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Enhancing Future Commercial Space Stations: Applying ISS Insights to Environmental Control and Life Support Systems (ECLSS) Development on Emergency Response

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The expansion of space exploration to commercial space stations represents a significant shift from traditional government-led endeavors to a new, competitive era driven by private companies and innovative forces. This transition, while promising, brings its own set of challenges, particularly in the intricate development of Environmental Control and Life Support Systems (ECLSS). Establishing effective ECLSS within commercial space stations is critical, as it ensures the safety and sustainability of long-term human presence in space. By applying the lessons learned from the International Space Station (ISS), particularly during the initial conceptual design phase, there is an opportunity to mitigate early-stage issues and optimize the development process for these commercial habitats. One aspect that has not been discussed often, and with limited literature on the subject, is emergency operations aboard the ISS. Emergency operations requires a multidisciplinary approach, which is essential for completing its primary objective. Due to the nature of this, the main three categories of emergency operations can be classified as fire hazards, toxic spills, and rapid depress. This paper focuses on the specifics of ECLSS based emergency operations, with an in-depth focus on emergency hardware and operations within the specified categories. By drawing on operational experiences from the ISS, this paper aims to provide valuable insight for the considerations, design, and operational readiness of future commercial space station, ensuring enhanced safety protocols and preparedness for emergency scenarios.

Acronyms and Nomenclature

AGA = Anomaly Gas Analyzer
BIT = Built-in Test
C&C = Command & Control
C&W = Caution and Warning
CSA-CP = Compound Specific Analyzer for Combustion Products
ECLS = Environmental Control and Life Support
EEGS = Emergency Eye and Gas Sampling
ETCS = External Thermal Control System
HDI = Hatch Depress Indicator
IFHX = Interface Heat Exchanger
IMV = Intermodule Ventilation
IPK/ИПК = Russian breathing Mask (Cyrillic)
ITCS = Internal Thermal Control System
ISS = International Space Station
LEO = Low Earth Orbit
MB/MB = Manovacuummeter (Cyrillic)
MCC = Mission Control Center
MDM = Multiplexer/Demultiplexer
PBA = Portable Breathing Apparatus
PCS = Portable Computer System
PFE = Portable Fire Extinguisher
PPE = Personal Protective Equipment

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RS = Russian Segment
SM = Service Module
SMACs = Spacecraft Maximum Allowable Concentrations
TCCS = Trace Contaminant Control System
USOS = United States On-Orbit Segment
USCV = United States Crew Vehicle

I. Introduction

The International Space Station (ISS) serves as an unparalleled testbed for scientific research and technology development, including advancing development of Environmental Control and Life Support (ECLS) systems which are essential for deep space human exploration missions. These systems undergo rigorous testing, validation, and refinement aboard the ISS to ensure their readiness for future missions.[1]

With the impending decommissioning of the ISS by 2030, NASA has initiated various Space Act Agreements to facilitate the establishment of new commercial space stations that will support the ongoing human presence in Low Earth Orbit (LEO).[2] Establishment of reliable ECLS systems while allowing for development of improved technologies will be key to the success of these commercial enterprises.

Previous paper, Enhancing Future Commercial Space Stations: Applying ISS Insights to Environmental Control and Life Support Systems Development[5], provided ISS lessons learned in most of ECLS subsystems but did not include emergency response. This paper aims to harness over two decades of ISS operational knowledge to inform the design of future commercial space stations in the area of emergency response. It focuses on the synthesis of system management and operational perspectives to create robust and efficient life support systems for sustained human occupation in space.

II. Background

Emergency response is not a conventional ECLS subsystem but serves as a critical mechanism enabling engineering and flight control teams to support crew operations during emergencies. These scenarios primarily fall into three categories: rapid depressurization, fire, and toxic spills, each with potential impacts to ECLS subsystems. Rapid depressurization involves a sudden unplanned loss of cabin pressure, requiring immediate actions to preserve crew safety and maintain life support functions. Combustion onboard that results in fire, smoke, or the release of hazardous substances, can compromise atmospheric quality. These situations necessitate coordinated responses to extinguish the fire at its source and manage the resulting hazards to ensure crew safety and maintain a habitable environment. Toxic spills involve the release of hazardous substances that can contaminate the cabin atmosphere, requiring containment and atmospheric scrubbing to protect crew health. By addressing these critical events, emergency response ensures system resilience and the preservation of habitability in challenging situations.

