Spacecraft Fire Safety Technology Development Plan

For Exploration Missions

Gary A. Ruff[1], David L. Urban[2], and Daniel L. Dietrich[3]
NASA John H. Glenn Research Center, Cleveland, OH, 44135

To date, NASA's spaceflight operations in the past five decades have been limited to a narrow range of conditions from a fire safety perspective. The currently anticipated missions outside of low earth orbit will substantially expand this parameter space to include, extended durations, dormancy intervals, increased oxygen concentrations, partial gravity conditions and the presence of surface dust. All of these changes can have significant impacts on fire safety system design and operations. The overall state of understanding is discussed in this paper along with the identification of the needs for spacecraft fire safety technology development. These needs have been assembled into a roadmap maintained by the Environmental Control and Life Support System Capability Leadership Team that has evolved as the exploration mission concepts have changed. This roadmap continues to communicate the spacecraft fire safety needs for exploration and guide technology development efforts. This paper summarizes the major recent developments in our understanding of spacecraft fire behavior and mitigation. A review of the major technology development needs and discussion of their objectives, status, and future plans is presented. The plan for transitioning knowledge, hardware, and modeling capability resulting from these development efforts to specific exploration vehicle programs and missions is also discussed.

Nomenclature

COG = chemical oxygen generator
ECLSS = Environmental Control and Life Support System
EVA = Extra Vehicular Activity
FPDS = fire protection, detection and suppression
HEPA = High Efficiency Particulate Air filters
ISS = International Space Station
Li-ion = Lithium-ion battery
STS = Space Transportation System (Space Shuttle)

I. Introduction

The progressive increase in the duration and extent of spaceflight missions beyond the surface of Earth has not been without risk. This history includes a number of catastrophic events[1]. Since the 1960s, of the 10 reported events that resulted in the loss of crew, two events involved fire (both in ground-based testing). On-orbit, there have

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[1] Spacecraft Fire Safety Demonstration Project Manager, Exploration Systems Office, MS 162-7, 21000 Brookpark Road, Cleveland, OH 44135.

[2] Branch Chief, Low-Gravity Exploration Technology Branch, MS 77-5, 21000 Brookpark Road, Cleveland, OH 44135.

[3] Combustion Discipline Scientist, Low-Gravity Exploration Technology Branch, MS 110-3, 21000 Brookpark Road, Cleveland, OH 44135.

been 13 fire or near-ignition overheat events of which two were grave and represented a clear risk to the crew. Although most of these events were limited duration component overheating or electric short events, two of these were open fires precipitated by the oxygen generator and included active extinguishment efforts by the crew. Collectively, these results provide evidence that fire continues to be a significant risk for spaceflight that requires ongoing research to adjust to future flight requirements. Although the frame of reference of spacecraft fire safety systems is often their terrestrial counterpart, addressing the fire risk in a spacecraft is more challenging owing to cramped quarters, limited resources for fire response, and limited evacuation opportunities. One advantage of spaceflight is that the configuration control and material usage control is very robust; consequently, the overall risk of an ignition can be kept acceptably low[2].

Although spacecraft fire safety has been studied since the beginning of the space program in the 1970s[3], the development of a significant and integrated program in material flammability, detection, suppression and post fire response only became a reality in the past two decades[4]. This paper summarizes the current status of that research and the planned road map for future studies.

A. Overview of Spacecraft Fire Safety Historical Issues

1. Previous Fire Events

As discussed in the introduction, to date, the loss of life or serious injury due to fires has occurred in ground-based testing either in the spacecraft itself (Apollo -1, 1967) or in ground-based test chambers (Russia, 1961 and US Navy, 1961)[1]. All of these incidents were in high oxygen environments. Based on the Apollo 1 experience, NASA vigorously improved material control within the spacecraft and made steps to improve egress and provide an extinguishment option. On orbit, there have been at least 13 documented cases of electrical shorts of overheating components[1, 5] all of these events were resolved safely. Two more serious on orbit events have been documented; both involved the Mir chemical oxygen generation system (COG). One such event was easily extinguished by a crewmember (1994) while the other was a more significant event (1997) that involved burns to the crewmember fighting the fire[6]. There are some reports that there may have been additional events on Russian spacecraft but detailed documentation is currently unavailable[6]. It is notable that all of the most serious events were in the presence of enhanced oxygen, either in an enriched environment or directly involving the oxygen generator. Chemical oxygen generators have also been the source of other fires including the ValueJet crash[7] and a submarine fire in HMS Tireless[8]. These events have caused NASA to avoid the use of chemical oxygen generators, where possible, and to require that fire extinguishers on flights that have COGs are able to extinguish such potential fires.

2. Prior Detection and Suppression Systems

Given the limited number of spacecraft fires to date, spacecraft fire detection and suppression systems have necessarily been based on terrestrial systems. Beginning with the Space Shuttle, the fire detection approach has been to use smoke detection systems that look for aerosol particulate created by the fire event and the suppression systems have included Halon, carbon dioxide and, recently, water mist with the requirement to address both enclosed avionics systems and open cabin fires[5]. Residential smoke detectors are required to be able to detect certain prescribed test fires. Fire extinguisher ratings are based on the size of standard fires the extinguisher can handle. Since there were no data concerning expected smoke particle sizes in low gravity and no reference fire sizes, both systems were adapted from terrestrial systems for spacecraft applications without verification of their effectiveness in low-gravity. Since it was recognized that smoke would not rise to the ceiling in low-gravity, detectors were placed at locations where air sampling was assured by the ventilation system. However, the impact of the well-mixed nature of the cabin volume on the detection threshold was not considered. The particle size sensitivities of the Space Shuttle (STS) and the International Space Station (ISS) detectors were quite different with the ISS detectors more sensitive to larger particles while the Shuttle detectors were designed to reject larger particles[9]. The design change was driven primarily by available technology for terrestrial systems rather than data concerning the targeted reference fire conditions.

