Research Questions and Challenges for Improved Spacecraft Fire Detection

A topical white paper submitted to the National Academies of Sciences, Engineering and Medicine (NASEM) for the Biological and Physical Sciences Decadal Survey, 2022-2032

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ABSTRACT: This paper describes challenges and recommendations for research to improve spacecraft fire detection. Because crew safety is critical to every spaceflight mission, effective fire detectors must detect a wide variety of fires to ensure the success of future space exploration. Fire emissions are affected by fuel type, heating conditions, gravity and exploration atmosphere. Advances in sensing technology provide a promising basis for future detectors, which must selectively detect a broad variety of fires. Addressing these areas will secure the success of future lunar and deep space missions.

INTRODUCTION

The potential for spacecraft fires poses a substantial threat to the future of long-duration crewed missions. "Fire" refers specifically to the heat and radiation produced from the reaction of a flammable material with oxygen. However, in practice, fire detection must also encompass the period of fuel overheating prior to flame development since early fire detection is preferred. Compared to terrestrial building fires, spacecraft fires are especially dangerous due to limited escape options and extinguishment resources. Furthermore, if a fire is survivable, toxic particles and gases from the event pose a serious risk to crew health. Detectable properties of fire include heat, radiation, and smoke. "Smoke" can include gases (e.g., CO, CO_2, water vapor, and volatile organics) and particles formed either from overheating the fuel ("oxidative pyrolysis") or from a flame (e.g., soot and ash). Although heat and radiation detectors are useful for select terrestrial applications,[1] smoke detection is particularly advantageous on Earth because buoyant flow drives hot combustion products upward, allowing convenient placement of detectors on ceilings where smoke concentrates. In microgravity, this buoyant flow does not occur, and this advantage therefore does not exist. Consequently, on the International Space Station (ISS), smoke detectors are placed in the cabin air return vents in front of the filters; this placement has other implications for fire detection that will be discussed later. Due to a lack of data characterizing microgravity fires, however, spacecraft fire detection strategies have necessarily relied on technological advances developed for terrestrial fire detection. For example, the ionization detector on the Space Shuttle represented the most advanced detection technology available in the 1970s, as ionization detectors were becoming broadly available for home use. Similarly, the ISS forward light scattering detector utilized improvements in photodiode technology developed in the 1990s.[2]

Recent research has demonstrated that current fire detection strategies are inadequate for ensuring crew safety on long duration missions. During the Smoke Aerosol Measurement Experiment (SAME), which was the first study to examine oxidative pyrolysis particles in microgravity, the ISS detector failed to alarm for Kapton smoke in half of the tests and for Teflon smoke in two-thirds of the tests, a troubling result considering that Kapton and Teflon are abundant in spacecraft electrical systems, where a spacecraft fire is likely to begin.[3–5] Furthermore, Urban et al. (2016) demonstrated that particle filtration rates provided by the Environmental Control and Life Support System (ECLSS) are rapid enough to outpace smoke accumulation in the event of a small or early-stage fire, suggesting that detection may fail or be delayed if an event does not produce smoke particle concentrations sufficient to bring the cabin to the detector's alarm threshold.[6] Finally, because the ISS detector does not select for smoke particles, the device is subject to nuisance alarms from suspended dust, which can desensitize spacecraft crew to real alarms. In fact, when ISS crew members vacuum the cabin, they typically disable the smoke detectors to prevent suspended dust from causing alarms. These observations suggest that a system relying on detection of a single fire property, like the forward light scattering detector on the ISS, is unlikely to achieve successful early fire detection under all relevant scenarios.

The ability to ensure spacecraft crew safety is crucial to the success of NASA's goals of lunar, Martian, and deep-space exploration. Therefore, future experiments must address the shortcomings of traditional fire detection methods and establish optimal methods of detection for future spacecraft. Additionally, as missions move deeper into space and utilize different exploration atmospheres, new risks emerge that must be evaluated. In particular, material flammability limits are not expected to meet current requirements under elevated O_2 (34%) and reduced pressure conditions (8.2 psi) planned for future lunar habitats; these conditions are also expected to effect fire emissions. Research topics to be investigated include the identification of realistic fire scenarios, characterization of gravity and exploration impacts on fire signatures, and the development of novel detectors to selectively detect a greater range of spacecraft fires.

