

A History of Space Toxicology Mishaps: Lessons Learned and Risk Management

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ABSTRACT

After several decades of human spaceflight, the community of space-faring nations has accumulated a diverse and sometimes harrowing history of toxicological events that have plagued human space endeavors almost from the very beginning. Some lessons have been learned in ground-based test beds and others were discovered the hard way - when human lives were at stake in space. From such lessons one can build a risk-management framework for toxicological events to minimize the probability of a harmful exposure, while recognizing that we cannot predict all possible events. Space toxicologists have learned that relatively harmless compounds can be converted by air revitalization systems into compounds that cause serious harm to the crew. Our toxic risk management strategy now includes an assessment of the fate of any compound that might be released into the atmosphere, and in addition, the environmental engineers determine if a compound could poison the air purification filter beds and thereby reduce their ability to protect crew health. We, of course, are aware that many propellants are highly toxic compounds, yet we have not always been able to thoroughly isolate the crew from exposure to these propellants. Leakage of fluids from systems has resulted in hazardous conditions at times, and the behavior of such compounds inside a spacecraft has taught us how to manage potentially harmful escapes should they occur. Potential combustion events are an ever-present threat to the wellbeing of the crew. Such events have been sufficiently common that we have learned that one cannot judge the health threat of a given fire by the magnitude of the event. Management of such risks demands monitoring of combustion products. In the category of unpredictable toxic events, if one assumes

that fires are predictable, we can place experience with toxic microbial metabolites, upsets during repair operations, and discharges from filters that have accumulated a substantial load of pollutants in their absorption beds. Management of such events requires a broad-spectrum, real-time analytical capability to discern the identity and concentrations of pollutants if they enter the atmosphere. Mistakes are an integral part of any human activity, and the space-faring community must learn as much as possible from mistakes that result in toxic exposures to crews and from mistakes that were near misses.

INTRODUCTION

Respirable air within a spacecraft bearing humans must be of acceptable quality if the crew is to perform up to their potential and remain healthy during and after the mission. The list of potential sources that could immediately compromise air quality or slowly contaminate the air over weeks or months is disturbingly long. Immediate threats to air quality include fires, large systems leaks, leakage from payload experiments, thermal regeneration of filters, rupture of batteries, and entry of toxic propellants. Sources that can gradually pollute the air include human metabolism, small leaks from systems or payloads, offgassing from materials, slow failure of the air revitalization system, and sustained use of utility compounds over a long periods of time.

Resources do not allow us to place rigid controls on each of these sources and monitor for the possible failures of containments or adverse events. By systematic examination of past toxicological events one

can begin to build a risk assessment framework for prioritizing resource utilization to address each potential source. Risk assessment entails at least a semi-quantitative combination of the probability that a given adverse event will occur and the harm that such an event could cause. Risk paradigms in common use ask us to place an “X” in some 2-dimensional grid that indicates probability and adverseness. In reality, this “X-marks-the-spot” view of risk obscures the reality that probability and adverseness are usually inversely related, so risk is best expressed along some line that profiles the two parameters. Data to construct such lines is sparse at best; however, in this paper I will demonstrate how one such curve can be built and then used to more-fully characterize toxicological risk.

One constraint to the analysis I will present is that I will limit my analysis to toxicological risk due to atmospheric pollution. Obviously, a large fire such as the one that occurred in the solid fuel oxygen generator aboard Mir in 1997 produces more important hazards to the crew than exposure to toxic compounds. Such a large fire could have seriously burned a crewmember or breached the integrity of the vehicle hull, causing instantaneous decompression of the cabin [1]. Similarly, leakage of a compound from a spacecraft system may be serious because of the loss of function of the system rather than the toxicity of any fluid released into the air. For example, large leaks of Freon 218 aboard the International Space Station from the Service Module air conditioners release the compound into the air in toxicologically harmless quantities; however, the loss of air conditioning capability leads to significant crew discomfort. I will focus only on the potential toxicity of the compound(s) at risk for release into the air and avoid any consideration of the other consequences.

the events can be broken into three categories: insignificant, critical, and catastrophic. Insignificant events are those that cause no more than transient, barely perceptible effects without actions required by the crew. Critical events are those that impair the crew’s ability to perform their normal duties for hours to a few days. Such events will require some kind of response to begin to recover to safe conditions. Catastrophic events are those that can severely restrict the crew’s ability to perform tasks, require procedures to recover safe conditions, and pose a substantial likelihood of permanent injury to crewmembers.

A second approach considers the intensity of the effect involved and the duration of the effect. Obviously, a moderate adverse effect that lasts only half an hour is less severe than one that lasts 2 days. One can sort the toxic events according to intensity and duration of the effect as shown in Tab. 1. Each of the events tabulated there is discussed in detail in subsequent sections. The table also gives the estimated number of occurrences of each type of toxic event in vehicles that involve activity by U.S. astronauts. One must expect that there is an underreporting of brief events that cause mild effects and any event without toxicological consequences.

EVENTS WITHOUT TOXICOLOGICAL CONSEQUENCES - In Table 1 two events are listed as having had no effect. This means that the event is toxicologically transparent to the crew. They sense no odour, nor do they feel any sort of toxic effect.