B. Changes in Vehicle Configurations that Drive Fire Risk

Terrestrial fire protection system designs are based on historical experience with fire behavior; modeling of the interaction of fires and human egress; and full-scale validation testing. Unfortunately, terrestrial experience does not provide useful guidance for spacecraft fire protection, detection, and suppression (FPDS) system design. More importantly, experience in terrestrial fire safety practices is probably more misleading than it is helpful.

1. Fire Detection Issues

While vehicle designers, starting with the space shuttle, recognized that the absence of buoyancy would require that they place the detectors in the path of the flow system, more subtle details of the impact of gravity on detection were not considered. Terrestrial smoke detection is dramatically simplified by the fact that, even in well-ventilated areas, absent a ceiling fan, buoyant flow creates a stratified smoke layer at the ceiling where the smoke is very concentrated and so detection of a fire against nuisance aerosol sources is much simplified. Not only can the smoke be expected to be in a predictable location, the smoke is concentrated at that location rather than diluted by other air in the volume. In spacecraft, the situation is much different, since the natural ventilation enjoyed by most buildings is not present, spacecraft life support designers ensure that the open volume of spacecraft is well mixed so that no pockets of hazardous gases can exist. This mixing dilutes the smoke such that, in most cases, the entire vehicle volume must be brought up to the alarm threshold rather than smoke collecting in a thin layer at the ceiling[10]. This problem is further complicated by the effect of the air filtration system. To protect the crews' eyes and respiratory systems, the ISS and future spacecraft will have High Efficiency Particulate Air filters (HEPA) in the Environmental Control and Life Support System (ECLSS) ventilation. These systems effectively remove smoke particulate so the smoke concentration cannot build up to the detection threshold as quickly. Of particular concern is the fact that these systems may not remove hazardous products as they remove particles. The net result is accumulation of hazardous compounds while alarm triggering is delayed[11].

These papers demonstrated that successful implementation of a smoke detection system requires analysis or modeling of the specific spacecraft in which it will be installed. Brooker et al.[10] demonstrated that for moderate smoke production rates, in a module corresponding to the ISS Destiny laboratory, the detection time could vary by over 2 minutes. Subsequently Urban et al.[11] estimated the time to trigger the ISS and STS smoke detectors in various spacecraft configurations for a variety of spacecraft materials. The accumulation of smoke was calculated depending on the filtration in the ECLSS system. At the same time, hazardous compounds were allowed to accumulate. In many cases, hazardous levels of multiple materials accumulated before the smoke alarm threshold was achieved. Based on the variation in results depending on the vehicle configuration and the air filtration, the authors concluded that spacecraft fire detection thresholds should not be based on terrestrial levels or on other spacecraft, but instead, need to be specifically selected based on the volume of the vehicle and the anticipated life support (air filtration and ventilation) systems. The interaction between all relevant systems must be considered (and usually modeled in detail) to ensure adequate detection.

2. *Impact of Stowage and Avionics Configuration*

Stowage and avionics configuration can also have a significant effect on fire detection and suppression choices. Both the ISS and the STS have enclosures with powered electronics and cooling air flow. This configuration was recognized to have increased risk of sustained fire so they were designed to be accessible for flooding extinguishment and to be covered by smoke detectors[2, 4]. Alternative approaches have been considered for future spacecraft, which included enclosing avionics systems to restrict airflow and using cold plates for avionics cooling. Applied correctly these approaches can eliminate the need for fire suppressant access to the enclosure. Proposed plans for Orion include ensuring any stowed items that have the potential of providing an ignition source (e.g. Li-ion batteries) are stowed with a fire barrier between the ignition sources and other flammable stowage. Implemented correctly (and backed by suitable testing), these design approaches can eliminate the need for both a fire extinguisher that can flood enclosed spaces and fire detection coverage of the enclosed spaces.

3. *Vehicle Scale Fire Modeling*

Studies by Dietrich et al. [12, 13] modeled the impact of a fire in a spacecraft considering effects including pressure rise, thermal injury to the crew, carbon monoxide and carbon dioxide and hazardous gas accumulation. The issues were found to scale in a generally non-linear manner with the fire and the vehicle sizes. Details including the size of the positive pressure relief valves had very important impacts on the outcome.

The critical conclusion from these prior studies is that, if there are flammable materials present, there is no simple fire detection and suppression approach that will work for all potential vehicle designs. Instead the specific vehicle must be modeled including the details of the air circulation and filtration; avionics cooling and enclosures; stowage strategy; vehicle volume; atmosphere composition; and relief valves. With these details included in the model the proposed requirements for detection and suppression can be quantitatively examined.

C. Future mission changes that will further change risk

Mission parameters also can have a significant effect on the fire safety requirements. Of these, mission duration, operational gravity levels, Extra Vehicular Activity (EVA) frequency, and dormancy all have important impacts. The impact from mission duration is primarily through the logistics requirements. Longer missions require increased stowed supplies and stowed waste material with the challenges of configuration control. Included in the additional supplies will necessarily be potential ignition sources including spare batteries and laptops, increased oxygen stores and potentially reactive ECLSS consumables. The operational gravity levels also strongly affect the fire safety design.

Designing a craft for reliable fire detection in both low-gravity and surface gravity environments is particularly challenging as the presence of buoyant flow will dominate the smoke transport even at Lunar g-levels. Consequently the design choices for each environment can be expected to be substantially different. Increased EVA frequency brings with it numerous issues: increased handling of high pressure oxygen, increased dust release in the cabin, use of higher oxygen concentration environments to reduce decompression sickness risk[4], and increased battery usage. Designing a spacecraft or habitat for extended periods of dormancy requires the ability to create a fireproof state (vacuum or very low oxygen concentration); remove or enclose all flammable materials; limit or eliminate all possible ignition sources; or provide automated fire suppression capability.

