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Topical: Recommendations for Fire Extinguisher Research for Crewed Missions

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Background

While NASA and commercial partners spend enormous effort designing and building vehicles and habitats with the goal of minimizing if not eliminating fire risk, there will always be a need for fire extinguishing systems. Further, future Lunar and Martian missions anticipate a habitat environment of 34% oxygen by volume, with a total pressure of 8.2 PSIA[1]. At these conditions, materials that are non-flammable become flammable, and flammable materials require lower ignition energy and burn faster with greater temperature and heat release rates than in normal atmosphere. For these reasons, among many others, fire extinguishers enable future low Earth orbit, Lunar, and Martian crewed missions by increasing the safety and resiliency of these missions[2].

Fire extinguishers have several criteria to meet for use in crewed space vehicles. They must be effective for many different fire and fuel scenarios. They must be usable in an open area with easy access to the burning material, as well as in constrained, enclosed, and/or tortuous areas such as behind equipment racks or panels. The extinguishing material must not be toxic to crew or damaging to environmental control systems and must not present onerous post fire clean up. The extinguishers must also put out fires from different fuel sources, from paper to plastic to lithium ion batteries to battling secondary fires around a damaged oxygen generator[1, 3]. Lithium ion batteries pose particular challenges, as they are ubiquitous in electronics, have been found to fail in terrestrial applications, and are a stored energy source which increases heat release and potential damage to the vehicle[4, 5]. Currently, the International Space Station (ISS) uses a mix of fine water mist extinguishers and carbon dioxide extinguishers in the U.S. segment, with water-foam extinguishers in the Russian segment[6].

Taken together, current knowledge of fire extinguisher performance requires further research. Performance in reduced pressure, elevated oxygen atmospheres affects not only the flame dynamics, but the extinguisher dynamics as will be discussed. The same is true of partial gravity situations; reduced buoyancy affects the flame dynamics, but also the extinguisher and extinguishing agent performance. Research into the performance of fire extinguishers in exploration, partial gravity environments will greatly improve future missions by adding margins of safety to crewed missions, particularly Lunar and Martian missions where crews may be far from home and help.

This white paper describes some of the areas for future work and development testing fire extinguishers for use in future space missions. The areas discussed include general considerations of water mist extinguishers and areas of need for future modeling and testing, the current use of scaling in terrestrial fires and the expansion of that concept to Lunar and Martian missions, and the potential for other extinguishing materials for use in crewed vehicles and habitats.

Water Mist and General Extinguisher Performance

Water and water mist extinguishers have been used for decades in terrestrial applications to fight fires. Water is plentiful, inexpensive, non-toxic, has high specific and latent heats to quench flames, displaces oxygen when evaporated in a flame zone, quenches and inhibits heat and fuel transfer by soaking or pooling on a fuel surface. Water mist extinguishers propel small droplets, including fine mist with mean droplet diameter between 20 and 100 μm[7-9]. These extinguishers have received much attention in the literature, as Halon fire extinguishers are generally phased out of use.

Water mist extinguishers mainly extinguish a flame through quenching. As the droplet approaches the flame zone, heat from the flame increases the sensible temperature to the boiling point, then evaporates the droplet, which absorbs more heat. Additional effects, such as displacing oxygen after evaporation and radiative adsorption in addition to conductive and convective effects, are important as well. One set of key criteria, though, are droplet size and velocity. Typically, the goal is to have droplets large enough and with sufficient momentum to penetrate the flame zone without evaporating before entering the flame zone, and with enough momentum not to be overcome by the flame's buoyant plume. If the droplets are too large, or possess too much momentum, the droplets will exit the flame zone without fully evaporating and potentially not removing enough energy from the flame to be effective. In this case, the droplets will then saturate the fuel surface. In some cases, such as wood crib fires or paper fires in an office, this may be a negligible or even beneficial outcome. In other cases, such as a fire over an oil fryer in a restaurant kitchen or onto still-energized electrical components, the outcome could be catastrophic[7].

