, Human Factors, Habitability, and Environmental Health, Revision D – September 2023

[V2 6023] Trace Constituent Monitoring and Alerting
[V2 6024] Combustion Monitoring and Alerting [V2 6025] Contamination Monitoring and Alerting [V2 6047] Toxic Hazard Level Three
[V2 6048] Toxic Hazard Level Four [V2 6049] Chemical Decomposition
[V2 6050] Atmosphere Contamination Limit [V2 6051] Water Contamination Control
V2 6062] Availability of Environmental Hazards Information
[V2 6063] Contamination Cleanup [V2 7043] Medical Capability
[V2 7069] Labeling of Hazardous Waste
[V2 7082] Surface Material Cleaning [V2 7083] Cleaning Materials
[V2 9024] Fluid/Gas Release [V2 9025] Fluid/Gas Isolation
[V2 9026] Fluid/Gas Containment [V2 9053] Protective Equipment
/2 9059] Fire Detecting, Warning, and Extinguishing
[V2 12005] Protective Equipment [V2 12032] Contamination Controls
[V2 12033] Containment of Fluids and Gases

Requirements

ISS	MPCV	CCP	HLS	Gateway	EHP	CLDP
SSP 41000 System Specification SSP 50808 ISS to COTS IRD SSP 50260 ISS Medical Operations Requirements Document	MPCV 70024 Human System Integration Requirements	CCT-REQ-1130 ISS Crew Transportation Requirement (Sustained) Document JSC-65993 CHSIR	HLS-HMTA-001 (Initial) HLS-HMTA-006	GP 10004 Subsystem Specification for ECLSS GP 10016 Subsystem Specification for CHP GP 10017 Subsystem Specification for HSR	xEVAS-SRD-001 HLS-HMTA-006	

CCP – Commercial Crew Program; CLDP – CCT- Commercial Crew Transportation; Commercial Low Orbit Development Program; COTS – Commercial Off-the-shelf; EHP - Extravehicular Activity and Human Surface Mobility Program; GP – Gateway Program; HLS – Human Landing System; HMTA – Health and Medical Technical Authority; IRD – Interface Requirement Document; LEA – Launch, Entry and Abort; MPCV – Multipurpose Crew Vehicle; SRD – System Requirement Document; SSP – Space Shuttle Program; xEVAS – Exploration Extravehicular Activity Services

14. Proposed Standard Updates

None

15. High Value Risk Mitigation Targets

- **Ensure that toxicological requirements in NASA Standard 3001 are appropriately implemented when developing requirements for new programs (Chief Health & Performance Officers [CHPOs] and subject matter experts [SMEs])**
- **Ensure that appropriate monitoring is included in ALL vehicles that are required for missions that exceed 30 days (even if the vehicle will be used for a 'portion' of the mission, i.e., < 30 days) (CHPOs and SMEs)**
- **Optimize spacecraft materials and hardware (vehicle system and payloads) and chemical selection (CHPOs and SMEs)**
  - Involve NASA SMEs early and often to avoid last minute issues and acceptance and/or mitigation rather than a more desirable solution during design
- **Continue developing reliable methods to monitor toxic releases of concern that involve small equipment and require no on-orbit calibration, etc. (CHPOs/SMEs)**
  - Hardware development for continuous carbon monoxide monitoring is recommended to monitor smoke particulate from combustion events.
  - Hardware development for (form)aldehyde monitoring is recommended to address vapor concentrations concerns (currently for ingress of cargo vehicles on ISS)**.**

16. Conclusions

- Given the operational evidence that toxic releases can and do occur during spaceflight, we recommend accepting the Risk of Toxic Release on the condition that appropriate requirements are implemented, appropriate monitoring exists, and appropriate protective equipment and procedures are in place to mitigate this risk.