II. Current state of understanding and needs for future research

A. Material Flammability, Ignition, and-Fire Growth

1. Flammability

Reduction of the risk of injury or damage due to a fire can be achieved (in principle) by either ensuring there are no flammable materials or there are no ignition sources. If neither of these two conditions can be guaranteed, then reduction of the fire risk can be achieved by understanding the potential size and growth rate of a fire and developing means to detect and extinguish it. NASA addresses both of the prevention approaches separately. The flammability risk is addressed through NASA STD 6001 Test 1[14], although this test does a significant job of identifying highly flammable materials for exclusion, prior work in low gravity has shown that some materials may be more flammable in low-gravity than in the normal gravity conditions of the test[15, 16]. These prior tests were limited to thin samples of a small number of materials that do not pass NASA's flammability test (i.e. are flammable in air). Marcum et al. showed that PMMA rods would burn at substantially lower oxygen concentrations in low-gravity than in 1-g.[17] Further testing, in extended low gravity, of materials that are typically used in spacecraft is necessary to better characterize the reliability of the current flammability standard.

2. Ignition

The best practice is to use only materials that are not flammable in the spacecraft environment (pressure, oxygen and gravitation). The reality, however, is that there will likely be materials in the spacecraft that are flammable in the spacecraft environment. The question then is not whether a fire can occur, but how to mitigate the risk of a potential fire. This involves understanding the conditions under which a fire might ignite and how fast the fire will grow if it ignites. Ignition prevention though is challenging to achieve in an absolute sense since the presence of any powered systems provides an ignition source. This approach is made even more challenging owing to the very configuration specific nature of ignition. Ultimately, ignition is controlled by the tradeoff between the energy produced by the ignition source and the early reactions against the heat loss to the surroundings. As the conditions approach the limit, small variations in a variety of parameters can change the heat losses. Consequently, it is not usually managed to a simple standard and instead is primarily addressed by traditional best practices. Given the wide variety of potential ignition sources (e.g. spark, friction, chemical reaction, heating) and the difficulty of establishing a test method that will cover these different mechanisms, there is not an identified research path that is expected to lead to a universal answer.

Rather than identifying a single test, the best approach to mitigate the ignition risk is to identify the highest risk ignition sources on a spacecraft and perform ground testing to understand the likelihood that a failure might initiate a fire. An example is a laptop computer that experiences a thermal runaway event. In this case while the energy released by the failed laptop itself might be a manageable event, the greater risk might be the likelihood that the failure will result in the ignition of other flammable material in the spacecraft. The risk mitigation in this case is not eliminating the ignition source or flammable material but configuration control of the flammable material and the ignition source.

3. Fire Growth

Once an ignition has occurred, the next critical step is the kindling chain where a small ignition grows to a larger, hazardous fire. While it is extremely difficult to break all possible kindling paths, identifying and avoiding the most threatening paths is possible and good practice. In normal gravity material flammability is strongly influenced by the presence of surrounding materials. One salient example is wood which is universally understood to be flammable and the participating fuel in the vast majority of unwanted fires. A single piece of wood will pass most flammability tests in normal gravity. However, two pieces of wood, separated by approximately a centimeter are much more easily ignited. It is possible that similar effects can be seen in low-gravity for different configurations. To date, this issue is entirely unexplored (in low-gravity) due to the limited number of test opportunities for extended duration testing of complex fuel geometries. Testing of this type, exploring a range of potentially hazardous configurations is an important area for future study. This work could be conducted first with traditional research materials. If hazardous configurations are identified, it would be valuable to test them with low-flammability spacecraft materials.

In the event that material and configuration controls have failed, the critical questions related to the rate of growth of the fire and the impact fire has on the spacecraft. Terrestrial fire safety is based on extensive experience with fires and associated experience with fire growth and spread rates. To date we have very limited experience with fire growth in low gravity. The Saffire experiments[18] are addressing this issue by establishing fires on realistic size materials and allowing the flame to grow while its progress is monitored. Sensors throughout the vehicle also measure the pressure and temperature rise to facilitate validation of computer models of the impact of the fire on the vehicle. This approach parallels that used in terrestrial fire safety where extensive testing has built a robust experience base for fire behavior in structures. A similar experience base must be developed in order for NASA to ensure the safety of future spacecraft.

B. Partial-Gravity Material Flammability

To date, study of material flammability in partial gravity has been limited to studies of thin fuels during low-gravity aircraft trajectories[21] and in the GRC 5.2 second drop tower using a centrifuge facility[21]. Both of these studies observed an extended flammability zone where materials were flammable at lower oxygen concentrations at partial gravity conditions near lunar gravity levels compared to both normal gravity and microgravity conditions. These results suggest that flammability limits determined in normal gravity may not be conservative however, the data set collected to date is very limited. Low gravity conditions also enable fires to persist in conditions where they are less likely to survive in low gravity e.g. inside narrow channels between fuel surfaces, smoldering in porous media, and deep seated fires. These various configurations can have a significant effect on material flammability but the extent of this impact as a function of g-level is not readily predicted and is an important area of future study.

C. Fire Detection: Validation and Vehicle Scale Transport

Brooker et al.[23] showed that the detection conditions in a low-gravity spacecraft are substantially different from normal gravity where buoyancy stratifies the smoke near the ceiling. By comparison, in low-gravity the cabin atmosphere is invariably well mixed and the entire volume must be brought to the alarm level. A space experiment[24] examining the smoke particle sizes from several materials found in spacecraft found that typical smokes aerosol sizes can range in size from 100 to 500 nm diameters of average mass. This range makes discrimination of smoke from dust particles difficult based simply on the aerosol concentration. Modeling the transport in a spacecraft equipped by and active ECLSS system equipped with HEPA filtration[25] found that the aerosol filtration by the ECLSS system can substantially delay fire detection and can lead to buildup of hazardous products. A further conclusion was that design of the smoked detection system is strongly dependent on the vehicle and ECLSS design and requires smoke transport modeling in the specific spacecraft. Furthermore the alarm levels needed for each vehicle depend on the details of the vehicle design and the detection approach.