RESEARCH TOPICS AND CHALLENGES

A. Identification of realistic fire scenarios and characterization of fire signatures from unstudied and understudied fuels. Because a spacecraft fire detection system must detect smoke from a variety of possible fire scenarios, fuels of interest must be identified and thoroughly examined. Experiments should examine both small scale (similar to SAME) and large-scale fires (similar to the Saffire experiments[7–9]) to evaluate detection in early stage and fully developed spacecraft fire scenarios, respectively. A fire source of major concern is the lithium ion battery (LIB), which is used in various on-orbit electronics including laptops, power tools, and space suits. In particular, laptop LIB fires constitute one of the most likely and most dangerous spacecraft fire scenarios threatening crew safety in long-duration missions.[10] As crewed missions move to the moon, Mars, and deeper into space, the space flight and space research community anticipates increased reliance on LIBs to power electrical components for longer periods of time.[11] While several studies have examined gaseous products of LIB fires,[12–15] and others have examined particles from large-scale LIB fires (e.g., car batteries),[16,17] we are aware of only one study that characterized the properties of smoke particles from laptop LIB fires.[18] Another fuel of immediate interest is the to-be-determined fabric that will compose crew clothing in future lunar missions. Because planned exploration atmosphere conditions are expected to increase material flammability potential, clothing worn by crew members on the ISS (e.g., cotton jersey t-shirts) may not be suitable for future lunar missions. Currently, researchers are working to identify a fire-resistant fabric for the crew to wear within the anticipated lunar habitat. This fabric must be investigated as a potential fuel to identify fire signatures, which will inform selection of an optimal fire detector.

Variations in particle properties due to differences in fuel heating methods further complicate identification of realistic fire scenarios. Ground experiments described in Meyer (2015) revealed that the same fuel heated to different maximum temperatures can yield particles with drastically different sizes and morphologies.[19] In addition, measurements performed in parabolic flight have shown that the longer fuel residence time experienced in reduced gravity drastically impact the formation and growth of particles,[20] fundamentally changing the propensity of a flame to generate smoke from a given fuel.[21] Future spacecraft smoke detection studies must attempt to recreate a variety of realistic overheating scenarios, including different maximum heating temperatures and different temperature ramp methods.

Since recent spacecraft fire detection systems have relied on sensing smoke particles, most spacecraft detection research to date has focused on characterization of smoke sizes and morphologies. However, due to challenges with particle detection, there is a need for expanded smoke measurements including but not limited to gas composition and concentrations, particle charge distributions, and particle chemical composition. For example, research has demonstrated that increased flammable gases released during microgravity fire events can contribute to flame propagation (e.g., vapor jetting of monomers during polymethyl methacrylate combustion[22]), and thus, monomers generated from polymer degradation during a fire constitute a potential detection target. Another example of potential gas-phase detection targets are electrolyte vapors vented in the early stages of LIB failure.

Characterizing fire signatures from spacecraft-relevant fuels will not only improve crew safety for future space exploration but will also benefit researchers and consumers on Earth. Ground measurements of particles and gases from spacecraft-relevant sources could inform future standards for terrestrial smoke detectors and could complement research in other topical areas. For example, since LIBs are commonly used in laptops and cell phones, and increasingly in electric vehicles, data from NASA-led experiments could be used to evaluate terrestrial smoke detection standards and inform air quality risks associated with LIB fires.

B. Evaluation of gravity impacts on fire signatures and plume transport. To date, spacecraft fire detection studies have focused on microgravity applications, with heavy reliance on results from complementary ground experiments. During SAME, smoke particles generated in microgravity were larger compared to those generated in ground experiments below an air flow threshold of 8.1 cm s^{-1}, with the most significant size and morphology differences observed during no-flow tests. Differences in particle formation and evolution in reduced gravity are attributable to increased residence times near smoke sources since smoke plumes take longer to disperse due to low air velocities and a lack of buoyant flow.[3,4] In lunar gravity, the dependence of smoke particle size on air flow remains unclear. To ensure that an appropriate detector is selected for a future lunar habitat, particle sizes must be characterized in reduced gravity under air velocity conditions relevant to that environment. Experiments must also examine particle growth over relevant timescales, which should be informed by cabin air transport parameters and environmental conditions unique to the space. Finally, the effects of reduced gravity on smoke particle properties should be examined for a variety of different spacecraft-relevant fuels.