17. Recommendations

Accepted:

- Inclusion in the record of operational evidence (since 2021) of the release of toxic substances, including their relative frequency and impact to crew.
- Change to risk posture based on increased acceptance of the risk combined with lack of monitoring
- Inclusion of new concerns related to lack of program level integration for Artemis missions

18. References

None

19. Acronyms and Abbreviations

BRESCB	Biomedical Research and Environmental Sciences Control Board
CCT	Commercial Crew Transportation
CEV	Crew Exploration Vehicle
CHPO	Chief Health and Performance Officer
CLDP	Commercial Low Earth Orbit Development Program
CO_2 Risk	Risk of Nominal Acute and Chronic Ambient Carbon Dioxide Exposure in Crewed Vehicles
CR	Change Request
DAG	Directed Acyclic Graph
DRM	Design Reference Mission
ECLS	Environmental Control Life Support
EHP	Extravehicular Activity and Human Surface Mobility Program
EIHSO	Risk of Earth Independent Human System Operations
Electric Shock Risk	Risk to Crew Health Due to Electrical Shock
GP	Gateway Program
HLS	Human Landing System
HSI	Human System Integration
HSR	Human System Requirements
HSRB	Human Systems Risk Board
ISS	International Space Station
LEO	Low Earth Orbit
LTH	Long-Term Health
LOC	Loss of Crew
LOM	Loss of Mission
LOMO	Loss of Mission Objectives

LxC	Likelihood and Consequence
Medical Conditions Risk	Risk of Adverse Health Outcomes and Decrements in Performance Due to Medical Conditions that occur in Mission, as well as Long-Term Health Outcomes Due to Mission Exposures
MPCV	Multipurpose Crew Vehicle
OPS	Operations
Pharm Risk	Risk of Ineffective or Toxic Medications During Long-Duration Exploration Spaceflight
PPE	Personal Protective Equipment
RMAT	Reliability and Maintainability Assessment Tool
sec	Second
SD	Space Medicine Operations Division
SK	Biomedical Research and Environmental Science Division
SME	Subject Matter Expert
SMOCB	Space Medicine Operations Control Board
SSP	Space Shuttle Program
STS	Space Transportation System
VOC	Volatile Organic Compound
yr	Year

Appendix - Existing Evidence Base

Existing Evidence — Rev A

Monitoring and Release Conclusions

- ❖ Releases are not restricted to a particular location or contributing factor type (payloads, vehicle systems, crew metabolism, etc.).
- ❖ Hardware fails (scrubbing and monitoring hardware) therefore, backup equipment is critical.
- ❖ Suspected and actual releases happen fairly often (several times/year) but generally do not impact crew health
    - High likelihood exists of toxic releases with minor consequences
    - Very low likelihood exists of toxic releases with major consequences

Existing Evidence — Baseline

Toxicological Risks in Spacecraft

- ❖ Compounds used in systems (ammonia, ethylene glycol, Freon 218)
- ❖ Payload chemicals (fixatives)
- ❖ Off gassed products (formaldehyde)
- ❖ Batteries (electrolytes and fire hazard)
- ❖ Products of corrosion
- ❖ External contaminants (e.g., Fuel Oxidizer Reaction Products)
- ❖ Human and microbial metabolites (carbon monoxide)
- ❖ Operational anomalies, hardware failures, and repair (Skylab heater)
- ❖ Thermal degradation of electronic components and other fires

Toxicological risks in spacecraft are addressed through:

- ❖ Requirements
  - Implementation of NASA-developed exposure limits for airborne and waterborne contaminant (Spacecraft Maximal Allowable Concentrations and Spacecraft Water Exposure Guidelines) in spacecraft development
- ❖ Pre-flight evaluations
  - Toxicity assessments that drive safety process for payload development
- ❖ Monitoring
  - Real-time and archival air and water sampling to ensure that requirements are met
- ❖ PPE
  - Generic for moderate releases and specialized for severe releases

Metrics of Toxic Exposure

Number of Events	Intensity of Effect	Duration Exposure
15	mild	<1 d
5	mild	1-10 d
0	mild	>10d
3	moderate	<1 d
2	moderate	1-10 d
1	moderate	>10 d
1	severe	<1 d
0	severe	1-10 d
0	severe	>10 d

James (2009).

