National Aeronautics and
Space Administration

HLS-PAP-026
BASELINE RELEASE
RELEASE DATE: JANUARY 7, 2022

CONSIDERATIONS FOR FIRE IN LUNAR GRAVITY

Publicly Available: Release to Public Websites Requires Approval of Chief, Office of Primary Responsibility, and approval via the Scientific and Technical Information (STI) process, if applicable

Considerations for Fire in Lunar Gravity

Emily Hacopian

NASA Johnson Space Center

Amir Sahaf

NASA Johnson Space Center

Mike Pedley

NASA Johnson Space Center

Gary A. Ruff

NASA Glenn Research Center

David Urban

NASA Glenn Research Center

Susana Harper

NASA White Sands Test Facility

October 2021

1.0 INTRODUCTION

The Apollo I fire tragically revealed the impossibility of eliminating all ignition sources from spacecraft designs. Aside from brief pre-EVA activities, NASA's Space Shuttle and International Space Station vehicles have operated at near sea level conditions. Most of our materials flammability knowledge and data is a result of testing performed for that atmosphere. Materials used for Shuttle, Orion, Commercial Crew, and ISS Airlock are therefore only tested and rated to 30% oxygen by volume at 10.2 psi. To minimize the pre-breathe time on the lunar surface, the exploration atmosphere was chosen for Human Landing System, or HLS, missions. The proposed HLS elevated oxygen environment will lead to an increased flammability of materials. This paper will define materials of concern for the proposed HLS environment. To further complicate the matter, recent studies have highlighted the scarcity of understanding that exists regarding the flammability of materials in lunar gravity. Theory and a few experiments chronicled in this paper suggest that the flammability of materials increases in the lunar gravitational field when compared to normal gravity, i.e., a flame will propagate at oxygen concentrations lower than on Earth. This effect would be exacerbated by the elevated oxygen environment and the use of materials that may already be near their flammability limit. Finally, considerations for the design and analysis of fire detection and suppression hardware in a lunar gravity environment will also be discussed.

2.0 MATERIALS SELECTION IN ELEVATED OXYGEN ENVIRONMENTS

NASA relies on the materials flammability requirements defined in NASA-STD-6001 Flammability, Odor, Offgassing and Compatibility Requirements and Test Procedures for the selection of materials used in habitable environments of spacecraft [1]. The upward flame propagation test (NASA-STD-6001 Test 1) of this standard articulates test procedures to evaluate whether a material is described as nonflammable, or self-extinguishing, when exposed to an engineered ignition source under its worst-case use configuration. The worse-case use configuration includes the combination of the total pressure, oxygen concentration, temperature, and material thickness that will result in the highest probability of ignition and propagation. Oxygen concentration determinations are calculated by volume and include the cabin operation setpoint along with sensor errors as well as control bands to ensure adequate margin is integrated into certification testing. The flammability of materials is affected by increases in both oxygen concentration and pressure, with oxygen concentration being the more dominant driver [2]. A testing margin that is not large enough would result in a more severe operational cabin atmosphere during the mission than was tested. Materials that fail the test under the standard defined criteria must undergo further scrutiny through a materials usage agreement or operational controls, so that they are nonflammable or nonpropagating in their use configuration.

Test data from previous NASA programs and projects is available in the Materials and Processes Technical Information System, or MAPTIS. However, very little materials flammability data exists above 30% oxygen by volume at any pressure. In the context of this paper, all oxygen concentration percentages are defined by volume. Since programs drive testing need, the test data available is limited to cabin environments in which NASA has recently operated. A comprehensive data set exists for materials in the 30% oxygen at 10.2 psia atmosphere used for the Space Shuttle Program, the International Space Station (ISS) Airlock, and the Orion Program. NASA also has extensive experience working at 24.1% oxygen at 14.7 psia for ISS. Flammability tests from both atmospheres are plentiful within MAPTIS.

For a proposed lunar lander environment of 34-37 percent oxygen, a main challenge would be the availability of materials flammability test data. Limited available data are from much higher oxygen concentrations used in the Apollo (100% oxygen) and Skylab (70% oxygen) programs. In a study by Hirsch *et al.*, a series of tests were conducted on select materials for NASA's Constellation program to determine self-extinguishment limits [3]. Data gathered from these tests include values of Upward Limiting Oxygen Indices

(ULOI) and Maximum Oxygen Concentrations (MOC) that help define when Self-Extinguishment will occur per NASA-STD-6001 Test 1 requirements for a variety of materials (plastics, fabrics, composites and foams) at 10.2 psia total pressure. In this test series various materials were identified to pass NASA-STD-6001 Test 1 flammability requirements at >37% Oxygen in all categories tested; including rigid plastics, fabrics, composite laminates, and foams. This demonstrated that though more limited, that flammability resistant materials could be identified in this higher oxygen concentration range.