A. Rapid Depressurization

1. System Introduction

Every pressurized spacecraft is subject to a certain degree of leakage, an unavoidable phenomenon arising from various design and manufacturing factors. These factors include the precision and integrity of pressure vessel joints, the quality and installation of seals, and material properties over time. Even with advanced engineering practices, achieving a completely airtight system is impractical due to microscopic imperfections in welds, fittings, and interfaces. Additionally, thermal cycles, mechanical stresses, and the harsh conditions of space can exacerbate these small leaks over time. For the ISS, the cabin is maintained at a total pressure between 96.5 kPa (14.0 psia) and 102.7 kPa (14.9 psia), creating a livable environment composed of oxygen, nitrogen, CO2, and trace gases. The free air volume, defined as the atmospheric equalization volume excluding structural elements, has grown from 434 m^3 in 2008 to 899 m^3 by 2011 with the addition of modules to the U.S. and Russian segments. In addition, docked cargo and crew vehicles provide additional free air volume. This increased volume extends the time necessary to compensate for leaks or add oxygen for metabolic needs. For instance, in early 2008, an air leak rate of 0.45 kg/day (1 lbm/day) would have reduced the ISS cabin pressure from 102.7 kPa (14.9 psia) to 96.5 kPa (14.0 psia) in approximately 70 days. By contrast, by March 2011, the same leak rate would have required 146 days to cause the same pressure drop. With the recent addition of the Multipurpose Laboratory Module on the Russian segment, this leak rate would require approximately 157 days for the same pressure drop. However, additional modules introduce more potential leak points. Despite rigorous ground testing, On-Orbit module leakage is 12–15 times higher than measured on the ground, primarily due to additional interfaces and launch vibrations. Stringent testing minimizes leakage risks, but On-Orbit conditions and module connections make exact isolation of leaks challenging. [3]

When there is an unintentional loss of cabin air, there are three levels of depressurization for ISS: rapid depressurization, fast leak, and slow leak. Rapid depressurization is defined as a leak rate equal to or greater than 0.87 millimeters of Mercury per minute (mmHg/min). Fast leak is defined as a leak rate equal to or greater than 0.4 mmHg/min and less than 0.87 mmHg/min. Slow leak is considered to be smaller than 0.4 mmHg/min, The smallest leak rate that can be reliably detected onboard is 2 mmHg/day.

The ISS pressure monitoring systems can detect cabin air loss through multiple methods. For slower leaks, monitoring of trending data allows ground teams to note any leakage. The vehicle's software systems issue an alarm to the crew and ground control when cabin pressure drops below a predefined threshold. In the case of faster leaks, where the depressurization rate (dP/dt) exceeds a specified limit as mentioned above, and cabin pressure falls by a certain amount, the system activates an emergency alarm. Additionally, if the crew or Mission Control Center (MCC) identifies a leak, they can manually trigger the emergency alarm.

During a rapid depressurization event, the most critical information for the crew is the time remaining before cabin pressure drops below a safe threshold, known as Reserve Time (T_{Res}). T_{Res} is the amount of time until the cabin pressure reaches the minimum allowable level ($P_{minimum}$). On the ISS, $P_{minimum}$ is defined as 490 mmHg (9.5 psia), a pressure at which critical equipment stops functioning and the risk of hypoxia increases. T_{Res} calculation is performed by on board computers, however crew are thoroughly trained on calculating the T_{Res} per the formula. A notional reserve time plot can be seen in the Figure 1, in the event a computer interface is not available to them. According to ISS procedures, the crew must stop emergency response activities and move to their safe haven if T_{Res} falls below 10 minutes.

$$T_{Res} = \frac{P_i * \ln(\frac{490\ mmHg}{P_i})}{\frac{dP}{dt}}$$

T_{Res} is in units of minutes where P is in mmHg, $\frac{dP}{dt}$ in mmHg/minute.

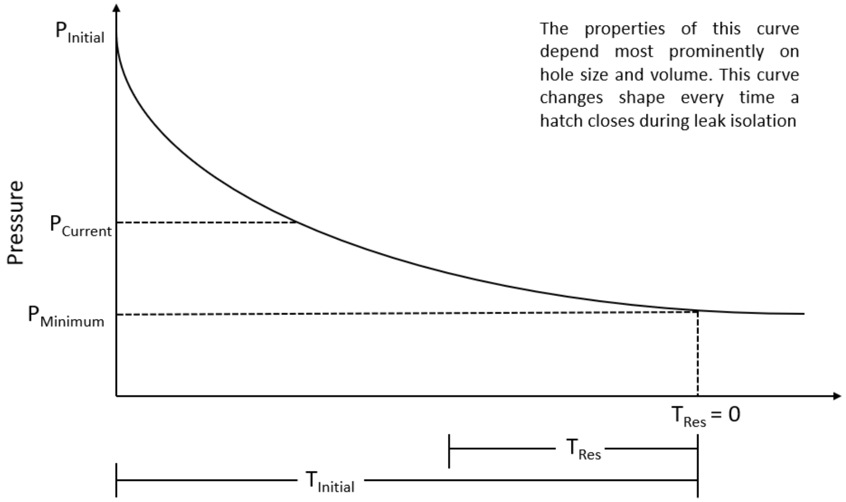

Figure 1. Notional Reserve Time Plot

2. *Hardware*

Throughout most of the rapid depressurization response, the crew's primary tools are a manual pressure gauge (manovacuumeter, MB), a flexible permeable screen which indicates the direction of airflow across a hatch (hatch depress indicator, HDI), and any available watch or timer (which are also used to calculate their Tres). Multiple units of these tools are stored in designated locations onboard the ISS. An MB is used to determine any changes in pressure in modules, while the HDI's are utilized to identify the leak location. HDI configurations exist for the United States