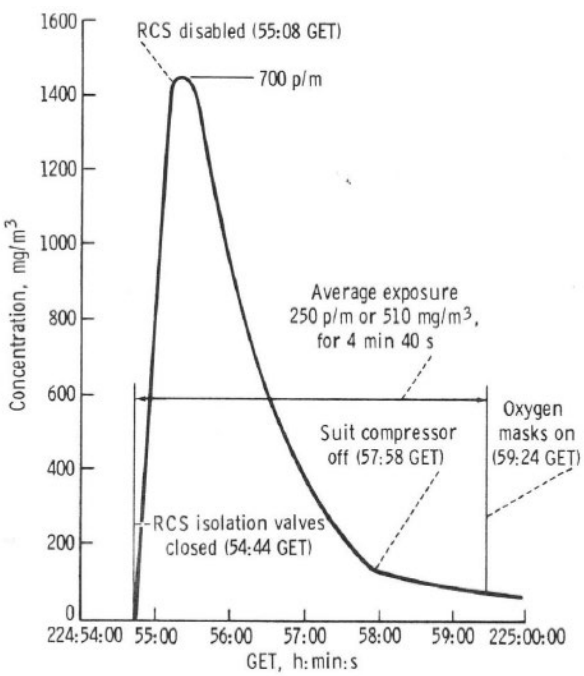
Examples of Mild Events that have Occurred

- Lithium hydroxide release from carbon dioxide scrubber
- Microbial metabolites (methyl sulfides) escape through walls of a mini-contingency waste container on Space Transportation System (STS)-95
- Fire in the solid fuel oxygen generator on Mir, the Russian space station (1986–2001)

Examples of Moderate Events that have Occurred

- Iodine release from in Skylab and Space Shuttle water
- Release of carbon monoxide from the burnt trace contaminant filter on Mir
- Space Shuttle, Space Transportation System (STS)-40's orbiter refrigerator freezer Fan Motor burnout and release of toxic fumes.
- Delayed regeneration of the metal oxide containers that are used to remove carbon dioxide from air resulted in elevated levels of CO2

Example of a Severe Event that has Occurred



Propellant Intrusion During Splashdown

GET - Georgia Standard Time is 4 hours ahead of Coordinated Universal Time (UTC) and is used during standard time in Asia and Europe; mg/m^3 milligrams per cubic meter; RCS – Reaction Control System

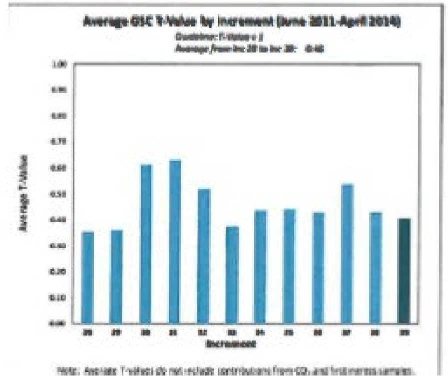
JSC-10638 APOLLO SOYUZ MISSION ANOMALY REPORT

ISS Toxicology Assessments

Table 1. Analytical Summary of ISS air analyses

Sample Location	Sample Date	NMVOCs[a] (mg/m^3)	Freon 218 (mg/m^3)	Alcohols[b] (mg/m^3)	T-Value[c] (units)	CO_2 (mg/m^3)	Formaldehyde (µg/m^3)
Lab	3/31/2014	17	2.9	14	0.4	7700	39
JPM	3/31/2014	16	2.7	13	0.4	6600	--
SM	3/31/2014	--	--	--	--	--	28
SpX-3	4/21/2014	14	2.5	11	0.2[d] 0.5	6900	--
Lab	4/28/2014	14	2.5	11	0.4	7300	70
Col	4/28/2014	14	2.8	11	0.4	7100	--
SM	4/28/2014	--	--	--	--	--	27
Guideline		*<25*	---	*<5*	*<1[e]*	*<9300*	*<120*

[a]Non-methane volatile organic hydrocarbons, excluding Freon 218



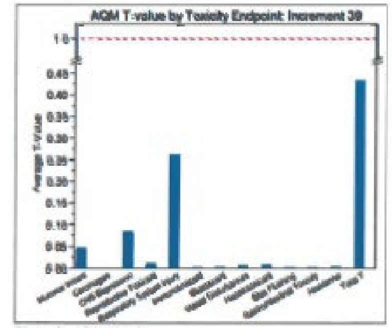


Figure 2. AQM T-values

Table 2. Average monthly concentrations (mg/m^3) of AQM target compounds.