The existing extensive test data for other environments would not be applicable to the specific lunar lander environment since there is no accurate method to extrapolate flammability data from lower oxygen concentration conditions to those that are higher. Harper *et al.* conducted a study of flammability data at different partial pressures and oxygen concentrations which concluded that flammability characteristics show a strong dependence on oxygen concentration [2]. At pressures above 6 psia, pressure impacts flammability, though to a lesser degree than seen for oxygen concentration. Below 6 psia pressure impacts were observed to become highly influential. A subset of materials, typically highly halogenated or aramid preferred flammability materials, demonstrated a stronger dependence on pressure increases. Preferred flammability materials are those exhibiting high MOC thresholds. Hirsch *et al.* observed similar variations in material flammability and pressure dependence. Hirsch's team found that the dependence of the MOC on pressure tends to be lower for materials with lower MOC, but generally increases as the MOC increases [4]. This indicates that preferred flammability materials are likely to be more sensitive to pressure variations in the HLS higher oxygen concentration vehicle conditions. Findings indicate that lower concentration/higher pressure data cannot be conservatively applied to higher oxygen concentration/lower pressure environments despite equivalent partial pressures of oxygen [2]. Oxygen concentrations while pressurizing the cabin for operations such as docking should also be considered. Hirsch *et al.* explored the flammability of materials and the oxygen concentration limit for a spacecraft cabin while pressurizing from 10.2 psia to 14.7 psia [4]. Therefore, to gain an accurate measure of flammability, a great deal of additional flammability testing would be required for concentrations above 30 percent oxygen.

Flammability test data for materials above 30% oxygen is scarce at any pressure. A highly curated subset of materials was tested by the Human Landing System Program as a risk reduction effort. Twenty-nine materials were tested using the Maximum Oxygen Concentration (MOC) NASA-STD-6001 Test 1 upward flame test and 20 were found to pass in 36% oxygen at 8.2 psia. Materials were selected that had a high chance of passing and the pass/fail percentage is not representative of all materials used in spacecraft. The reality will be much lower. This data is currently available within the MAPTIS database.

2.1 Environments with 70% Oxygen and Above

Certification of materials for flammability at high oxygen concentrations can prove challenging, nevertheless NASA has successfully flown crewed spacecraft with atmospheres containing 100% oxygen (Apollo) and 70% oxygen (Skylab) both at 5 psia. However, the available materials for such high concentrations are very restricted (only 1-2 percent of non-metal materials are nonflammable in 70% oxygen at 5.0 psia). The following are a few examples showing challenges facing NASA programs with certification of materials for environments with 70% oxygen and above, and the compromises that had to be made with the limited number of passing materials.

Crew clothing on Skylab was fabricated from a fire-retardant-treated polybenzimidazole (PBI). The only choices in nonflammable crew clothing for this environment would be PBI, Beta Cloth (a Teflon-coated glass fabric used extensively in the Apollo and Skylab programs, but not for clothing), and Durette fabric, which would be an uncomfortably heavy material for clothing.

In another example, stowage locker cushions for Apollo were custom fabricated from a complex and very heavy mixture of silicone rubber and glass beads. A fluorocarbon foam was used for Skylab, but it swelled when pressure was reduced from ambient to 5 psia which made removal of stowed hardware very difficult.

In some cases, alternative options must be considered when operating at such high oxygen environments. Anodized aluminum would be preferred over paint for the surface of the inner walls, although paint may still be acceptable if the aluminum is at least 10 mil thick. Organic matrix composite structures would probably be replaced by aluminum structures and only heavily fluorinated and, as such, more expensive polymeric materials could potentially be acceptable.

Although there is a very limited number of nonflammable materials in higher O_2 environments, it is worth noting that evaluation of materials for 70% and above oxygen environments has concluded that there are only a few applications for which no commercially available materials existed and the increased cost of using alternative materials (sometimes 5 to 10 times higher) was not a major cost driver in terms of the overall cost of these programs. The same assumption may be held today, although one exception would be in the area of commonly used off-the-shelf items such as cameras, multimeters, personal computers, and tablets. Replacement of these items with customized nonflammable hardware could drastically impact the overall program costs.