On-Orbit Segment (USOS) and United States Crew Vehicle (USCV) hatch configurations. If symptoms of hypoxia are observed in any crew member, a Portable Breathing Apparatus (PBA) is available, which provides a face mask and approximate 7 minutes (dependent on breathing rate) supply of Oxygen.

3. *ISS/USOS Response*

There are two levels of response during a depressurization event: the ISS vehicle response and the ISS crew response.

Vehicle Response:

Upon alarm activation, the ISS command and control algorithms execute a series of actions aimed at mitigating the leak and assisting the crew in locating and isolating its source. The ISS automatically performs module/vehicle isolation and systems safing. Additionally, computer algorithms are activated to assist the ISS crew and MCC in determining the appropriate crew response. Data derived from these algorithms and instrumentation is transmitted to the Russian laptop and USOS Portable Computer System (PCS). Overboard valves are commanded to close to eliminate them as potential leak sources. All intermodular and intramodular fans are turned off, enabling the crew to use tools for leak detection and possibly hear the sound of the leak. Any automated gas introductions are terminated to allow accurate measurement of the leak rate. Finally, the system powers down or safes equipment susceptible to damage in a lower-pressure environment, ensuring their future usability without requiring additional crew intervention.[4] This data outlines automatic operations triggered by the depressurization event, including closing vacuum valves, activating the T_{Res} calculation mode, deactivating fans, and initiating the air flow sensors' working mode to identify the depressurized element.

Crew Response:

All USCV crew members will relocate to Node 2. After relocation, their first task is to perform the following initial steps:

I. Collect emergency procedure books and MB.
II. Use MB to note initial ISS pressure reading and note time. If the Russian laptop has displayed an ISS reserve time, crewmember will note this time. One crewmember will be responsible for maintaining cognizance of current pressure and calculating reserve time.
III. Silence the emergency depressurization alarm.
IV. Stop manual gas introduction by closing gas introduction valves.
V. Reestablish communication with MCC by performing emergency multi-element communication setup.

Following the relocation, the USCV crew will identify whether the leak is toward their USCV or in the rest of the ISS stack by using an HDI on the Node 2 Forward (Overhead) hatch or by closing the Node 2 Forward (Overhead) hatch while remaining in Node 2. If all escape vehicles are confirmed to be leak-free, and the ISS reserve time is sufficient (greater than 10 minutes) after completing the leak check, the crew will reenter the ISS to continue performing leak checks and isolating affected modules.

During leak isolation, the following principles apply:

I. Crew and Escape Vehicle Access:
    All crewmembers must ensure there is no closed hatch between them and their designated escape vehicle. This precaution prevents crew separation from their escape vehicle.
II. Hatch Behavior in Rapid Depressurization:
    A large pressure differential in rapid depress scenarios can cause a closed hatch to reopen or make a closed hatch difficult to reopen.
III. Critical Reserve Time or Pressure Levels:
    If the ISS reserve time falls to 10 minutes or the internal pressure drops to 491 mmHg, the crew will immediately stop leak isolation efforts and retreat to a known safe location and close the appropriate hatch(es) to isolate the affected area.
IV. Determining Leak Locations:
    By closing (but not latching) a hatch, the leak location can be identified by assessing the force needed to move the hatch. Additionally, the crew will continuously use the MB to monitor pressure decay on their side and evaluate reserve time.

Once the leaking module or segment is located, and sufficient time remains, the crew may reopen hatches to pinpoint the exact leak location, carry out repairs, or deactivate affected systems as necessary.

Bailout Criteria:

The crew should initiate bailout procedures if any of the following conditions are met:

I. Critical Reserve Time:
  a. If the Reserve Time (T_{Res}) drops to 10 minutes, the crew must retreat to a known safe location and close the appropriate hatch(es) to isolate the affected area.

V. Hypoxia Symptoms:
  a. If any crew member exhibits symptoms of hypoxia, they must immediately don a PBA. All crew members will cease current tasks and retreat to a known safe location to ensure safety.

B. Fire

1. System Introduction

A fire condition aboard the ISS is identified when any of the following criteria are met:

I. The crew observes flames, smoke, or detects a burning odor within the station.
II. A single USOS cabin smoke detector triggers a FIRE status flag, provided there are no passive or active Built-in Test (BIT) alarms in progress at the time.
III. Fire conditions are confirmed if an alarm is actuated by the smoke detectors in the Russian Segment.