D. Fire Detection: Transfer Standard

Terrestrial smoke detectors are typically qualified against performance standards such as[26] where the detector must be demonstrated to respond to a set of reference fires in a defined period of time. This set of fires was developed based on experience with the most common hazardous fires for homes and other structures. Owing to the limited experience with spacecraft fires, no such database exists nor are they readily defined. Space experiments and terrestrial testing have established a good understanding of the expected particle sizes and concentrations for several spacecraft materials[24, 27]. Background aerosol particulate on the ISS have been sampled for size and composition analysis[28] and ground-based testing has been conducted with reference aerosol instruments and smoke aerosols[29, 30]. Separately, modeling efforts have helped provide a means to predict aerosol particulate level profiles in a spacecraft as a function of the fire size and ECLSS system design[23]. It is too cumbersome to expect detector designers to develop a test capability to replicate the detection scenario to validate their detector performance and alarm level. Instead it is proposed that using the aforementioned data, a set of transfer standards could be developed that manufacturers could use to validate their system performance. To establish these standards, further work is needed both on the modeling front and to characterize other expected smoke and nuisance aerosol sizes.

E. Contingency Monitor

Testing to establish the quantity of hazardous species from overheated spacecraft polymers[29, 30] has provided initial estimates of the quantities of several hazardous compounds (HF, HCl, HCN) that can be produced. This testing also provided a means to evaluate the performance of candidate instruments. These results also have shown that HF HCl transport in a spacecraft needs further study to understand the level of adsorption to spacecraft materials. Testing with burning laptops containing lithium ion (Li-ion) batteries has been conducted at White Sands Test Facility to understand the hazardous product release from these events. Further work is needed with other spacecraft compounds and fire sources to fully characterize the compounds that should be monitored.

F. Post-Fire Cleanup & Emergency Breathing Apparatus

This topical area depends on the smoke production and chemical species production data[29, 30] combined with fire modeling results that are also required for the detection and monitoring elements. A post-fire cleanup system will be tested in Saffire IV-VI which will provide valuable on-orbit validation. Proper design of such systems will require improved prediction of the possible level of contamination of the spacecraft in a post-fire environment. These predictions must be developed based on understanding developed in the fire growth and spread topics discussed above combined with details of the planned spacecraft configuration. In addition, continued technology evaluation and demonstration is needed to validate designs for new spacecraft and to test new technologies.

G. Fire Suppression

Depending on the mission design, fire suppression requirements can vary from human operated to automated and can include fires in open areas and within avionics enclosures. As partial gravity mission are considered, the requirements will change further. The choice of suppression agent depends on the scale of the vehicle and the expected fire risk[31]. In addition to the fire growth and vehicle impact modeling discussed above, further technology validation testing is needed to examine new suppression concepts and application of existing concepts to different configurations. Testing of at least one suppression concept is proposed for the Saffire VII-VIII flights.

H. Characterization of Lithium-ion Battery Fires

The full impact of a Li-ion fire on a spacecraft cannot be reliably predicted at this time owing to limited knowledge of the heat and hazardous product release from a burning laptop in low-gravity. Specific tests must be conducted that quantifies the heat release, product composition and risk for fire spread from burning Li-ion batteries in relevant configurations. The effectiveness of containment and extinguishment methods in low-gravity should also be more fully understood.

I. Integrated Testing

As described above, detection, suppression and cleanup systems are all dependent on the scale of the fire and the vehicle size and ECLSS components. Many of these issues can be addressed by component testing and modeling but integrated testing both in 1-g and where possible in low-gravity is essential to validated the system effectiveness.

III. Road map for research and plan for transition results to design guidance

The Environmental Control and Life Support (ECLS) System Capability Leadership Team (SCLT) maintains a series of roadmaps that identify the research needs to accomplish the planned exploration missions. Roadmaps have been prepared in areas such as life support systems, logistics reduction, radiation safety, and particulate monitoring, and spacecraft fire safety, to name a few. These roadmaps are not only used to identify the technology development needs for exploration but also to track the progress of work to address those needs. A number of sources funds the various activities shown on the roadmap. The roadmap is shown in Figs. 1 – 4. The need dates for the major exploration programs are shown across the top of each roadmap. The major horizontal “swim lanes” are as follows:

- Material Flammability, Ignition and Fire Growth
- Partial-Gravity Material Flammability
- Fire Detection: Validation and Vehicle Scale Transport
- Fire Detection: Orion
- Contingency Monitor
- Post-Fire Cleanup
- Emergency Breathing Apparatus
- Fire Suppression
- Characterization of Li-ion Battery Fires
- Integrated Testing

The following sections will discuss the major activities in each of these areas.

A. Material Flammability, Ignition and Fire Growth

The focus of the tasks in this area is to expand our understanding of the flammability of materials under realistic spacecraft conditions. Saffire-I-III experiments were conducted in 2016-2017[17] and were the first to investigate material flammability and fire growth using large-scale samples. Saffire-IV-VI series of experiments has built on these results to conduct tests at elevated oxygen and reduced pressures that could be used on exploration missions. The Saffire IV-VI series will also examine fire growth through studies of large samples for longer durations than studied in Saffire I-III[17] These experiments will also demonstrate impact of a fire on a spacecraft and the effectiveness of prototype fire response hardware. Transport and adsorption of HCL and HF in a spacecraft fire environment will also be studied. Therefore, these experiments show up in several "swim lanes" in the roadmap. While the Saffire experiments on Cygnus are excellent for evaluating the impact of a large-scale fire on a spacecraft, there is very limited capability to change test conditions or samples based on what was learned in previous tests. ISS experiments such as the Solid Fuel Ignition and Extinction (SoFIE) insert in the Combustion Integrated Rack (CIR)[19] or the planned Microgravity Combustion Wind Tunnel facility (underdevelopment as an expanded version of the BASS insert[20])in the Microgravity Science Glovebox are better candidates to conduct tests more rapidly. Each of these facilities has unique capabilities that make them much more effective in addressing needs in low-g ignition and flammability when used in tandem.