The first of these refers to leaks of the heat-exchange fluid Freon 218 from either of the two Service Module air conditioners aboard the ISS. The compound, perfluoropropane, is nearly devoid of toxicity and has no odour. Except for a brief period of time in 2008 when the

Table 1. Toxicological Events Classified by Intensity and Duration			
Intensity/duration	<1 d	1-10 d	>10 d
none			Freon 218 leaks (ISS) 1-Formaldehyde offgas (ISS)
Mild/Odor	3-Lunar dust (Apollo) 2-LiOH dust (Shuttle) 1-SFOG fire (Mir) 1-Excess CO ₂ (Shuttle) 1-Poor local ventilation (ISS) 5-Minor pyrolysis (Shuttle) 2-Elektron pyrolysis (ISS)	2-Excess CO ₂ (ISS) 1-Microbial odors (Shuttle) 1-Velcro offgassing (ISS) 1-CO ₂ near 2% (Apollo)	
Moderate	1-EG floating liquid (Mir) 1-CO from BMP (Mir) 1-Crystals in eyes (Shuttle)	1-STs-40 ORF (Shuttle) 1-Metox Regeneration (ISS)	1-EG vapor from leaks (Mir)
Severe	1-Propellant (N ₂ O ₄) in cabin (Apollo)		

RISK ASSESSMENT PARADIGM

Grouping toxic events according to their severity is not a straight-forward undertaking. As the simplest approach,

ESA experimental analyzer ANITA (Analytical Interferometer for Ambient Air) was present [2], the only on-board means of detecting a leak is loss of pressure in the system. Since Freon 218 is difficult to scrub from

the air, the compound can remain in the air for months. The compound is also released when the air conditioning system is recharged after a leak. The frequency of discrete events seems irrelevant for our purposes since some level of this compound has been detected in all grab samples returned from the ISS.

The second event that was toxicologically transparent to the crew was the accumulation of formaldehyde in ISS, presumably from materials offgassing, although some may have come from curing of bonding compounds. The primary toxic effect of formaldehyde is irritation of mucosal surfaces such as the eyes and respiratory tract. Adsorption badges were being used in pairs in the Service Module and U.S. Laboratory Module to take 24-hour samples, which were analyzed later in ground-based laboratories. At the time the standard for exposure was 0.05 mg/m³, and levels in the Laboratory Module consistently exceeded those from the Service Module. For a period of several months the difference in the levels was unusually large and levels in the Laboratory module exceeded the standard. The crew did not report any mucosal irritation. During this time it was discovered that “dust bunnies” had formed in some of the intermodular ventilation ducts, and when this material was removed, the formaldehyde levels in the Laboratory Module dropped below the exposure standard.

We have learned the hard way that offgassing of formaldehyde can affect crew health. During the ground-based Lunar Mars Life Support Test (LMLST) a few years ago formaldehyde levels were steadily increasing during the first few weeks to 0.25 mg/m³, which was well above the standard at the time of 0.05 mg/m³, and soon one of the four crewmembers reported mucosal irritation. Many materials were removed from the chamber, the formaldehyde levels dropped, and the symptoms abated [3].

EVENTS WITH MINOR TOXICOLOGICAL CONSEQUENCES - Numerous mild toxicological events lasting less than one day have occurred during spaceflight. A mild event is one noticed by the crew to cause effects (e.g. headache or mild mucosal irritation) or one that generated sufficient odours to warrant respiratory protection or the acquisition of an air sample. The diverse nature of these events illustrates the wide range of sources that can cause a toxic event.

Moon dust, which had entered the Apollo crew's living area, was generally manageable until the Lunar Module launched from the moon's surface and reached micro-gravity conditions. The dust floated in the cabin and in some cases caused eye irritation and once caused respiratory symptoms. When the dust became annoying, the crew simply put their helmet back on to keep the material from access to eyes and noses. Exposures were not prolonged; however, moon dust has properties quite different from earth-based mineral dust, and the

potential for adverse effects caused by prolonged exposures is under investigation.

In the Shuttle, LiOH canisters are used to absorb carbon dioxide from the cabin. Periodically the crew reports that they know when a canister has been changed because they sense a very mild respiratory effect, which is presumably from the LiOH dust discharged from the fresh filters. A more serious version of this scenario can occur during filter change-out if the canisters have LiOH dust on the outside and this reaches the eyes. At their option, the crew can don eye protection to manage this risk. Furthermore, it seems to be only the old LiOH canisters that have LiOH dust on the outside surfaces.

Although the Solid Fuel Oxygen Generator (SFOG) fire that occurred aboard Mir in 1997 threatened the integrity of the vehicle, toxicologically it was no more than a minor event. The fire started after an “oxygen candle” was improperly initiated. The crew immediately donned respiratory protection because of the unknown level of pollution. The cabin seemed to fill with smoke; however, this was most likely water mist from the use of an aqueous-based fire extinguisher in an attempt to put out the hot, oxygen-rich fire. An excellent set of air samples was acquired by the medical officer during the hours following this event. These showed that benzene was above its 7-day SMAC for a few hours, but by 32 hours after the fire, the benzene levels had returned to normal. One grab sample of air shortly after the fire showed that carbon monoxide levels were about 20 ppm, which is not a harmful concentration. The lack of carbon monoxide from this fire was due to the oxygen produced by the ignited oxygen candle, which converted any carbon monoxide to carbon dioxide as the former was produced.

Carbon dioxide itself has periodically been a problem aboard ISS. This compound is the major product of human metabolism and must be scrubbed from the atmosphere to protect crew health. Rarely the whole-module carbon dioxide level will reach sufficiently high levels that sensitive crewmembers report mild headache or vague symptoms that can be associated with CO₂ exposures. This can go on for more than a day and seems to occur only when whole-module levels exceed 0.7 %. Since CO₂ is human generated, a risk exists that local concentrations can form that are much higher than the average within the module. In the Shuttle, crews experienced headaches after sleeping in areas with poor ventilation due to obstructions in the general air flow. Similarly, an early ISS crew reported symptoms when working behind panels in the functional cargo block with panels removed. When the panels were removed the bulk air flow was disrupted, and because there is no convection in micro gravity, the crew essentially rebreathed the air they just exhaled. Forced ventilation is critical in space vehicles [4].