These criteria ensure a swift and standardized response to potential fire hazards onboard.

In the event of a fire, the "fire triangle" is a widely used model to understand its occurrence. A fire or combustion event requires three key elements: oxygen, fuel, and an ignition source (heat), which together form the fire triangle. Removing any one of these elements extinguishes the fire. Human-rated spacecraft are specifically designed to minimize the presence of all three elements. Oxygen levels are tightly controlled and mixed effectively, materials are carefully selected and tested to ensure low flammability, and power systems are shielded to eliminate potential ignition sources. During a fire emergency, the response strategy targets reducing oxygen and eliminating ignition sources, as fuel cannot be practically removed during the event.

2. Hardware

In the event of a fire aboard the ISS, detected by smoke detectors, various specialized hardware is used to ensure crew safety, suppress the fire, and restore the environment post-incident. PBAs and the Russian [ИПК-1М] masks provide clean air to crew members, protecting them from smoke and harmful combustion products during emergencies. The ISS Portable Fire Extinguishers (PFE), which are available as either CO2 or water mist configuration, are employed to suppress fires while minimizing damage to onboard systems. Emergency masks equipped with fire cartridges further safeguard crew members by filtering out toxic combustion byproducts during firefighting, cleanup, or evacuation.

To locate the fire source and assess air quality, the Compound Specific Analyzer for Combustion Products (CSA-CP) is utilized, while the Post-Fire Cleanup Kit helps address residual soot and debris, restoring the module to a safe condition. Hardline oxygen systems ensure a reliable air supply for extended emergencies, supplementing portable systems if needed. Additionally, the soon-to-be-deployed Anomaly Gas Analyzer (AGA) will enhance the detection of hazardous gases and provide more precise evaluations of air quality during and after fire events. Together, this suite of equipment is integral to the ISS's fire response and crew safety protocols.

3. ISS Response

Vehicle Response:

The fire protection system in the Russian Segment (RS), known as СППЗ, features a centralized, modular fire alarm design integrated with the onboard computer system in the Service Module. Each RS module is equipped with a fire detection system, and its caution and warning (C&W) panels (4ПСС) display fire hazard signals accompanied by audio alarms. When a fire is detected, a "FIRE" signal with a siren sound is triggered on C&W panels in the Service Module and other modules, including the USOS, and the affected module is identified. Additionally, Russian laptops display the "FIRE" signal on the Russian C&W interface, and this signal is relayed to USOS C&W panels, which activate a corresponding siren. USOS PCS displays also indicate the "FIRE" signal, accompanied by messages on the C&W Summary laptop display.

The USOS employs photoelectric smoke detectors operating on the principle of light scattering. These detectors use a monitoring algorithm in the Tier III Multiplexer/Demultiplexer (MDM), which evaluates scatter and obscuration measurements to detect smoke. The algorithm can be enabled or disabled by crew or ground commands. Each smoke detector is powered independently through a Remote Power Controller, while the Internal Systems (INTSYS) and Command & Control (C&C) MDMs coordinate the automatic fire response for the USOS.

Applications of U.S. Smoke Detectors:

- Monitoring the atmosphere in an open cabin.
- Monitoring the atmosphere in payloads or systems racks.

When smoke is detected, the Tier III MDM alerts the higher-tier MDMs, which initiate an automatic vehicle-wide response. This includes shutting down ventilation, closing Intermodule Ventilation (IMV) valves, halting oxygen introduction, and removing power from affected racks in cases of rack-specific smoke detection. Unlike the RS system, U.S. equipment remains deactivated until re-powered by the crew or ground command. The monitoring software minimizes false alarms by requiring three consecutive fire threshold exceedances before announcing a fire condition.

For smoldering fires behind closeout panels, the CSA-CP device can be used to sample air from fire-ports, helping to pinpoint the fire's location.

Crew Response:

The ISS crew commander holds ultimate responsibility for crew and station safety, overseeing all crew activities. However, all crew members are expected to recognize and respond to off-nominal situations, such as indications of fire. If flame, smoke, or a burning odor is detected before the activation of smoke detectors, the crew should manually initiate a fire alarm by pressing the “FIRE” button on a C&W Panel (USOS or RS) or using the C&W toolbar display on a U.S. PCS or Russian laptop. Once the alarm is raised, the crew must report to MCC and follow its instructions. All crew members must then gather in a safe location, ensuring everyone is accounted for.

Fire Response Strategy:

I. Initial Actions:
   - Gather in a safe location away from the fire, confirming all crew members are present.
   - Identify the affected module and acknowledge the alarm.
   - Shut down inter- and intra-module ventilation either via automatic software responses or manual commands.
   - Close all supply valves from Progress or Resupply Air Tanks, if applicable.
   - Reconfigure Service Module (SM) condensate transfer line valves from the [СРВ-К] position to the condensate collector position.