	March	April	May	Increment Average
2-Propanol	0.14	0.15	0.17	0.15
Methanol	0.38	0.37	0.39	0.38
Acetone	0.20	0.24	0.27	0.24
1,2-Dichloroethane	ND	ND	ND	ND
Hexanal	ND	ND	ND	ND
Acrolein	ND	ND	ND	ND
Hexane	ND	ND	ND	ND
Benzene	ND	ND	ND	ND
Acetaldehyde	0.13	0.15	0.16	0.15
o-Xylene	0.06	0.07	Trace	0.06
OMCTS	Trace	Trace	Trace	Trace
DMCPS	2.2	1.85	1.76	1.94
HMCTS	1.8	1.75	1.94	1.83
Ethanol	3.3	4.25	4.99	4.18
n-Butanol	0.12	0.14	0.17	0.14
Trimethylsilanol	0.28	0.31	0.32	0.31
Ethyl Acetate	0.07	0.21	0.11	0.14
Toluene	Trace	ND	ND	ND
Dichloromethane	0.05	0.05	0.05	0.05
m,p-Xylenes	ND	ND	ND	ND
2-butanone	Trace	Trace	Trace	Trace

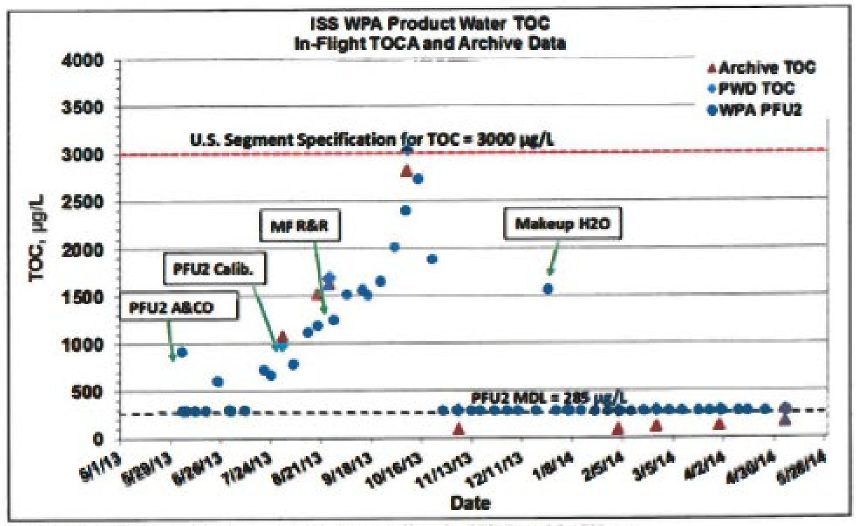
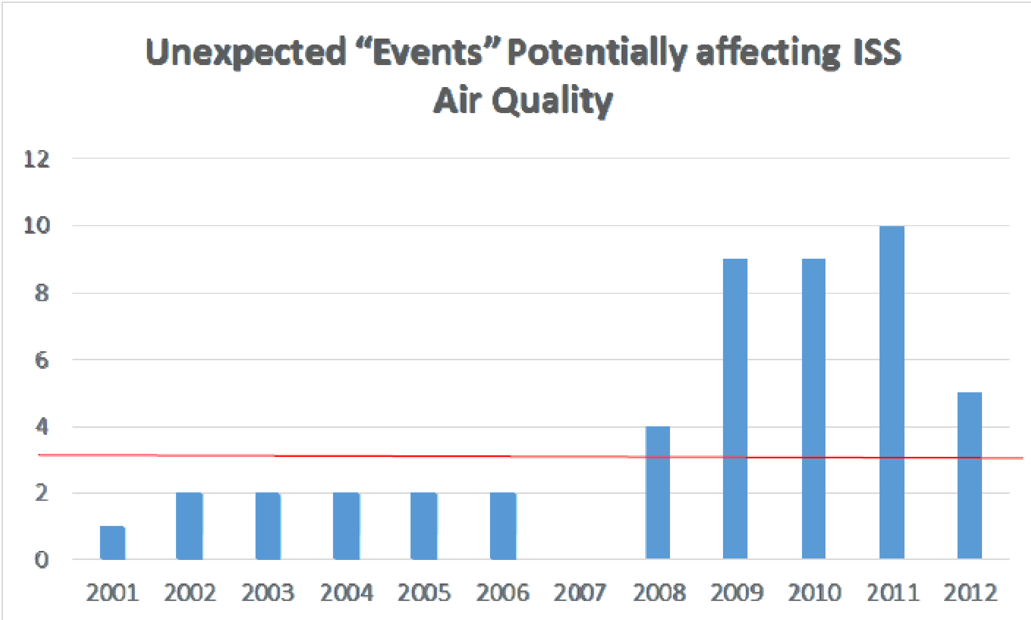