B. Partial-Gravity Flammability

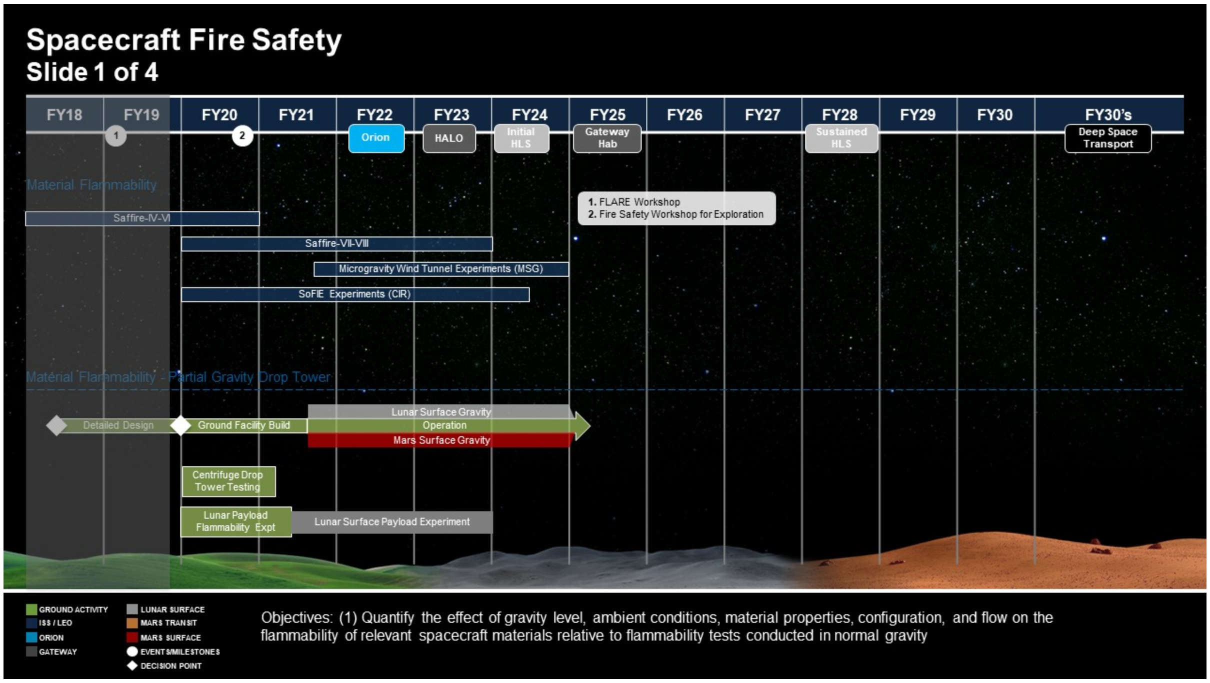
A major gap in our understanding of flammability on exploration missions is the flammability in partial-gravity. Many of the fire safety protocols that are in place for spacecraft in low-gravity, such as the material screening performed by NASA-STD-6001 Test 1 and shutting off the spacecraft ventilation upon detecting a fire, are questionable or ineffective in partial-gravity. Unfortunately, there is no terrestrial facility in which to conduct these experiments. Preliminary designs and testing for a partial-gravity drop tower at NASA John H. Glenn research Center are being made. Once complete, extensive tests would be conducted in Lunar and Martian gravity levels. In the meantime, small-scale tests are planned in a centrifuge drop rig developed at NASA-GRC[22]. Preliminary designs are being developed for a flammability experiment to be conducted in payload on a commercial lunar lander. None of these activities can completely address the unknowns associated with spacecraft fire safety in partial-gravity but are needed because there is no testing capability currently available.

C. Fire Detection: Validation and Vehicle-Scale Transport

There is no common fire detector used on existing spacecraft. With the increase in commercial crew vehicles, this trend will likely continue. At issue is that different detector technologies have differing responses to the range of size and type of smoke aerosols. The Saffire-IV-VI series of experiments has diagnostics that will measure the size distribution of the smokes produced by the experiment in low-g and how the smoke aerosol is transported throughout the vehicle and its interaction with the various filters on board. This data will be compared post-flight with particulate and combustion product transport models. This comparison will enable validation of our predictions of aerosol transport in spacecraft to be used for definition of smoke detection systems in future spacecraft.

D. Fire Detection: Transfer Standard

Because there is no common smoke detector used on spacecraft and it is unrealistic to test candidate smoke detectors for all types of smoke aerosols produced by common spacecraft materials, the identification of a transfer standard using common reference aerosols is essential for providing consistency in alarm thresholds and detection. This task will obtain that data and then apply it as smoke detectors for different types of missions are identified. For example, detection technologies for use in Gateway/HALO and Human Landing Systems (HLS) will be evaluated for that specific application with new measurements and development tasks defined and accomplished as needed.