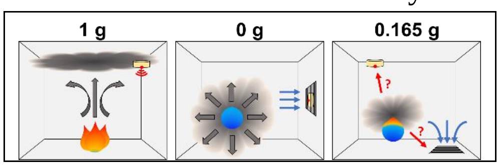

Figure 1. Comparison of smoke plume transport in terrestrial (left), micro- (center), and lunar (right) gravity.

The magnitude of gravity influences smoke plume transport as illustrated in Figure 1. The optimal location for a smoke detector within a lunar vehicle cabin must be evaluated through further research. Lunar dust is expected to pose a significant threat to crew health and materials in future lunar missions, and air returns placed on cabin floors would improve removal of lunar dust from cabin air by utilizing gravitational settling. If buoyant transport is sufficient to overcome downward flow, it may be advantageous to place detectors on the cabin ceilings. Modeling smoke transport in lunar gravity is therefore prioritized for upcoming fire safety research. Furthermore, the development of a lunar gravity smoke model could provide the framework for Martian studies in the future.

Lastly, future fire safety modeling studies will rely on smoke emission factors (i.e., mass of smoke component per mass fuel burned) from microgravity and partial gravity experiments.[6] These emission factors provide realistic smoke source scenarios that, when paired with habitat filtration and mixing parameters, enable alarm time predictions. Because spacecraft cabin air is typically well-mixed and heavily filtered, determination of realistic emission factors for different fuels and fire scenarios are critical for predicting times to alarm and informing detector placement.

C. Evaluation of exploration atmosphere impacts on fire signatures in reduced gravity. The planned environment for future lunar habitats is 34% O_2 and 8.2 psi.[23] These parameters, in conjunction with reduced gravity, are expected to influence material flammability, flame spread rates, and smoke emission for materials in future spacecraft.[21,24–26] Lee et al. (2000) found that for methane flames, soot surface growth and oxidation rates increase as O_2 % increases.[27] Similarly, Edland et al. (2020) demonstrated that for propane flames, soot inception and surface growth rates increase by orders of magnitude, with substantial changes occurring above 30% O_2.[28] However, below a critical pressure at which soot formation is maximized, reduced pressures are expected to reduce soot formation.[29] Based on these studies, the elevated O_2 concentration and reduced pressure conditions targeted for future lunar vehicles are expected to impact sizes, and therefore detection, of soot from fully developed fires. Additionally, we note that these studies utilized gaseous fuels rather than solid fuels, and more research is needed on O_2 and pressure impacts on solid fuel combustion. Effects of O_2 concentration and pressure on oxidative pyrolysis particles remain unclear and must also be investigated.

D. Development of improved fire detection systems. Experiments to characterize fire signatures under a variety of spacecraft-relevant conditions will provide the basis for improved fire detection technology. For example, a CO detector in parallel with a smoke detector was suggested as a solution to address rapid particle filtration by the ECLSS in Urban et al. (2016).[6] Ultimately, an ideal spacecraft fire detection system would incorporate a network of instruments and sensors to monitor fire properties (e.g., temperature, radiation, gas composition and concentrations, particle properties and concentrations) within the spacecraft cabin. The feasibility of such a system must be addressed in future work. A network of sensors within a detection system could also utilize monitoring technology already incorporated into the spacecraft for other purposes, like cabin air quality monitoring. For example, gas monitors currently on the ISS, including a laser spectroscopy-based combustion products monitor,[30] could be incorporated into a greater fire detection network in a future vehicle.

An array of sensors continually monitoring for pre-determined fire signatures would not only expand the subset of detectable fires but would also reduce false alarms. For example, a future detection system measuring particle chemical composition or charges could differentiate between smoke particles and lunar dust, which would greatly improve fire safety in future lunar spacecraft. Advances in chemical measurement technology (e.g., gas chromatography mass spectrometry) have enabled in situ molecular-level particle and gas chemical characterization, and recent efforts have focused on shortening analysis times, reducing power and physical footprints, and increasing robustness for these instruments,[31–33] making them potential candidates for future selective smoke detectors. Chemical characterization of particles and gases produced during a fire can also provide further information about the fire including the material burning, the approximate temperature of the fire, and the toxicity or harmfulness of the materials produced. Immediate knowledge of these factors would aid in determining the best response to the fire.[34] Additionally, novel data analysis strategies, including machine learning techniques like positive matrix factorization[35–37] and deep long-short term memory neural networks with variational autoencoders,[38] could be used to reduce complex data sets and efficiently identify analyte sources.