II. Protective Gear:
   - Don protective equipment (ИПК-1М or PBA) if smoke, flame, or contaminants are present, when discharging a PFE, or based on crew discretion.
   - Fire Cartridge Masks can be used in the USOS if visibility allows (crew can see an outstretched hand), the environment is safe (no high heat, and CO2 PFEs have not been discharged). On the RS, only the ИПК-1М should be used for active fires.

III. Specific Crew Roles:
   - Space Flight Participants should return to their Soyuz unless instructed otherwise by the ISS Commander.

IV. Fire Suppression:
   - Identify the fire’s location using laptop/PCS data and/or visual inspection by crew equipped with protective gear.
   - Suppress RS fires using Russian extinguishers and USOS fires using U.S. extinguishers. In near-catastrophic situations, the commander may authorize the use of U.S. extinguishers in the RS. Russian extinguishers must not be used in the USOS due to the risk of electrical shock from its 120-volt DC system.

V. Critical Situations:
   - If all extinguishers are expended or the situation is life-threatening, isolate the affected module by closing hatches (if feasible), transfer to rescue vehicles, prepare for undocking, and contact MCC.

The decision to evacuate the ISS rests with the ISS commander, in consultation with MCC when possible, and is based on the following:

- The fire cannot be extinguished or isolated without cutting off access to escape vehicles.
- The ISS atmosphere is contaminated beyond the capacity of scrubbing systems to restore acceptable levels before exhausting all protective equipment, including PBAs, Fire Cartridge Masks, Russian gas masks (ИПК-1М).

If the fire is successfully extinguished, during post-fire cleanup, if the atmosphere in the affected module is deemed unacceptable, the module will remain isolated for days while scrubbing operations are conducted. Crew members, equipped with personal protective equipment (PPE), will access the module every ~12 hours to perform canister replacements. Post-fire clean up kits and/or ISS atmosphere revitalization systems, such as the Trace Contaminant Control System (TCCS), will be utilized to cleanse the atmosphere.

C. Toxic Spill (Hazardous Release)

1. System Introduction

A toxic release can occur on the ISS due to the breach of containment involving fluids, gases, or solid particles containing chemical materials. Such incidents can originate from ISS systems, payloads, or cargo and transport vehicles and modules docked with the station. These situations pose a significant risk to crew health and require prompt and effective response measures.

The response to toxic releases on the ISS is tailored to the severity of the hazard, which is classified into four toxic levels. These classifications help prioritize actions and ensure appropriate measures are taken based on the specific risks posed by the release.[4]

- Hazardous Level 0 represents a nonhazardous release, posing no immediate risk to the crew or station operations and requiring no special precautions.
- Hazardous Level 1 is the least hazardous type of release. While these incidents may require monitoring and minor interventions, they pose minimal risk to crew safety and typically do not disrupt operations significantly.
- Hazardous Levels 2 and 3 encompass hazardous releases requiring heightened precautions. These incidents may involve contaminants that could harm crew health or compromise station functionality, necessitating protective equipment and coordinated response efforts.
- Hazardous Level 4 involves the most hazardous releases, with materials that present a significant threat to crew safety and station operations. These scenarios demand immediate and comprehensive responses, including isolation of the affected area and use of full emergency protective equipment.

To further guide responses, toxicologists evaluate all materials flown to the ISS and assign a severity level for potential contaminants in the event of a spill or release. These severity levels are categorized into three zones:

- Green Zone: This represents contaminant concentrations with minor health effects and minimal productivity loss compared to normal operations. PPE is generally not required in this zone.
- Yellow Zone: This level indicates contaminant concentrations that may cause symptoms and up to a 20% loss in physical productivity. The use of PPE may be necessary, and medical experts should be consulted to determine where to don or doff PPE during cleanup. Planning for doffing PPE should aim for the lower end of this zone to minimize risks during the cleanup phase.
- Red Zone: This represents contaminant concentrations that pose an immediate health threat and result in significant productivity loss compared to normal operations. The use of full PPE is essential to safeguard crew health in this zone.

By combining toxic level classifications and zone severity designations, the ISS ensures a structured and effective approach to managing hazardous material releases, prioritizing crew safety and operational continuity.

2. Hardware

In the event of a toxic spill aboard the ISS, several specialized pieces of hardware are utilized to ensure crew safety and mitigate the hazard. The PBA and emergency masks equipped with ammonia cartridges are essential for providing immediate respiratory protection. For ammonia spills, an Ammonia filter assembly is set up in the USCV safe haven vehicles, to scrub ammonia from the atmosphere while the Emergency Air Supply ensures access to clean air during the response. On the Russian segment, an RS Ammonia Filter is utilized to ensure safe breathing air to the crew while in safe haven.