Spacecraft Fire Safety
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FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY30's

1 2 Orion HALO Initial HLS Gateway Hab Sustained HLS Deep Space Transport

1. FLARE Workshop
2. Fire Safety Workshop for Exploration

Material Flammability

Saffire-IV-VI

Saffire-VII-VIII

Microgravity Wind Tunnel Experiments (MSG)

SoFIE Experiments (CIR)

Material Flammability - Partial Gravity Drop Tower

Detailed Design

Ground Facility Build

Lunar Surface Gravity

Operation

Mars Surface Gravity

Centrifuge Drop Tower Testing

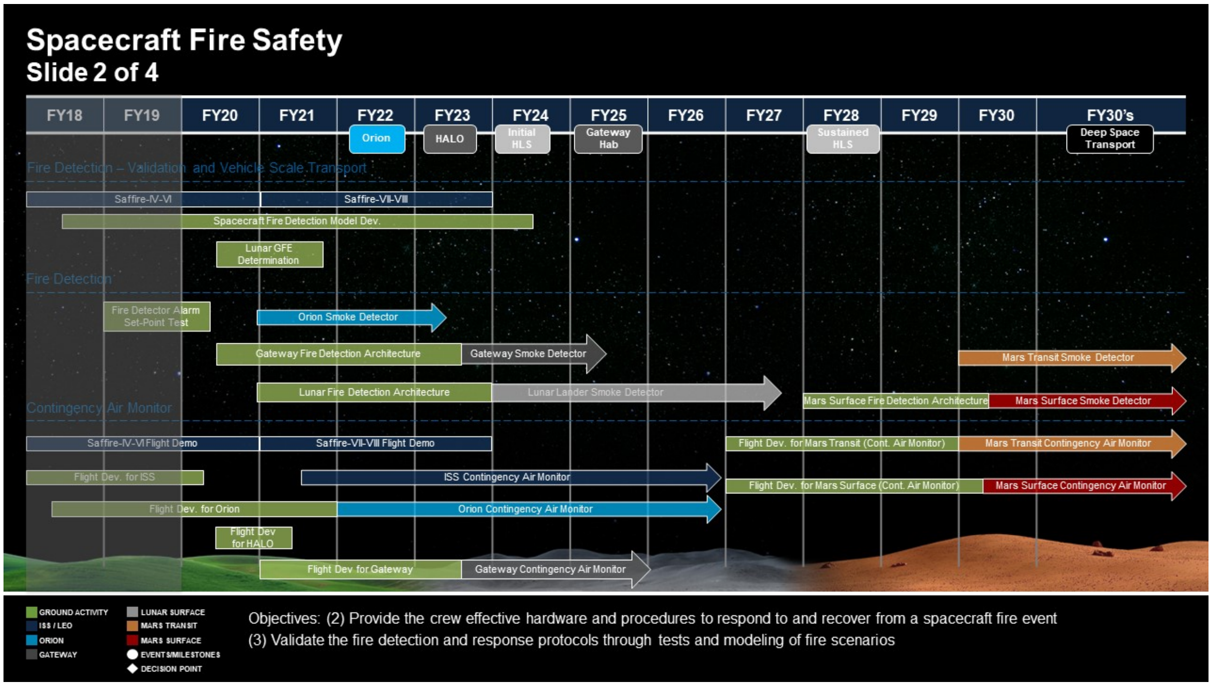
Lunar Payload Flammability Expt

Lunar Surface Payload Experiment

🟩 GROUND ACTIVITY
🟦 ISS / LEO
🟦 ORION
⬛ GATEWAY
⬜ LUNAR SURFACE
🟧 MARS TRANSIT
🟥 MARS SURFACE
● EVENTS/MILESTONES
◆ DECISION POINT

Objectives: (1) Quantify the effect of gravity level, ambient conditions, material properties, configuration, and flow on the flammability of relevant spacecraft materials relative to flammability tests conducted in normal gravity

Figure 1. Spacecraft Fire Safety Roadmap – Page 1 (October 2019)



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FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY30's

Orion HALO Initial HLS Gateway Hab Sustained HLS Deep Space Transport

Fire Detection – Validation and Vehicle Scale Transport

Saffire-IV-VI

Saffire-VII-VIII

Spacecraft Fire Detection Model Dev.

Lunar GFE Determination

Fire Detection

Fire Detector Alarm Set-Point Test

Orion Smoke Detector

Gateway Fire Detection Architecture

Gateway Smoke Detector

Mars Transit Smoke Detector

Lunar Fire Detection Architecture

Lunar Lander Smoke Detector

Mars Surface Fire Detection Architecture

Mars Surface Smoke Detector

Contingency Air Monitor

Saffire-IV-VI Flight Demo

Saffire-VII-VIII Flight Demo

Flight Dev. for Mars Transit (Cont. Air Monitor)

Mars Transit Contingency Air Monitor

Flight Dev. for ISS

ISS Contingency Air Monitor

Flight Dev. for Mars Surface (Cont. Air Monitor)