CAPABILITIES

Table 1 lists a subset of resources currently available for spacecraft smoke characterization research. At the NASA Glenn Research Center (GRC), the Gases and Aerosols from Smoldering Polymers (GASP) laboratory[19] and the new Battery Test Facility (BTF) are available for ground testing under terrestrial O_2 and pressure conditions. Parabolic flights provide short durations of microgravity or partial gravity (approximately 30 s), allowing an opportunity to prove experiment feasibility prior to longer-scale missions.[20,21,39] The zero-gravity research facility (ZGRF) drop tower centrifuge rig can currently provide 5.2 seconds of lunar gravity,[40] and planned improvements to GRC's drop tower facility will extend reduced gravity durations to 10 seconds.[41] Experiments on lunar vehicles (e.g., through Commercial Lunar Payload Services) are necessary to thoroughly investigate the influence of partial gravity on fire emissions. Additionally, continued combustion experiments on the ISS (e.g., using the microgravity science glovebox, MSG[42,43], or the combustion integrated rack, CIR[44]) and future low-earth orbit spacecraft are needed to improve fire detection in microgravity, which remains relevant for future deep-space missions.

As previously discussed, improvements in sensing technology for both particles and gases will enable unprecedented measurements within the constraints of a spacecraft environment. In addition to instrumentation already successfully implemented within a spacecraft,[30,45] novel sensors can be calibrated to reference aerosols and instruments to provide particle size distributions and concentrations.[46,47] Particle and gas sensors increasingly feature smaller footprints and power requirements, offering logistical advantages for future lunar and deep space chamber studies.

The ability to use Computational Fluid Dynamics (CFD) to assess the ability to detect fire effluent as it evolves from the source location is crucial for determining detector design and placement strategies. One such model is the NIST Fire Dynamics Simulator (FDS), which is designed for fire flows in any gravity environment with fire or other heat sources.[48,49] Recent updates to FDS include advancements in aerosol dynamics modeling, accounting for particle size distributions and transport dynamics affecting particle sizes and concentrations (e.g., coagulation, deposition, and thermophoresis). As the FDS software is freely available and open source, the code may be modified to account for currently un-modeled physics.

Table 1. Partial list of experimental resources enabling investigation of smoke particle characteristics and transport under various gravity and cabin atmosphere conditions.

Resource/Location	**Duration**	**Gravity (g)**	**O_2 (%)**	**Pressure (psi)**
GASP and BTF (GRC)	Full burn	1	21	14.7
MSG[42,43] (ISS)	Full burn	0	21	14.7
CIR[44] (ISS)	Full burn	0	10-40	0.29-44
ZGRF drop tower centrifuge rig[40] (GRC)	5.2 s	0.165	21	14.7
Parabolic Aircraft/DIAMONDS (CNES)[20,21,39]	~30 s	0-0.379	<21	7.3-20
Blue Origin New Shepard Rotating Capsule	~120 s	0.165	~34	~8.2
Commercial Lunar Payload Services Experiments	Full burn	0.165	~34	~8.2

CONCLUSIONS AND RECOMMENDATIONS

Transformative spacecraft fire detection research is paramount to ensuring crew safety in future lunar and deep-space missions. We recommend the following priorities for future study:

1. **Identification of realistic fire scenarios and characterization of fire signatures from unstudied and understudied fuels.** Fuels prioritized for immediate testing include LIBs and the crew clothing fabric to be selected for Artemis missions.
2. **Evaluation of gravity impacts on fire signatures and plume transport.** Proof-of-concept studies in simulated lunar gravity will provide a starting point for lunar habitat experiments. Emission factors from these studies will enable computational simulations of smoke plume transport and inform detector placement in future spacecraft cabins.
3. **Evaluation of exploration atmosphere impacts on fire signatures in reduced gravity.** Elevated O_2 and reduced cabin pressure conditions will influence fire signatures and therefore fire detection. Each variable must be investigated individually in both ground and reduced gravity experiments.
4. **Development of improved detection systems using data from spacecraft fire safety experiments.** A transformative fire detection system would be capable of rapidly identifying smoke components through a combination of different particle and gas measurement techniques. Such a system would increase the number of detectable fires and reduce nuisance alarms from suspended cabin and lunar dust.

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