Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

Topical: Spacecraft Materials Fire Safety

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Introduction

Fire safety in spacecraft, and in future Lunar and Martian habitats, is of critical importance to the mission objectives of NASA. A fire in a spacecraft has had, and will continue to have, dire consequences to crew safety if the ignition hazards and fire growth potential are not carefully controlled through spacecraft and habitat material choices and design from inception. The physics of ignition, flammability, and fire in microgravity, and especially partial gravity (between 0g and 1g, such as on the Moon or Mars), are difficult to study in Earth gravity and therefore present unknown risks. Of new concern, proposed exploration objectives push spacecraft and habitat atmospheres towards higher oxygen concentrations and reduced pressures for human physiological and habitat structural reasons, increasing material flammability and burning rate. The planned longer mission durations to the Moon and Mars must emphasize fire safety because rescue, resupply, repair, or quick return are difficult if not impossible.

NASA's primary method of addressing this risk is through materials testing and controls, specifically, limiting the amount of fuel loading in the spacecraft habitat and stowage of flammable commodities not currently being utilized. From a flammability perspective, materials are flight-qualified by passing the NASA-STD-6001B Test#1, which is an ignition and upward flame spread test in normal Earth gravity at the worst end-use ambient oxygen concentration and pressure. Historically, this was thought to be a conservative estimate of the material flammability and fire spread potential in microgravity due to the fast upward accelerating spread of the flame in Earth's gravitational field as a result of fluid buoyancy. However, over the last decade, materials flammability testing in actual low gravity and partial gravity conditions has shown that this is sometimes not the case, at least for materials preferred by fire researchers, which notably are often different than the actual materials used in spacecraft[1] [1-12]. To add to the risk, aside from the normal flight-qualified materials, flammable (sometimes very flammable) materials can be granted waivers from the normal control process for use out of necessity or crew comfort (i.e., clothing, cotton towels, Delrin camera mounts, hair length, paper notebooks, etc.).

It is a testament to the current protocols and careful oversight that the International Space Station (ISS) has been occupied continuously for over two decades without a major fire incident. A careful balance is struck between safety and undue restrictions on the flight hardware design and crew operations. Nevertheless, the amount of waivered material is apparent in photos taken onboard ISS. Figure 1 shows the US laboratory in 2014 (photo iss040e006890); open notebooks and procedure sheets, laptop computers, a Ziploc bag, bungee cords, clothing, and possibly other flammable items etc. are visible.

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[1] It is a regrettable fact that fire and flammability researchers often use pure materials such as acrylic (polymethyl methacrylate, or PMMA) for scientific or housekeeping reasons, such as being able to compare results to numerical models or to maintain clean burning conditions, which do not fully represent actual composites or other flammable material used on spacecraft. Another discrepancy between research and actual use is that for drop facility tests very thin samples must be used to get ignition and flame spread in the time available, while such materials are normally thicker in actual use, and material thickness has an important effect on ignition, flammability, and flame spread rate.