2.2 Challenging Material Categories in the HLS Environment

A closer look at the available flammability data suggests that even in the 34-37% oxygen range, there are some material categories that are going to be more problematic to certify and may require consideration of nonflammable alternatives or mitigation strategies. These material categories are discussed in the following paragraphs:

Composites: Flammability of composites is mixed and very variable depending on the type of composite materials. Of five graphite-epoxy composites tested by WSTF for the Constellation program, two failed to meet flammability requirements in 30% oxygen, three met requirements at oxygen concentrations above 50% and one graphite/bismaleimide composite met requirements in 100% oxygen (all at 10.2 psi) [3]. As many composites will struggle to meet flammability requirements in 36 percent oxygen, they may need a protective layer such as an aluminum facing.

Commercial Off-The-Shelf (COTS) Hardware: Many COTS hardware has outer cases that are made of polycarbonate or polycarbonate/ABS blends and would not be acceptable for 34-37% oxygen. Therefore, they should either have a metallic case or wrapped in aluminum tape. Use of a metallic case might interfere with wireless communications and as discussed earlier, replacing commonly used items as cameras and personal computers by customized nonflammable hardware would be expensive. Testing would also be needed to verify that the aluminum tape coating provides a nonflammable outer layer for certification. Many other loose COTS items that are stowed away in a nonflammable container when not in use can be acceptable as the crew can control them for flammability. Items like these will require operational controls as well as a materials usage agreement.

Polycarbonates: Windows, light covers and other application where transparency is required are usually made of polycarbonates most of which will likely fail to meet requirements in 34-37 percent oxygen. There are not many good alternatives as other clear polymers are even more flammable and glass-based materials are heavy and fragile.

Radiation Shielding Materials: Polymers that are suitable for use in radiation protection, are mostly going to be flammable at 34-37% oxygen. Common solutions such as wrapping the polymer in aluminum tape or enclosing it in a Nomex bag might not be sufficient and a custom design with possibly thicker aluminum protection layer is necessary. Another candidate for radiation shielding is water (fine for flammability but with containment/stability issues).

Fabrics: Natural Nomex is a very common fabric extensively used by NASA as a fire barrier for protecting flammable materials in stowage containers and only marginally passes in 30% oxygen at 10.2 psia [3] and will probably be unacceptable for 34-37% oxygen. One color of fire retardant treated Nomex Synergy Pro has been tested and passed at 36% oxygen in 8.2 psia. Nomex could be replaced by Beta cloth or PBI for storage bags.

Clothing: All commercial off-the-shelf clothing that NASA has tested has been highly flammable. Beta cloth and Polybenzimidazole PBI are good candidates for possibly passing flammability requirements. Ortho fabric is another candidate to be considered and tested. With confirmation from proper flammability testing, limited use of cotton T-shirts and flammable underclothing may be acceptable beneath nonflammable outer layers. Lunar missions will involve a much longer return to safety than the ISS if an accident were to occur and treatment options may be limited during the mission.

Foams: Polyethelene foams (such as Plastazote) and Polyurethane foams will be flammable. Melamine and Polyimide foams pass at 30% oxygen but will probably be flammable at the HLS environment. Zotek [3] foams have a good chance of passing at 34-37%. Usage of flammable foam is also possible as long as the foam is not exposed and covered with a nonflammable fabric, or it is inside containers such as cargo bags.

An important consideration to point out is the flammability of human hair. The control of a crewmember's hair is a sensitive topic, as one's hairstyle is such a significant part of their identity. A 2009 study analyzed flame spread rates across human hair in varied spacecraft cabin environments [5]. Oxygen concentration had the greatest effect on flame spread rate over any of the other variables. Concurrent flame spread rates increased by an order of magnitude from 21% O_2 to 30%O_2. This raises great concerns for cabins designed to operate at elevated oxygen concentrations. The flame spread rates seen in these experiments would equate to serious injury to a crewmember's head in seconds before the flames could be extinguished. Finding acceptable mitigation strategies is suggested to prevent events like these.