Silver shield gloves and sleeves are available for protection, and chemically absorptive mess-up mitts and pillows are available to clean up the spill.

Additional tools include the Ammonia Measurement Kit, which helps monitor ammonia levels, and the Ammonia Response Medical Kit, which is used for treating potential exposure-related medical issues. If needed, the Emergency Eye and Gas Sampling System can also be deployed. Future upgrades to response capabilities will include the AGA, which is slated to deploy soon and will enhance the ability to detect and analyze hazardous gases effectively.

3. ISS Response

Vehicle Response:

The ISS does not have automatic Emergency (Class I) signals to alert the crew to toxic contaminant hazards in the station's atmosphere. The sole exception is a software-detected Interface Heat Exchanger (IFHX) rupture, which results in high-pressure ammonia flowing from the External Thermal Control System (ETCS) into the Internal Thermal Control System (ITCS). This event is characterized by a rapid pressure change and an increase in ITCS fluid levels, triggering a Class I Toxicity Alarm. The response strategy for an IFHX rupture is unique and differs from the protocols for other types of hazardous material releases.

In response to an ATM alarm activation, the USOS automatically initiates IMV isolation and safing of relevant systems. Data from these automatic operations is transmitted to both the Russian laptop computer and the U.S. PCS, ensuring comprehensive monitoring and situational awareness across the station.

Crew Response:

For all toxic material releases other than the specific ammonia case mentioned above, the crew relies on manual annunciation systems. These include pushbuttons on C&W panels located in select U.S. and Russian modules, as well as alert icons on PCS laptops in the USOS. When activated, these systems alert the entire crew to the presence of a toxic agent in the ISS atmosphere.

Manual activation of the ATM alarm is necessary when the toxic substance is unknown and crew members exhibit symptoms of exposure, or when the crew must wear oxygen masks (such as PBA or ИПК-1M) to protect their health. Additionally, the ISS Commander may determine the need to activate the alarm based on the severity of the situation. If a hazardous release is not contained, manual activation of the alarm is strongly recommended to safeguard the crew and maintain operational safety.

Before pressing the Atmosphere (ATM) button to signal a toxic hazard, crew members announce three times: “Toxic Spill, Hazard Level [x], in [location].” This ensures that all crew members are aware of the situation. After the announcement, the crew verifies that everyone has been notified and takes appropriate follow-up actions.

Crew follow up actions are dependent upon the hazard level of the spill and the ability to access the spill area for cleanup. In the event of an ammonia leak or other airborne toxic spill, crew evacuate to safe haven where an ammonia filter is activated to provide breathable atmosphere while crew prepare to return. For liquid spills, it may be possible clean up the spill with PPE and absorbent materials.

III. EMER Lessons Learned and Improvement

A. Rapid Depressurization

The ISS Rapid Depress procedural flow has evolved over the years as new modules and return vehicles have been added. Despite these changes, it has consistently adhered to the core philosophy of first ensuring the return vehicle is in a good condition and then maintaining a clear path to it while checking the integrity of segments and modules. Throughout these checks, the crew remains constantly aware of the remaining total pressure and has clearly defined exit points in case the leak worsens.

For slower leaks, the response is typically less urgent, addressing the issue outside of emergency procedures over the course of days, weeks, or even months. The ISS has experienced 2 “slow leak” events: In 2003 a decrease in pressure noted by on orbit trending was determined to have been caused by a leak in a window pressure equalization hose. In 2019 on orbit trending noted an increase in the ISS atmospheric leakage rate, with a further increase occurring in 2020. The leak was found to be in the SM PrK Transfer Tunnel. ISS teams continue to monitor this leak, isolate the module and assess methods for repair.

Hatch constraints play a critical role in leak investigations. Negative pressure can cause “hatch burping” on certain ISS hatches, and the station's differently sized hatches result in varying delta-pressure constraints for reopening. To ensure safety during leak checks, procedures are designed to limit the force required to reopen a hatch to no more than 50 lbf while searching for the leak.

The mechanism by which a hatch closes also impacts its use during leak checks. For example, some hatches use sliding closures, while others rely on worm gear actuation, which influences their operation. Current ISS procedures include a “Tap Technique” for certain Russian Segment hatches. This method involves holding the hatch in the closed position without fully sealing it for a set period to measure delta pressure. This approach prevents the crew from being sealed in a leaking compartment and ensures they can safely reopen the hatch if needed.

To enhance safety and efficiency, the ISS also employs the HDI as mentioned in the earlier section. This tool accelerates the leak-hunting process and reduces risks to the crew, as it does not require hatch actuation to function.

These advancements reflect the ISS's commitment to safeguarding the crew and maintaining operational integrity during depressurization events.

From a software perspective, the core ISS requirement for emergency response is to close any overboard vent paths within 30 seconds of the emergency annunciation. To meet this requirement, software coding methods must be designed to support rapid and reliable execution. Additionally, the response protocol isolates all potential gas introduction sources, enabling an accurate evaluation of the baseline leak rate through telemetry data.