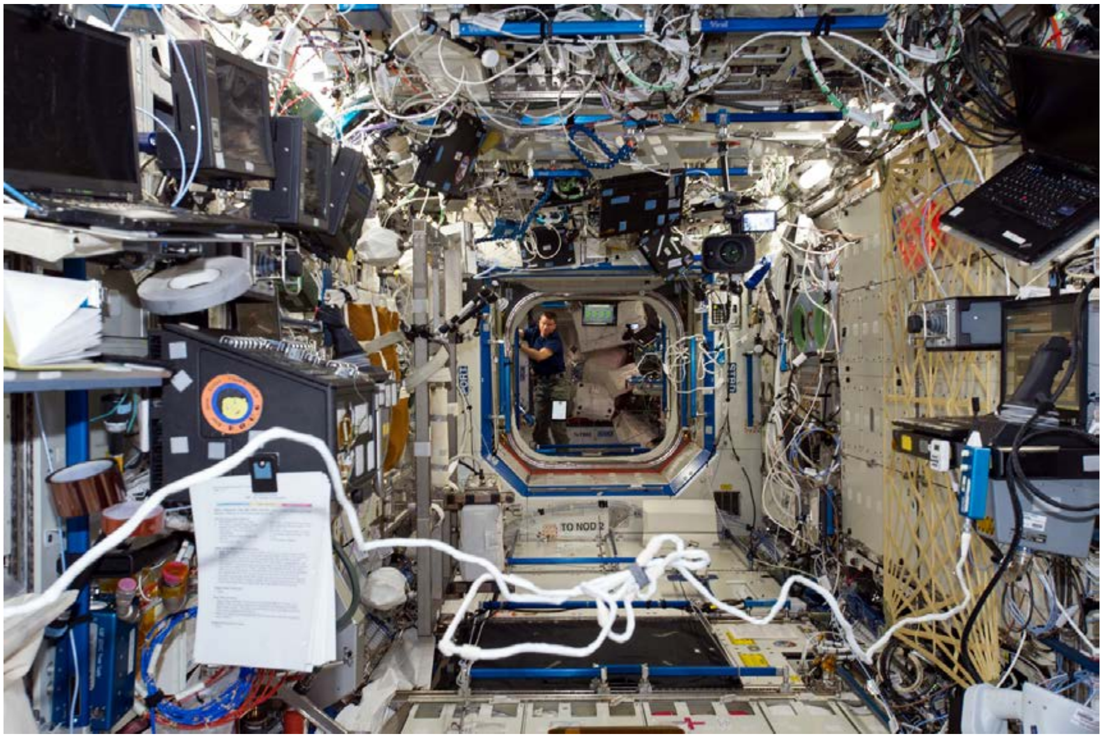

Figure 1 Photo iss040e006890 6/3/2014 by Alex Gerst, with Reid Wiseman in the background.

<u>Overview of Research on Solid Fuel Accomplished Since the Previous Decadal Survey:</u>

Detailed study of solid fuel combustion using mostly “model” materials in low gravity is relatively new. The majority of the work has been carried out over the last decade in accordance with the previous decadal survey recommendations. As a solid fuel retrofit of the Smoke Point in Co-flow Experiment (SPICE) wind tunnel for the Burning and Suppression of Solids (BASS) and BASS-II reflight [1], BASS-M (commercial partner experiment), and BASS-Confined Combustion [13,14], hundreds of solid fuel test points were conducted in the Microgravity Science Glovebox (MSG) aboard ISS in actual long-duration microgravity conditions. Polymethylmethacrylate (PMMA) and SIBAL fuel (an idealized cotton/fiberglass blend to prevent sample curling during burning, facilitate experimental observation, and simplify computer modeling) were the primary fuels burned. The highly productive facility has produced 70 conference and journal articles on microgravity solid fuel combustion to date. In addition, some real-world materials: Nomex, Ultem, Mylar, and proprietary Milliken fabrics still in development were studied for their fire safety properties in microgravity. The BASS series of experiments were limited to 1 atmosphere, and oxygen concentrations below 22% due to MSG constraints. While appropriate for ISS operations, these are not the conditions that are proposed for future exploration campaigns, which might include oxygen concentrations up to 34%.

Figure 2 depicts a flammability boundary as a function of oxygen mole fraction and ambient flow speed. Most materials in normal gravity blow off (like blowing out a candle) rather than quench due to heat losses. The minimum in the flammability boundary is where the flow speed is expected to be near Lunar gravity buoyant flow conditions. As shown in Table1, the differences in the 1g and 0g or partial g Upward Limiting Oxygen Concentration (ULOI) and Minimum Oxygen Concentration (MOC) are largest for the Lunar g level, indicating poor safety margins.

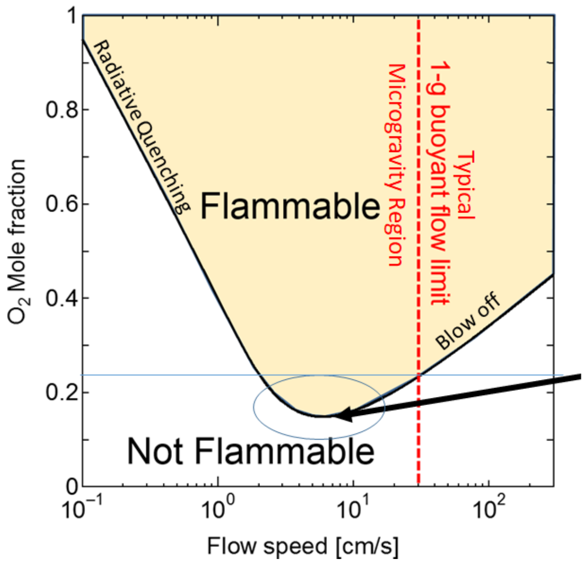

Table I: Limiting Oxygen Molar Concentrations and Oxygen Margin of Safety for Different Gravity Levels