2.3 Historically Acceptable Items for Flammability

Despite all the challenges mentioned, there are some items NASA has used in past programs such as Shuttle and ISS that would be potentially easier to certify for the 34-37 percent oxygen environment. That said, any material is acceptable for flight at the designed environment only after establishing an appropriate basis of material compliance and certification. Aluminum pressure shells, even when painted with a primer (with or without an additional topcoat), are mostly fine for flammability at oxygen concentrations well beyond 37 percent. Wire and cable runs do not have much potential to cause a problem (up to 40%), because standard aerospace practice is to use Teflon or Teflon-Polyimide hybrids for wire insulation. Accepting adhesives and sealant materials for flammability should be easier because they are always sandwiched between other surfaces with very little material exposed at the edges. Hook-and-loop fasteners such as Velcro can also be certified even if flammable, as long as they are used on metallic or painted metal surfaces (with dimensional and separation limitations).

Another group of items that will not pose much challenge for certification are metallic boxes. Metallic boxes with no forced air convection are likely to contain any fire from internal materials. Metallic boxes with forced air convection may be acceptable but require testing. Composite boxes with no forced air convection may also be acceptable, provided that the composite selected meets flammability requirements. Adequate testing is needed to validate barrier protection in the lander cabin atmosphere.

3.0 EFFECTS OF GRAVITY ON FLAMMABILITY

The proposed environment for HLS poses a challenge by increasing flammability of materials due to the elevated oxygen concentration, but a series of studies also implies that the lunar gravity on the surface of the moon will also play a role in the flammability limits of materials. Theory suggests that gravitational accelerations correspond to the environment's buoyant velocity. As the gravitational acceleration increases, so does the velocity of the buoyant flow. A flame can be strengthened by a reduced buoyant velocity because of a reduction in heat loss by convective heat transfer. The reduced buoyant velocity will decrease the oxygen flux to the flame but at elevated oxygen, there still could be enough to sustain the flame. The competition of these reactions leads to the complex behavior of flame spread and flammability of materials with respect to gravitational acceleration. For example, in microgravity, the buoyant flow is so low that if a fire were to occur, shutting off the forced convection system will allow the flame to diminish until it ultimately goes out on its own. In the presence of a gravitational field, a buoyant velocity, or natural convection, is introduced and removing forced convection may not be effective to extinguish the flame.

A 1988 study by Olson *et al*. aimed to understand flame spread behavior and extinction limits in various opposed-flow, or convective, environments [6]. Olson and her team focused on a quiescent atmosphere in microgravity, forced convection in microgravity, and natural convection in normal gravity and observed flame spread characteristics in each. These experiments were conducted using thin cellulose fuel and a centrifuge rig in NASA Glenn Research Center's Zero Gravity Facility (ZGF) droptower. Flame spread behavior was found to depend heavily on the magnitude of the relative velocity between the atmosphere and the flame itself. In fact, in microgravity the most flammable flow condition observed occurs at relative velocities from 6 to 10cm/s for these thin cellulose fuels. This range corresponds to an environment with a gentle flow of air movement, which is most typical in spacecraft cabins. Olson *et al*. also performed another series of tests in microgravity onboard the International Space Station [7]. PMMA rods were ignited using a hot wire in oxygen concentrations ranging from 13.6% to 22.2%. This study concluded that the time it takes to ignite a material decreases as oxygen concentration increases. When designing for cabins with elevated oxygen concentrations, it is important to keep in mind that ignition of materials may occur much sooner than in other vehicle environments.

Sacksteder *et al*. performed a set of experiments to investigate the downward, opposed-flow flame spreading behavior present in partial gravity [8]. Tests were conducted aboard aircraft flying parabolic trajectories to simulate gravitational accelerations from 0.05g to 0.6g, including the lunar and martian levels. A semi-autonomous apparatus was engineered to support resistance-heated wire ignition tests on thin cellulosic tissues (Kimwipes). The apparatus was capable of oxygen concentrations of 13-21% by volume. Flame visualizations through a Schlieren system concluded that the samples were able to self-extinguish within shorter distances in 1g than what was seen in partial gravity. Additionally, the oxygen concentration by which samples were able to self-extinguish was lower in partial gravity than in 1g. However, aircraft gravitational simulation testing does have some drawbacks. One major limitation is the g-jitter, or perturbations and variations in acceleration. These perturbations are generally lower at lower accelerations ranging from 0.02g to 0.04g, with durations ranging from eight seconds at lower accelerations to 50 seconds at the higher end, or 0.6g. At the lunar gravitational level, this g-jitter could cause enough error to change the outcome of the experiments.