Figure 4. Total Organic Carbon (TOC) trending in US Potable Water

All Figures from Meyers, TOX-VM-2014-06, 2014 AQM – Air quality monitor; CO2 – carbon dioxide; Col - The Columbus Module of the ISS; DMCPS – Decamethylcyclopentasiloxane; HMCTS – Hexamethylcyclotrisilazane; JPM – The Japanese Pressurized Module of the ISS; Lab – The US Laboratory module of the ISS; MF R&R = Multi-filtration bed Remove and Replace; NMVOCs - Non-Methane Volatile Organic Compounds; OMCTS- Octamethylcyclotetrasiloxane; PFU2 A&CO - Second prototype flight unit activation and checkout; MF R&R = Multi-filtration bed Remove and Replace; PWD – Potable Water Dispenser; SM - Russian Service Module of the ISS; TOCA - Total Organic Carbon Analyzer; T-Value - Toxic Hazard Index, is determined by comparing dividing the concentration of off gassed chemicals in the air with the established exposure limits for those chemicals. A T-value less 1 is considered safe; WPA – Water Process Assembly



Events compiled from Operations Console Logs

Metrics of Toxic Exposure

	Medical Condition	Likelihood of Event*
49	Smoke Inhalation*	0.067 per mission (1 in 15 missions)
67	Sepsis*	0.0027 per mission (1 in 370 missions)
72	Hypovolemic Shock*	0.0017 per mission (1 in 588 missions)
73	Medication Overdose*	0.0012 per mission (1 in 855 missions)
76	Decompression Sickness*	0.00091 per mission (1 in 1,099 missions)
77	Stroke*	0.00087 per mission (1 in 1,149 missions)
78	Head Injury*	0.00070 per mission (1 in 1,429 missions)
80	Choking/Obstructed Airway*	0.00060 per mission (1 in 1,667 missions)
83	Chest Injury*	0.00043 per mission (1 in 2,326 missions)
84	Sudden Cardiac Arrest*	0.00033 per mission (1 in 3,030 missions)
85	Altitude Sickness*	0.00017 per mission (1 in 5,882 missions)
87	Seizures*	0.00011 per mission (1 in 9,091 missions)
92	Cardiogenic Shock*	0.00003 per mission (1 in 33,333 missions)
93	Radiation Syndrome*	0.00003 per mission (1 in 33,333 missions)
94	Neurogenic Shock*	0.00001 per mission (1 in 100,000 missions)
95	Toxic Exposure – Ammonia*	0.00001 per mission (1 in 100,000 missions)
96	Anaphylaxis*	0 per mission (<1 in 100,000 missions)

"This list has been extracted from the Medical Evidence Database (iMED), which houses the input for the Integrated Medical Model (IMM). The above data was gathered for request # D-20141003-168 to answer the question, "Which conditions require oxygen for treatment on ISS?". The likelihood numbers are based on an ISS 6-month mission and crew. The iMED contains data from multiple sources including terrestrial data, analog data, and in-flight data."

References (Appendix)

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Meyer, V.E. (2014). Toxicological Assessment of ISS Air and Water Quality: March 2014 - May 2014 and SpaceX-3 First Ingress (Increment 39). NASA Technical Memorandum Number TOX-VM-2014-06. https://ntrs.nasa.gov/api/citations/20140011497/downloads/20140011497.p