Fuel	**Mylar® G** 10.2 psia	**Ultem®** 1000 10.2 psia	**Nomex®** HT90-40 14.7 psia
1g ULOI	21.2	23.5	23.5
1g MOC	20.0	23.0	22.1
Martian ULOI*	18.0	22.0	19.9
Martian MOC*	17.0	21.1	19.0
Lunar ULOI*	15.6	21.0	21.0
Lunar MOC*	14.1	19.9	19.9
0g* ULOI* (30 cm/s)	17.0	24.0	23.0
0g* MOC* (30 cm/s)	16.0	23.0	22.0
Martian ΔO_2 %	**-3.1**	**-1.7**	**-3.35**
Lunar ΔO_2 %	**-5.75**	**-2.8**	**-2.35**
0g ΔO_2 %	**-4.1**	**0.25**	**-0.3**

Figure 2 Flammability map showing partial and microgravity regions being the most flammable.

Larger scale fire research in spacecraft began in 2016 with the advent of the Saffire experiments [15]. Saffire launched with a Cygnus resupply vehicle and remained dormant until the Cygnus undocked and departed the ISS. The Saffire tests used the air in the vehicle to burn the fuel samples, and the data were relayed to Earth prior to the vehicle deorbit and destructive reentry into the Earth's atmosphere. To date, five Saffire experiments have been performed with one more waiting for launch, some with multiple tests and in most cases increasing sample sizes by one to two orders of magnitude over any previous tests (some samples were close to a meter long). The tests showed that fires can continue to burn for extended periods of time after the flow is turned off, due to the thermal mass of thick molten fuel. The fuel can generate local flows due to fuel vapor bubble ruptures at the surface that entrain ambient air flow and allow the flame to survive in the otherwise quiescent environment. Charring materials can smolder for extended periods of time in a quiescent environment, and the smoldering spots can re-ignite the fuel when the air flow is turned on. Flames can ignite adjacent fuel samples, and flames can extinguish other flames that are downstream by starving them of oxygen [16, 17]. These results indicate that the ISS fire-safety first response to turn off the ventilation is not enough to guarantee a fire will be extinguished. Additional reliable mitigation and more research are needed.

A centrifuge for NASA's Zero Gravity Research Facility (ZGRF) capable of producing variable amounts of partial gravity was recently revamped for solid fuel experiments. This facility has shown that the limits of flammability clearly depend on gravitational level, and that the most flammable upward flame spread conditions for certain fuels are near Lunar gravity levels. As humans return to the Moon with high oxygen, low pressure atmospheres within the habitats and vehicles, fire safety becomes critical. Finding materials that are intrinsically safe at these exploration conditions is proving to be very challenging, and one area that needs further research. The centrifuge, while useful, does suffer from Coriolis forces and is limited to very mall samples. A proposed upgrade to the ZGRF to extend the microgravity time and to allow for partial gravity experiments would be a welcome addition to NASA's facilities.

In coming work, the Solid Fuel Ignition and Extinction (SoFIE) insert for the Combustion Integrated Rack (CIR) aboard the ISS is scheduled to launch in 2022 to support five separate peer-reviewed NASA NRA-selected solid fuel combustion experiments (GEL, MIST, SMURF, RTDFS, NCA). These experiments are focused on understanding the burning behavior and flammability limits of idealized PMMA fuel in various geometries, and in one case under an imposed heat flux. This fuel was chosen for its idealized burning which can support multiple test points per sample to maximize results in the difficult-to-open CIR chamber, and to permit comparisons to detailed numerical models. The CIR/SoFIE facility is capable of studying solid fuel combustion at a wider range of pressures and oxygen concentrations compared to MSG, extending to the expected exploration atmospheres at 34% oxygen and reduced pressures. Note that this facility cannot reach Extra Vehicular Activity (EVA) oxygen concentrations of 100% due to hardware limitations.