In 2011, Ferkul *et al*. evaluated maximum oxygen concentration (MOC) that materials will self-extinguish for micro-gravity, lunar gravity, and normal gravity [9]. Mylar, Ultem, and Nomex were used as solid fuels for tests to determine the MOC at which the material would self-extinguish. The objective of the test program was to understand the margins of safety for materials tested in 1g that will later be used in other gravitational accelerations. A benefit of the MOC approach is the ability to quantify the flammability limits of a material, instead of the less informative pass/fail test at a single atmosphere. The experiments utilized a centrifuge rig that was able to simulate various gravitational accelerations throughout the duration of a fall in a drop tower. One of the constraints of this study is the short time in which self-extinguishment is needed to occur. The total length of time for each drop is about 5.18 seconds, meaning the flame must extinguish within that time for the material to pass in the given environment. This made comparison with 1g tests more difficult, as the time duration limit was not imposed on that set of tests. The authors state that comparisons between the tests should be treated as conservative estimates in the context of these experiments. Results of these tests concluded that the limiting oxygen level at lunar gravity was up to 5.75% lower than normal gravity. For microgravity, this difference was up to 4.1% O2 less than the normal gravity limits. This trend of lunar gravity and micro-gravity flammability limits being lower than those of normal gravity suggests that screening tests performed in 1g may not be the most severe case. Though data acquisition techniques have limitations, there is concern that materials screened in 1g for flammability may actually be flammable in other gravitational accelerations.

Flammability limits of materials in microgravity were also studied by Osorio *et al*. in a series of parabolic aircraft flights [10]. Osorio and his colleagues also sought to understand the impact of external radiation or heating on the material flammability. ETFE insulated wires were chosen due to the inherent risk that wiring may pose for ignition in space flight. A propagation/no propagation definition was used to describe the flame behavior in oxygen concentrations ranging from 20% to 32% in both 1g and micro-gravity. As expected, the addition of a radiant heat flux decreased the oxygen concentration needed to support propagation in 1g and micro-gravity. The magnitude of the external radiant flux needed to alter flame propagation behavior decreases as the oxygen concentration increases. Finally, once more, a reduction in the limiting oxygen index is seen in micro-gravity experiments versus normal gravity. Recognizing the limitations in tests simulating various gravitational accelerations, data still suggests an increase in flammability of materials (decrease in the oxygen flammability limit) with gravitational accelerations less than that of earth.

4.0 CONSIDERATIONS FOR FIRE DETECTION

Fire survivability depends on the detection of and response to a fire before it has produced an unacceptable environment in the vehicle. The detection time is the result of interplay between the fire burning and growth rates; the vehicle size; the detection system design; the transport time to the detector; and the rate at which the life support system filters the atmosphere, potentially removing the detected species or particles. In micro-gravity, the detection time is controlled by the level of mixing in the vehicle [11]. In lunar gravity, the plume from a fire will rise although at a slower velocity than a normal-g plume. Given the large differences in critical vehicle parameters (volume, mixing rate, filtration rate, and gravity level), the detection approach that works for a large vehicle in micro-gravity (*e.g.* the ISS) may not be the best choice for a smaller crew capsule or for a lander or habitat on the lunar surface.

Fire detection begins with the production of smoke aerosol and combustion gases from a pyrolysis event. The rate of production of smoke and combustion products depends on the fire growth rate. At this time, we don't have data to guide predictions of fire growth in lunar gravity. It is expected that it will be less that the t^2 growth typically seen in terrestrial fires but greater than that seen in micro-gravity, but no data or predictions are currently available. In lunar gravity, a hot plume will rise, albeit at a slower velocity than in normal gravity. On Earth, the rising plume concentrates smoke near the ceiling and fire detectors placed on the ceiling encounter the largest concentrations of smoke as the fire progresses. In the confined volume of a lander or habitat, the smoke plume will rise but it will also interact with the Environmental Control and Life Support System (ECLSS) ventilation flow that could prevent a smoke layer from concentrating near the ceiling.

In micro-gravity, the best place for smoke detectors is in front of the filters on the ECLSS air return ducts. Because of the potential for lunar dust being in the habitable volume, positioning smoke detectors at the air returns could make them more susceptible to false alarms during the removal of lunar dust from the cabin. The location of the air returns would also play a role in the ability to detect a fire. If they are near the floor to better remove the settling lunar dust, they cannot take advantage of the rising smoke plume. The competing effects of smoke production rate, a rising plume, and the direction of the ECLSS ventilation will all play a role in the selection and location of a fire (smoke) detector in a lunar lander or habitat.