However, unexpected software interactions can occur and must be addressed to ensure system reliability. For instance, a false Rapid Depress event was triggered on the ISS while the Airlock was isolated at 10.2 psi during EVA preparations. The emergency response software automatically equalized the Airlock with the rest of the ISS to allow crew egress. This sudden airflow movement caused dust to activate smoke detectors, resulting in a false fire alarm. To prevent recurrence, the software was updated to inhibit smoke detectors during depressurization execution.

Another example involved the original response protocol, which powered down the Pressure Control Assemblies to prevent overboard venting. However, this action also disabled the ISS's most accurate pressure sensors, complicating pressure monitoring during the event. Subsequent software updates adjusted the response to perform a power cycle of the Pressure Control Assemblies instead, ensuring continued access to precise pressure readings.

Module isolation and monitoring – once it is determined what area is leaking, it is important to be able to isolate that area to prevent further atmosphere loss and monitor pressure changes in the isolated area. If there is not a pressure measurement device already in the area, a portable unit such as the MB is needed for this monitoring. However, the MB requires a crewmember take a visual reading, it does not transmit data. In this instance the MB pressure gage was placed inside the module and located so the gage could be seen thru the hatch window. An improved method would be to have a gage that would transmit data to on orbit crew and/or ground teams for monitoring and trending.

Leak location - Once the module was determined, further investigation of the actual leak location proved to be difficult. Auditory leak detectors require crew access the area that is leaking so it cannot remain isolated during the inspection. Surrounding equipment can interfere with auditory instrument readings, especially with slow leaks. The ISS crew found that distributing several small lightweight material items which could float on the airflow was very enlightening. The material was drawn to the leak point and was able to get in small areas which were not easily visible. This helped direct crew to look behind equipment and eventually find cracks which were to be repaired.

These examples underscore the importance of iterative software and hardware updates to address unexpected interactions and refine emergency response protocols, ensuring both crew safety and system effectiveness.

B. Fire

The ISS has encountered false fire alarms frequently, primarily due to dust or unexpected interactions. Over the past six years, the automated fire emergency response has been triggered at least 20 times, all of which were later determined to be false alarms. These incidents were often caused by dust particles, erroneous telemetry readings, or improper software configurations. To mitigate these occurrences, smoke detectors are inhibited during activities known to trigger false alarms, such as EVA preparation, weekly housekeeping tasks, or when crew members are working near cabin smoke detectors, potentially dislodging dust. During these activities, the crew remains the primary line of smoke detection. Future designs for microgravity smoke detection should assess the impacts of floating dust and debris on the unit functionality and ways to reduce false alarms without impeding alarm in an actual emergency event.

Operational decisions regarding fire events are influenced by *NASA Spacecraft Maximum Allowable Concentrations (SMACs)* for key combustion product indicators, specifically CO, HCl, and HCN. For a detailed list of SMACs, reference JSC-20584. The ISS employs a masking threshold of 200 ppm CO, 5 ppm HCl, and 5 ppm HCN, with the assumption that crew exposure at these levels will not exceed four hours before actions are taken to reduce combustion products further. While mixing small amounts of "smoke" with the larger ISS atmosphere is occasionally an option, the general protocol is: "Safe/Extinguish, Isolate/Contain, Assess Damage/Contamination Level, Cleanup, and Reintegrate."

Although the ISS has not experienced any fires, there have been several "smoke" events, with the highest localized readings being 30 ppm CO (2009), 4 ppm HCl (2014), and 2 ppm HCN (2006). The RS uses both optical and ionizing smoke detectors with two alarm thresholds: Smoke and Fire. In contrast, the USOS uses optical smoke detectors with a single alarm threshold for Fire.

Post-fire cleanup resources are derived from legacy Shuttle hardware, with limited quantities maintained On-Orbit. While the Post-Fire Cleanup Kit has not been formally deployed for post-fire scenarios, its fan has been repurposed for contingency CO_2 removal or air ventilation.

Stopping oxygen introduction during fire events is a critical software consideration. For powered oxygen generators, this typically involves a rapid shutdown or power-off, which can negatively affect the hardware. While acceptable for real events, the frequency of false alarms should be considered to avoid unnecessary damage. When a module's smoke detector triggers an alarm, intra-module ventilation is automatically terminated. However, for manually announced alarms by the crew, ventilation remains active to help draw smoke toward the detectors, aiding in identifying the source of the issue.

Fire alarms must be routed accurately to ensure effective responses. For instance, a cargo vehicle once caused repeated false alarms, leading to the inhibition of what was thought to be the primary data path for the alarm signal. Despite this, alarms persisted, revealing the existence of a secondary path to the ISS C&C MDM for the same data bit. This highlights the importance of robust testing for all emergency command inputs and outputs to ensure reliability in real scenarios.