Mars Surface Contingency Air Monitor

Flight Dev. for Orion

Orion Contingency Air Monitor

Flight Dev for HALO

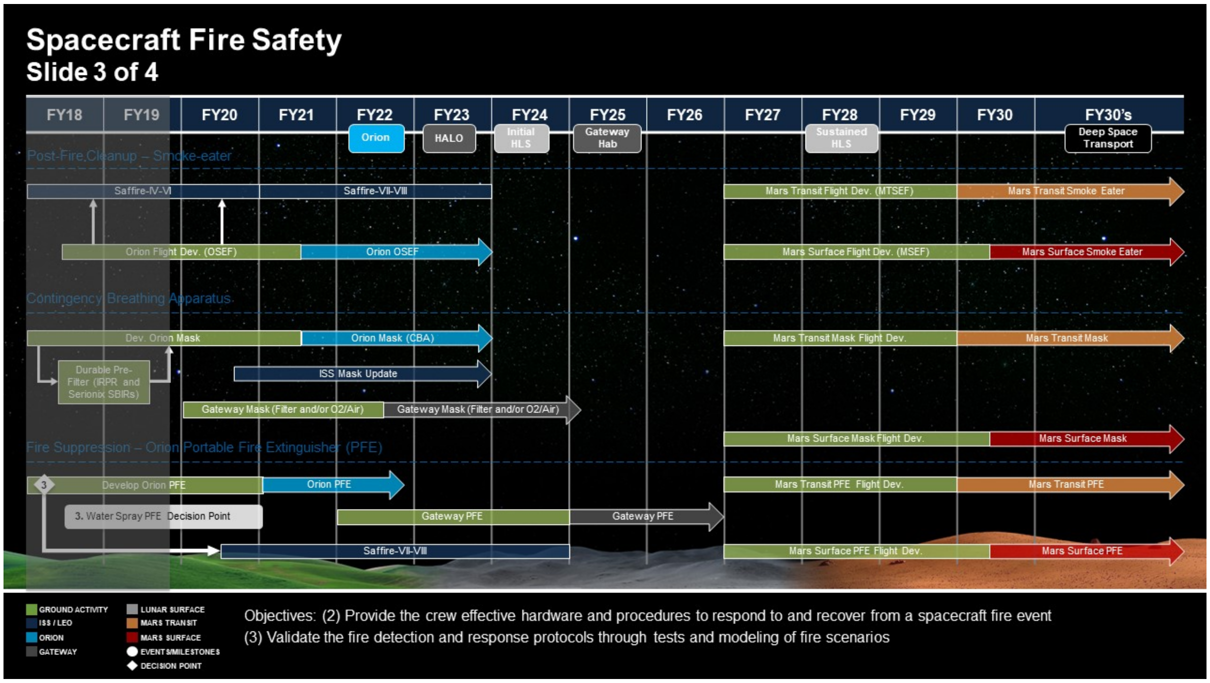
Flight Dev for Gateway

Gateway Contingency Air Monitor

🟩 GROUND ACTIVITY
🟦 ISS / LEO
🟦 ORION
⬛ GATEWAY
⬜ LUNAR SURFACE
🟧 MARS TRANSIT
🟥 MARS SURFACE
● EVENTS/MILESTONES
◆ DECISION POINT

Objectives: (2) Provide the crew effective hardware and procedures to respond to and recover from a spacecraft fire event
(3) Validate the fire detection and response protocols through tests and modeling of fire scenarios

Figure 2. Spacecraft Fire Safety Roadmap – Page 2 (October 2019)



Spacecraft Fire Safety
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FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27 | FY28 | FY29 | FY30 | FY30's

Orion | HALO | Initial HLS | Gateway Hab | Sustained HLS | Deep Space Transport

Post-Fire Cleanup – Smoke-eater

Saffire-IV-VI
Saffire-VII-VIII
Orion Flight Dev. (OSEF)
Orion OSEF
Mars Transit Flight Dev. (MTSEF)
Mars Transit Smoke Eater
Mars Surface Flight Dev. (MSEF)
Mars Surface Smoke Eater

Contingency Breathing Apparatus

Dev. Orion Mask
Orion Mask (CBA)
Durable Pre-Filter (IRPR and Serionix SBIRs)
ISS Mask Update
Gateway Mask (Filter and/or O2/Air)
Gateway Mask (Filter and/or O2/Air)
Mars Transit Mask Flight Dev.
Mars Transit Mask
Mars Surface Mask Flight Dev.
Mars Surface Mask

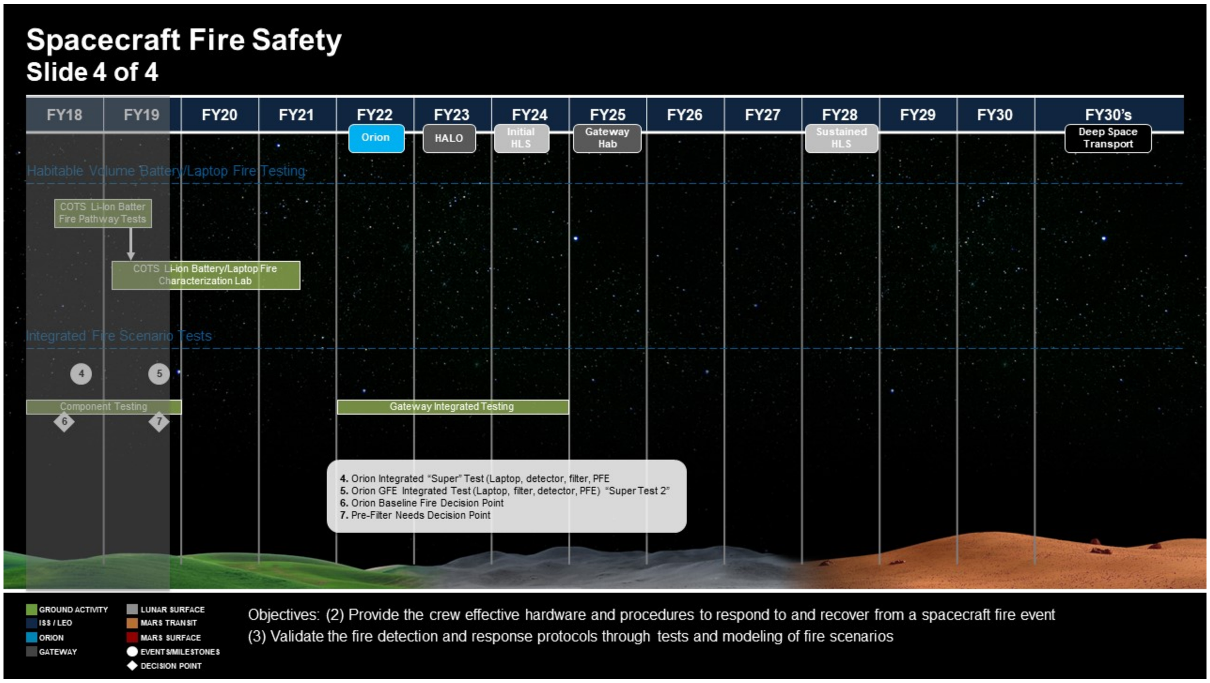
Fire Suppression – Orion Portable Fire Extinguisher (PFE)