These competing effects for a spacecraft in micro-gravity are discussed by Urban *et al*. [12] that examines the impact of vehicle size and environmental control and life support system parameters on the detectability of fires in comparison to the hazard they present. The presence of lunar gravity and the impact of the rising plume on fire detection will contribute to the analysis described in this paper. A similar analysis should be performed for each vehicle and habitat using the specific volume, ECLSS system ventilation rates, and smoke production rates from a most likely fire.

Smoke detection systems are expected to be very similar to those used in orbiting spacecraft. Although results have shown that gravity has a strong influence on the particle size distribution, these differences were not seen to be large compared to the variation caused by differences in the overheated material [13, 14]. Detection of fire events via chemical species has received significant study [15] however aerosol particulate remains the strongest universal fire indicator.

5.0 CONSIDERATIONS FOR FIRE SUPPRESSION

The major factors that determine the selection of a fire suppression agent for a lunar spacecraft or habitat are the types of materials for the worst-case fire, the atmosphere of the habitable volume (%O_2 by volume and pressure), the details of the environmental control and life support system, and the effect of buoyancy. A lunar spacecraft will also experience both lunar and micro-gravitational fields. Fire suppression in lunar gravity may be more like fire suppression on Earth versus micro-gravity. Heated gas will rise by natural convection and draw fire suppressant into the fire which will aid in the suppression process, just as it does in normal gravity. The lunar buoyant velocity is lower than on Earth – approximately 0.4 that of the buoyant velocity on Earth based on scaling analyses of the equations for the buoyant driving force. Turning off the ECLSS ventilation flow will not be an effective suppression strategy in lunar gravity because natural convection will continue to draw oxygen into the flame. However, turning off the ECLSS flow upon receiving a fire alarm may still be a useful step in the response procedure so as not to exacerbate the fire growth rate.

Table 1. Fire suppression methods and requirements on previous space vehicles.

Space Habitat	Suppression Method	Requirements/Capabilities
Mercury	Water from the food rehydration gun; Depressurize habitat	No specific operational requirements
Gemini	Water from the food rehydration gun; Depressurize habitat	No specific operational requirements
Apollo	Portable aqueous gel extinguishers; Water from the food rehydration gun; Depressurize habitat	Extinguishers capable of expelling 0.06 m^3 of foam in 30 seconds
Skylab	Portable aqueous gel extinguishers; Depressurize habitat	Extinguishers capable of expelling 0.06 m^3 of foam in 30 seconds
Mir	Portable aqueous gel extinguishers	Unknown
Shuttle/Spacelab	Distributed rack/subfloor mounted Halon bottles with distribution lines; Portable Halon extinguishers; Depressurize habitat	Total flooding with a six percent mean concentration of Halon in less than 10 seconds and a 10 second hold time
S. S. Freedom	Centralized CO_2 distribution system	Suppressant deliver rate of 1.0 lbm/s at normal pressure
	Portable CO_2 extinguishers	Oxygen dilution to 10.5 percent by volume in 33 percent of element's racks
ISS	Portable CO_2 extinguishers; fine water mist extinguishers (US modules)	Oxygen dilution to 10.5 percent by volume (CO2); Extinguishment of test fires (FWM)
	Aqueous foam fire extinguishers (Russian modules)	Unknown
Orion	Water spray fire extinguishers	Extinguishment of test fires (FWM)

Obviously, one of the first considerations when selecting a fire suppression system is to consider what has been used in previous spacecraft. Table 1 below summarizes the fire suppression agents used on previous and existing spacecraft. Excluding Halon which is no longer used, water, aqueous gel or foam, or gaseous CO_2 have generally been used in spacecraft. The selection of one of these fire suppression agents for Lunar applications will depend on the worst-case fire scenario as determined by the results of the material flammability testing of materials used in the habitable volume.

The atmosphere in the habitable volume of a lander or habitat (ambient pressure and oxygen mole fraction) will play a large role in the selection of a fire suppression agent. If the habitable volume is at reduced pressure and elevated oxygen, such as 8.2 psia and 34% O_2, several of the agents used on previous spacecraft become impractical. At elevated oxygen levels and in the confined environment of a spacecraft, using a CO_2 extinguisher will put the crew at risk of CO_2 poisoning because of the high concentrations required to reduce the oxygen concentration sufficiently to extinguish the fire. A portable breathing apparatus in which the crew breaths oxygen is also problematic because exhalations released back into the cabin contain high levels of oxygen which will exacerbate the fire suppression process in a confined environment.