These experiences underscore the need for continuous improvement in hardware, software, and procedural measures to maintain safety and operational integrity on the ISS.

C. Toxic Spill (Hazardous Release)

The protocols for addressing ammonia contamination and hazardous material spills on the ISS have significantly evolved over time as NASA's understanding of these scenarios deepened and new hardware became available. Procedures are designed to account for worst-case scenarios, even as improved assessments and hardware upgrades have helped to better quantify risks. For instance, Computational Fluid Dynamics models are used to estimate worst-case contaminant concentrations, and assessments have identified weak points in the ITCS maximum design pressure. Where feasible, these vulnerabilities have been mitigated through targeted hardware upgrades.

Over time, software and telemetry systems have also presented unexpected challenges during response efforts. For example, the ammonia response protocol relies on accumulator sensor readings. On several occasions, biased sensors or telemetry routing issues within the MDM caused false ammonia response activations. In one case, an affected sensor had to be inhibited until it could be replaced. These incidents emphasize the need for robust software testing and updates to address unforeseen interactions and maintain reliability. The software response is particularly crucial for isolating airflow between modules, which is key to preventing the spread of hazardous substances.

Materials flown to the ISS are carefully documented in the Hazardous Materials database, with hazard levels assigned to each substance. Substances rated at Hazard Levels 3 and 4 are strictly regulated. Identifying hazardous compounds early in the payload development process is essential, as it allows teams to communicate potential risks and implement appropriate mitigation measures including hardware safing to avoid potential spills, as well as PPE to be required when the payload is accessed.

Design and fitting of PPE is critical to ensure crew safety in the event of a hazardous spill. Mask fit is particularly critical to prevent exposure to toxic gasses. A full-face mask such as the PBA requires a seal along the forehead, temples, cheeks and chin; however, this seal can easily be interrupted due to eyeglasses, facial hair, or facial features. Use of the PBA in full flow mode creates positive pressure inside the mask, reducing but not eliminating the chances of toxic fumes entering the mask. The Emergency Mask is a full hood and respirator which provides protection to crewmembers with facial hair, eyeglasses, and narrower facial features that may not seal in the PBA. In 2023 engineering teams determined that the neck seal of the Emergency Mask was not adequate for smaller crewmembers and ISS has recently added smaller versions to support a larger diversity of crew. Mask design and fit should be assessed for the possible toxic spill cases and variety of crew.

Careful consideration is also required when selecting materials for cleanup to avoid unintended chemical interactions. For instance, a wet/dry vacuum used to collect spilled material required a detailed assessment to determine how to clean and return it to normal service. In another example, the compound used as a urine pretreat was found to react exothermically with standard dry wipes, necessitating the use of specialized hardware and procedures for safe cleanup. These cases highlight the importance of understanding the properties of hazardous materials and planning cleanup processes accordingly.

IV. Conclusion

Emergency response is a fundamental aspect of spaceflight safety, ensuring crew protection in the event of critical incidents. The ISS has provided served as a critical testbed for scientific research and technological advancements over the past 25 years, providing invaluable experience in handling rapid depressurization, fire hazards, and toxic spills.

Effective emergency response capabilities are indispensable for ensuring the safety and operational integrity of human spaceflight, particularly within the evolving domain of commercial space exploration. Drawing from over two decades of operational experience aboard the ISS, this paper highlights critical insights into managing rapid depressurization, fire hazards, and toxic spills—each necessitating tailored, robust response strategies. ISS experiences underscore the importance of iterative improvements in hardware, software, and procedural protocols to handle emergency scenarios reliably.

The lessons learned from the ISS demonstrate that emergency response is not a static discipline, but one that requires continuous adaptation to emerging risks, evolving system configurations, and the increasing diversity of crew profiles. Detailed analysis of past ISS events reveals the value of proactive design features, such as flexible hatch operations, integrated alarm systems, and portable monitoring tools, as well as reactive strategies including reserve time management, automated isolation procedures, and comprehensive PPE planning. These measures have proven essential in maintaining habitability and mitigating potentially catastrophic outcomes.

Looking forward, commercial space stations must embed these principles into their foundational design and operational planning. Emphasis should be placed on cross-disciplinary coordination, real-time telemetry interpretation, and the integration of artificial intelligence to support anomaly detection and decision-making. Furthermore, emergency response procedures should account for broader crew demographics, including physical diversity and varying operational expertise, ensuring inclusive safety standards.

By integrating these valuable lessons learned, future commercial space stations can significantly enhance their emergency preparedness. This will not only safeguard crew safety and mission continuity, but also establish a framework of resilience and responsiveness that is critical for the long-term sustainability of human presence in low Earth orbit and beyond. The continued application and refinement of ISS-based emergency strategies serve as a vital foundation for this new chapter in human spaceflight.

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