In a reduced gravity environment, both the temperature field, buoyant effects on the gas, and body force effects on the droplets change compared to those found in normal gravity applications. This means that, while the requirement for "just right" droplet size distribution and momentum is still critical, the actual "just right" conditions change with the gravity level experienced by the vehicle or habitat. These factors are also difficult to model numerically, as most models now used do not account for changes in flame temperature and profile, change in buoyant laminar versus turbulent flow, or kinematics of droplets in non-Earth gravity. In addition to the changes in flame characteristics and behavior in reduced gravity, the atmospheric environment also plays a role. As discussed, future crewed missions to the Moon and Mars anticipate a standard habitable atmosphere of elevated oxygen concentration in low total pressure. Research has shown that reduced atmospheric pressure decreases water mist extinguisher mean droplet diameter as well as the axial droplet velocity[10]. Thus, both the atmospheric and gravitational effects on flames and extinguisher behavior must be investigated.

The change in fire and extinguisher dynamics, and the interaction of these, calls for research into fire and fire extinguisher use in the appropriate environments. These include elevated

oxygen at reduced pressure and partial gravity environments. Experiments in drop towers, sounding rockets, and aircraft can form a basis for this work, but larger scale experiments should also be considered as the body of knowledge in the appropriate environment builds. This research should not only explore the dynamics of fire extinguishment, but practical concerns, such as how large and how capable a fire extinguisher capability should be, and when and how to fight a fire in a space craft or habitat module.

Modeling

Modeling the spray characteristics and interaction between flame and suppressant is an ongoing area of research in terrestrial fire extinguishment, and presents opportunities and challenges in reduced gravity, exploration environments. This work includes the development and use of computational fluid dynamics as well as modeling "packages", such as the Fire Dynamics Simulator (FDS) developed by the National Institute of Standards and Technology (NIST)[11]. This work includes the interactions of flame and extinguishing agent as well and include models of droplet behavior, using statistical distributions of droplet size and velocity to predict flame interaction and extinguishment[12-14]. Other modeling efforts have focused on the water spray dynamics. These efforts attempt to predict the statistical droplet diameter and velocity distributions[15-18]

Future work in modeling calls for many of these same types of studies but performed using the gravitational and environmental conditions of reduced gravity, Lunar, and Martian environments. Changes in flame dynamics and buoyancy, changes in the diameter and velocity distribution due to gravity and atmosphere, and tortuous paths, closed systems, and obstructed flames in vehicle habitats all add complexity and changes to the work necessary in providing fire extinguishment capability to future missions. The authors here recommend the development of numerical models to predict behavior in such conditions, and experiments to validate, test, and provide insight into the real-world dynamics of extinguishing flames in reduced gravity.

Additives to Water Mist and Other Extinguishing Materials

Water mist extinguishers are by no means the only extinguishers available for use on crewed vehicles and habitats. Other extinguishing strategies have received attention in the fire safety community and should be considered for future space vehicle applications. The criteria, as mentioned above, include choosing effective extinguishing media[19], the ability to put out obstructed fires or flames with tortuous paths, extinguish multiple fuel sources, be safe to crew, environmental and other vehicle systems, and to be easy to clean up after a fire event.

Additives to water mist extinguishers are one way to increase the efficacy of the extinguisher. Research in this area includes adding a salt to a water source in water mist extinguishers[20, 21]. This work, among others, found the ions from salt interacted with ions in the flame reaction zone, increasing the effectiveness of water mist. Water-based foam extinguishers are already in

use on the ISS and present another option for extinguisher media[3]. Halon replacement gases have also been studied extensively[22-24]. Other choices include using an inert gas, such as the current carbon dioxide on the ISS[4] or xenon[25]. Finally, inert particles[26] may also be an option, particularly in Lunar or Martian missions with significant gravity. While outside the scope of this white paper, future use of fire blankets and "fire bags" to contain potentially burning material should also be explored. We recommend future studies should explore other extinguishing media, including inert particles, for use in Lunar and Martian spacecraft.