On Earth, oxygen enriched environments generally use water spray or dry chemical suppression agents. Dry chemical agents have not been used in spacecraft either in micro- or lunar gravity and could pose very difficult problems for post-fire cleanup. Lastly, any fire suppression agent must be compatible with the rest of the ECLSS system and not foul the trace contaminate control system.

The considerations discussed above provide some guidance on the selection of fire suppression agent for a lunar vehicle or habitat. In any event, the fire suppression agent and extinguisher system should be demonstrated to extinguish the worst-case fire anticipated in the crewed volume based on a material flammability analysis of its contents.

6.0 CONCLUSIONS

A limited data set exists for the flammability of materials above 30% oxygen. Previous findings indicate that lower concentration/higher pressure data cannot be conservatively applied to higher oxygen concentration/lower pressure environments despite equivalent partial pressures of oxygen. Therefore, to gain an accurate measure of flammability, a great deal of additional flammability testing would be required for concentrations above 30 percent oxygen. Additionally, preferred flammability materials are likely to be more sensitive to pressure variations in new HLS higher oxygen concentration environments than materials previously used in lower oxygen concentration vehicle conditions. From what is available, materials of concern for cabins with elevated oxygen concentrations include fabrics, COTS items, radiation shielding materials, foams, and certainly human hair. The list of items that will not pose as much of a concern is limited mostly to metals and metal electronics boxes with no forced air. Cabins with elevated oxygen limits are feasible from a materials flammability standpoint but will be quite restrictive. The increased flammability of materials in this atmosphere could be further increased in lunar gravity.

Creating high fidelity test methods for flammability in lunar gravity is incredibly difficult to achieve on Earth. Though the theory predicts the flammability of materials to be the highest in partial gravitational fields, obtaining data to validate hypothesis have proven to be challenging. Each of the methods discussed above have their shortcomings. A centrifuge rig in a drop tower limits test times to just a few seconds, which makes comparison with 1g tests complicated. Data from these tests have shown a lowering of the flammability threshold of materials in lunar gravity. Parabolic aircraft test results have shown similar trends as the drop tower data but are prone to the effects of g-jitter. These flight-induced perturbations in the lunar gravitational field regime are high enough in amplitude and occur for long enough time periods to impact the flammability limits of the experiments. The data from those studies shows the same trend of lower flammability thresholds in lunar gravity compared to normal gravity. Experiments performed on the ISS require a large amount of crew time. Modeling can also be used to attempt to understand this phenomenon, but there is limited data for comparison. Conducting a flammability experiment on a rotating sub-orbital capsule could improve the fidelity of the measurement and tests are planned to be conducted in 2023. Of course, the higher fidelity options would be testing performed on board a rotating capsule or on the surface of the moon itself. These longer term options using rotating spacecraft and tests on the lunar surface would require a great amount of funding and time, but would contribute toward a deeper understanding of flammability in lunar gravity and sustaining a long-term human presence on the moon.

Finally, careful analysis is required to ensure robust fire detection and suppression systems for the lunar surface. The detection time is the result of interplay between the fire burning and growth rates; the vehicle size; the detection system design; the transport time to the detector; and the rate at which the life support system filters the atmosphere, potentially removing the detected species or particles. In lunar gravity, the plume from a fire will rise at a slower velocity than a normal-g plume. Given the large differences in critical vehicle parameters (volume, mixing rate, filtration rate, and gravity level), the detection approach that works for a large vehicle in micro-gravity (e.g. the ISS) may not be the best choice for a smaller crew capsule or for a lander or habitat on the lunar surface. In the confined volume of a lander or habitat, the smoke plume will rise but it will also interact with the Environmental Control and Life Support System (ECLSS) ventilation flow that could prevent a smoke layer from concentrating near the ceiling. The location of the air returns would also play a role in the ability to detect a fire. If they are near the floor to better remove the settling lunar dust, they cannot take advantage of the rising smoke plume. An analysis of the detectability of fires compared to the hazards they present is needed in lunar gravity using specific volumes, ECLSS system ventilation rates, and smoke production rates from a most likely fire. The cabin atmosphere of the habitable volume of a lander or habitat (ambient pressure and oxygen mole fraction) will play a large role in the selection of a fire suppression agent. If the habitable volume is at reduced pressure and elevated oxygen, such as 8.2 psia and 34% O_2, several of the agents used on previous spacecraft become impractical. Fire suppression agents must be effective at putting out the fire without causing harm to the crew or ECLSS system. Ultimately, the proof of a fire detection and suppression system on a lander or habitat should be evaluated on a worst-case fire as determined by a flammability assessment of the contents of the habitable volume.