Outline of Recommended Research Areas:

It is imperative to the safety of the spacecraft crew and mission assurance that NASA expands research on fundamental fire research and flammability of real-world utilized materials, including more realistic configurations which promote flammability such as a fiber mesh, fuel samples with exposed edges and corners, discrete fuel configurations, and parallel samples. All research on terrestrial fires includes burning real materials at actual scale, while NASA's samples have necessarily been limited almost exclusively to flames on small-scale, model materials (Saffire did use some larger-scale samples, but they were still idealized fuels). More ground-based and flight tests are needed with real flight materials to determine the level of conservatism of the NASA-STD-6001B Test#1. Large scale fire research in spacecraft should continue to utilize cargo vehicles, and new research efforts should explore realistic fire scenarios of battery fires or other externally energized flames which drive pyrolysis via radiation and heat.

While material flammability in microgravity is still in its childhood, even less is understood about the flammability dangers in partial gravity (especially Lunar and Martian). Previous testing has shown that Lunar gravity may present a maximum flammable condition by buoyantly pumping a just the right amount of oxidizer into the flame stabilization zone (critical for continued burning) while not exceeding the entrainment velocity which causes flame blow-off (See Figure 2). Most partial gravity work has been conducted in the Centrifuge drop rig in

NASA's Zero Gravity Research Facility [18], which is very limited in size, but a few test campaigns have been performed in parabolic aircraft [19, 20]. Additional work needs to be done with large enough sample sizes to reach steady flame sizes in Lunar g levels. Fuel configurations should be studied that have recirculation zones in the wake region which allow the flame to survive beyond the normal blow-off limit as they anchor in the recirculation wake. Realistic materials proposed for use on the Moon should be evaluated if they are either waivered or controlled but borderline passing 6001B Test 1, as they might become flammable in the new partial gravity conditions. These larger complex tests will require a facility such as a centrifuge in space (orbital or sub-orbital), a facility actually on the Lunar surface (lander or habitat), parabolic aircraft flying partial gravity parabolas, and/or an upgrade to the ZGRF to allow for partial gravity drops. Finally, the new exploration atmospheres of up to 34% oxygen will likely require the retest of many materials even under the current protocols, and potential new tests such as the Narrow Channel Apparatus (NCA) which have a much higher throughput, and better represent microgravity conditions, should continue to be developed [21].

In summary, we have identified the following needs for the coming decade:

- Testing of material flammability in partial gravity to support Lunar/Martian habitat fire safety. Potential test facilities/platforms include the ZGRF centrifuge, the ZGRF upgrade, parabolic flight, orbital or sub-orbital centrifuge, Lunar lander or habitat glovebox.
- Testing of more real-world materials (waivered and controlled borderline materials) in reduced gravity, exploration atmospheres (i.e., higher oxygen and lower pressure).
- Continued access to long-duration, microgravity for realistically thick materials, including tests of the effect of flow such as with the planned Microgravity Wind Tunnel.
- Need for new materials and retardant additives and coatings with reduced flammability in high oxygen microgravity environments. (e.g., safe clothing for 35% oxygen).
- Need more testing of configurations which promote or inhibit flammability in microgravity, externally driven radiation, radiation feedback between surfaces, etc.
- Although batteries are rigorously screened, they represent the potential for high energy release. Battery fires should be studied to determine how the reduced natural convective environment might reduce battery life and cause overheating failures.
- A new materials flammability standard which better represents low gravity conditions.
- Continued development of higher throughput material screening tests such as the NCA so that materials can be tested faster under the new exploration atmospheres in flow conditions that better represent those on spacecraft.
- Larger flames and fires need to be studied to extrapolate to scales that pose a hazard (ideally, those actual scales would be tested).
- Establish best-practices guidebook for material selection and utilization in low-gravity and partial-gravity.
- Analytical and numerical models involving real materials, actual fires, and partial gravity effects need to be improved.

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