Scaling Fires and Fire Extinguishers

The fire safety community has used the Froude number to scale model fires and extinguishers as test beds for realistic fire scenarios. The Froude number,

$$\frac{u_0^2 T_\infty}{Lg(\Delta T_0)}$$

relates inertial to gravitational forces, where u_0^2 is the plume velocity, T_∞ is the ambient temperature, L is a flame length scale (size of fuel sample, fire diameter, etc.), g is the gravitational accelerations, and ΔT_0 is the difference between the flame and ambient temperature. Assuming temperatures are constant in both the realistic fire and scaled fire, and that the flame zone is turbulent and well mixed, velocity scales as the square root of length. This scaling also requires relaxing the constraint of equal Reynolds Number across the realistic and scaled flame scenarios, allowing the velocity to vary from scale to scale. Applying this scaling leads to mass flux, heat flux, and pressure scaling as powers of the length as well and allows for scaling flames across sizes. Further, assuming the trajectories and diameter characteristics of droplets from a water mist extinguisher or sprinkler are the same across scale, the behavior of droplets in terms of heat removed, evaporation, and other factors to also scale as various powers of the length. This analysis allows for the use of scaled test fire and sprinkler systems up to a factor of 10 to narrow the requirements for fire safety in real world applications, even if scaled fires do not fully model an actual, expected fire scenario[27-32].

This scaling, however, has not been used for modeling or testing fires in space vehicles. The model is not valid across gravitational levels (i.e. Earth vs Lunar) due to differences in temperature between the two gravity levels, non-buoyant flames not becoming turbulent to provide mixing outside the flame zone, changes in flame temperature due to transport, differences in droplet trajectory due to gravitational differences, and many other factors.

Future work, though, provides test beds to explore, develop, and test model fires and extinguisher configurations for future Lunar and Martian missions. This work includes proposals for use in drop towers with rotating platforms to induce partial gravity, parabolic flights on test aircraft, Blue Origin rockets, and future robotic Lunar missions. The authors propose using the existing scaling relationships to develop scale model flames using these test beds, with the Froude number scaling already used for terrestrial, commercial applications. The scaling data

can inform the length and time scale necessary for model experiments in these platforms to mimic realistic fires and fire extinguishment in Lunar or Martian vehicles and habitats. These models can provide insight into potential, full scale fires in Lunar or Martian habitats and methods for fighting those fires. These insights will inform design requirements, criteria, and operational procedures for the crewed vehicles and habitats. These data will be both directly applicable as well as inform future, larger- to full-scale fire and extinguisher testing in partial gravity environments.

Recommendations

The use of fire extinguishers in future space missions is of critical importance, and the performance of the extinguisher must be shown in the relevant gravity and atmospheric environment. The extinguisher must put out a fire, in reduced gravity, at elevated oxygen concentration and reduced total pressure, with a variety of fuel sources including stored energy reactions, and with tortuous path and hidden fires. The authors make the following recommendations for future work in these areas:

- Explore the dynamics of fine water mist extinguishers, determining the appropriate droplet diameter distribution and momentum to transport droplets to a fire, have droplets penetrate to the reaction zone, and minimize post-fire clean up. This work should also address the size of a fire extinguisher and/or extinguishing system, and when and how it should be used. This includes work in reduced gravity facilities such as drop towers, aircraft, sounding rockets, building towards microgravity, Lunar, and (in the future) Martian experiments.
- Build computational modeling expertise and experience, to include the various effects of reduced gravity and enhanced oxygen environment on both flame dynamics as well as droplet dynamics, and the interactions of these phenomena. This work will also inform the sizing and use of a fire extinguisher.
- Explore other fire extinguisher media, including but not limited to additives to water-mist extinguishers, halon-replacement chemicals, inert chemicals, and inert particles, again meeting the criteria to extinguish a flame and minimize post-fire cleanup.
- Pursue current scaling relationships used for demonstration, scaled fires in terrestrial applications to model fire and extinguisher scenarios. This includes testing existing scaling relationships in the relevant environment, pursue other or additional scaling relationships, and exploring potential scaling relationships that allow for modeling fire and extinguisher scenarios across gravity levels. This also includes numerical modeling efforts as well as experimentation.

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