7.0 REFERENCES

[1] NASA STD 6001B, *Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures "Test 1",* NASA, August 2011.

[2] S. A. Harper, A. Juarez, H. Perez III, D. B. Hirsch and H. D. Beeson, "Oxygen Partial Pressure and Oxygen Concentration Flammability: Can They Be Correlated?," *Journal of ASTM International,* pp. 1-15, 2016.

[3] D. B. Hirsch, J. H. Williams, S. A. Harper, H. Beeson and M. D. Pedley, "Oxygen Concentration Flammability Thresholds of Selected Aerospace Materials Considered for the Constellation Program," 2008.

[4] D. B. Hirsch, J. H. Williams, J. P. Haas, H. D. Beeson, G. A. Ruff and M. D. Pedley, "Pressure Effects on the Self-Extinguishment Limits of Aerospace Materials," *SAE International,* 2009.

[5] S. Olson, D. Griffin, D. Urban, G. Ruff and E. Smith, "Flammability of Human Hair in Exploration Atmospheres," *SAE International,* 2009.

[6] S. L. Olson, P. V. Ferkul and J. S. T'ien, "Near-Limit Flame Spread Over a Thin Solid Fuel in Microgravity," in *Twenty-Fifth Symposium (International) on Combustion/The Combustion Institute*, 1988.

[7] S. L. Olson and P. V. Ferkul, "Microgravity Flammability Boundary for PMMA Rods in Axial Stagnation Flow: Experimental Results and Energy Balance Analyses," *Combustion and Flame,* vol. 180, pp. 217-229, 2017.

[8] K. K. Sackdester and J. S. T'ien, "Buoyant Downward Diffusion Flame Spread and Extinction in Partial-Gravity Accelerations," in *Twenty-Fifth Symposium (International) on Combustion/The Combustion Institute*, 1994.

[9] P. V. Ferkul and S. L. Olson, "Zero-Gravity Centrifuge Used for the Evaluation of Material Flammability in Lunar Gravity," *Journal of Thermophysics and Heat Transfer,* vol. 25, no. 3, pp. 457-461, July-September 2011.

[10] A. F. Osorio, K. Mizutani, C. Fernandez-Pello and O. Fujita, "Microgravity Flammaiblity Limits of ETFE Insulated Wires Exposed to External Radiation," *Proceedings of the Combustion Institute,* vol. 35, pp. 2683-2689, 2014.

[11] J. E. Brooker, D. Urban and G. Ruff, ""ISS Destiny Laboratory Smoke Detection Model" Paper Number 07ICES-113," in *2007 International Conference on Environmental Systems*, Chicago, July 2007.

[12] D. Urban, D. Dietrich, J. E. Brooker, M. Meyer and G. A. Ruff, ""Fire Detection Tradeoffs as a Function of Vehicle Parameters" Paper Number ICES-2016-318," in *46th International Conference on Environment Systems*, Vienna, Austria, July 10-14, 2016.

[13] M. E. Meyer, D. L. Urban, G. W. Mulholland, V. Bryg, Z. G. Yuan, G. A. Ruff, T. Cleary and J. Yang, "Evaluation of Spacecraft Smoke Detector Performance in the Low-Gravity Environment," *Fire Safety Journal,* vol. 98, pp. 74-81, June 2018.

[14] G. W. Mulholland, M. E. Meyer, D. L. Urban, G. A. Ruff, Z. G. Yuan, V. Bryg, T. Cleary and J. Yang, "Pyrolysis Smoke Generated Under Low-Gravity Conditions," *Aerosol Science and Technology,* vol. 49, no. 5, pp. 310-321, May 2015.

[15] M. E. Meyer, P. Mudgett, S. Hornung, M. McClure, J. S. Pilgrim, V. Bryg, D. Makel, G. A. Ruff and G. Hunter, "Materials Combustion Testing and Combustion Product Sensor Evaluations in FY12," in *43rd International Conference on Environmental Systems*, Vail, CO, July 14-18, 2013.