3 Develop Orion PFE
Orion PFE
3. Water Spray PFE Decision Point
Gateway PFE
Gateway PFE
Saffire-VII-VIII
Mars Transit PFE Flight Dev.
Mars Transit PFE
Mars Surface PFE Flight Dev.
Mars Surface PFE

🟩 GROUND ACTIVITY
🟦 ISS / LEO
🟦 ORION
⬛ GATEWAY
⬜ LUNAR SURFACE
🟧 MARS TRANSIT
🟥 MARS SURFACE
● EVENTS/MILESTONES
◆ DECISION POINT

Objectives: (2) Provide the crew effective hardware and procedures to respond to and recover from a spacecraft fire event
(3) Validate the fire detection and response protocols through tests and modeling of fire scenarios

Figure 3. Spacecraft Fire Safety Roadmap – Page 3 (October 2019)



Spacecraft Fire Safety
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FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | FY25 | FY26 | FY27 | FY28 | FY29 | FY30 | FY30's

Orion | HALO | Initial HLS | Gateway Hab | Sustained HLS | Deep Space Transport

Habitable Volume Battery/Laptop Fire Testing

COTS Li-Ion Batter Fire Pathway Tests
COTS Li-ion Battery/Laptop Fire Characterization Lab

Integrated Fire Scenario Tests

4
5
Component Testing
6
7
Gateway Integrated Testing

4. Orion Integrated "Super" Test (Laptop, detector, filter, PFE
5. Orion GFE Integrated Test (Laptop, filter, detector, PFE) "Super Test 2"
6. Orion Baseline Fire Decision Point
7. Pre-Filter Needs Decision Point

🟩 GROUND ACTIVITY
🟦 ISS / LEO
🟦 ORION
⬛ GATEWAY
⬜ LUNAR SURFACE
🟧 MARS TRANSIT
🟥 MARS SURFACE
● EVENTS/MILESTONES
◆ DECISION POINT

Objectives: (2) Provide the crew effective hardware and procedures to respond to and recover from a spacecraft fire event
(3) Validate the fire detection and response protocols through tests and modeling of fire scenarios

Figure 4. Spacecraft Fire Safety Roadmap – Page 4 (October 2019)

E. Contingency Air Monitor

The Anomaly Gas Analyzer has been under development for use on ISS and Orion for the past several years. The suitability of this technology for use in other platforms, such as Gateway/HALO or HLS will be assessed as the mission parameters and the vehicle design are defined. Improvements in laser technology could lead to smaller and more capable instruments that may be better suited for future exploration missions. If so, new instruments will be developed and implemented as necessary. Further testing with additional materials including burning lithium-ion batteries will be conducted.

F. Post-Fire Cleanup

The Orion Smoke Eater Filter (OSEF) is being developed as a stand-alone filter that will quickly remove particulate and gaseous combustion products from the spacecraft environment following a fire event. These filter material is included in the Saffire-IV-VI experiments with an increased fidelity system planned for the Saffire-VII and VIII experiments. As other missions become better defined, the methods for post-fire cleanup, including an OSEF-like filter, will be re-evaluated. Additional tasks could be added as necessary to develop appropriate technologies.

G. Fire Suppression

Similar to the OSEF and Contingency Air Monitor, a water spray portable fire extinguisher is being developed for use in Orion. Current plans are to incorporate water spray fire suppression into Saffire-VII and VIII to extinguish the planned Li-ion battery fire. Whether this technology is suitable for use on Gateway/HALO or future exploration mission will depend on multiple factors such as anticipated fire scenarios, compatibility of water spray with avionics and ECLS systems, and crewed and uncrewed mission phases.

H. Lithium-ion Battery Fire Characterization

One of the worst-case fire sources on a spacecraft would be fire caused by a lithium-ion battery. The batteries could be in battery packs used in tools or a laptop. There have been a significant amount of work to prevent battery packs used in tools from progressing into a multiple-cell thermal runaway but commercial-off-the-shelf items like laptop computers are still susceptible. The objective of this work is to quantify the heat release and gaseous combustion products that result from a thermal runaway of lithium-ion batteries, battery packs, and laptop computers. This information can be incorporated into computational models of a spacecraft fire scenario to define the rate of change of the ambient environment including temperature, pressure, particulate, and gaseous products. Simulation of clean-up strategies could then predict the time required to return the atmosphere to a breathable environment.

I. Integrated Testing

In the last several years, Orion engineers have been developing fire response equipment such as the OSEF, Contingency air monitor, water spray fire extinguisher, and contingency breathing mask. A crucial step in this development has been the integrated testing of these components to determine the response when faced with a practical (or worst-case) spacecraft fire scenario. These tests have been invaluable to providing data to characterize their performance and demonstrate their effectiveness in responding to a spacecraft fire. As other exploration systems are developed, the fire response equipment may change depending on the mission objectives. As the hardware changes, additional integrated tests could become necessary to certify the hardware and response strategies. This will be evaluated each time new systems are defined.

As development of exploration missions progresses, we will need to review, update, and revise many aspects of this roadmap. It needs to evolve as the hardware and operational scenarios are developed and as we continue to learn more regarding spacecraft fire safety on long-term exploration missions and increase our capability to predict and test fire scenarios.

IV. Discussion

The research to date, combined with technology advances and improvement in our models of spacecraft fires, have substantially improved our understanding of the spacecraft fire risk and our ability to mitigate that risk on future missions. Additional work remains, particularly with respect to the challenges associated with partial gravity habitation. The Spacecraft Fire Safety Roadmap has identified the priority research areas to guide the next steps in research.

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