

Fire in Orbit:
Equipping the Commercial Spaceflight Industry for Fighting Fire in Micro-Gravity
(Revised and amended September, 2015)

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List of Terms

CCiCap	Commercial Crew Integrated Capability
ECLSS	Environmental Control and Life Support System
EVA	Extra-Vehicular Activity
FWM	Fine Water Mist
ISS	International Space Station
LEO	Low Earth Orbit
PFE	Portable Fire Extinguisher
UHPFE	Ultra High Pressure Fire Extinguisher
USOS	United States Orbital Segment

Abstract

For several years, Orbital Technologies (ORBITEC) has had keen interest in the development of a portable fire suppression system intended for use in commercial spaceflight applications. With the aid of recent developments in fine water mist (FWM) atomization technologies, and partnerships with the University of Wisconsin – Platteville, a portable fire extinguisher (PFE) prototype has been developed and constructed. The commercial extinguisher is capable of operation in both gravity and microgravity environments regardless of orientation, and eliminates the use of toxic carbon dioxide as a fluid suppressant. Preliminary testing of the PFE prototype has demonstrated promising discharge ranges and rates at various pressures. Testing has also confirmed the prototype’s ability to extinguish stored energy fires, in the form of lithium ion batteries.

Introduction

In the design of new space habitats and vehicles, considerations for the prevention and suppression of fires must be made. As far back as the Mercury and Gemini missions, astronauts had at their disposal various methods by which to extinguish fires (Friedman, 1999). PFE technology used today onboard the ISS is outdated, expensive, and not conducive for investment by the commercial spaceflight industry. Advances in fire suppression technology can be applied to new PFE systems which are effective at eliminating many common microgravity fire threats while being cost effective, lightweight, and portable. ORBITEC stands at a position currently to leverage industry experience towards creating a new PFE system for microgravity environments. In order to move forward, a strong foundation must be established in the history, causes, and current methods used to extinguish fires in space. A first-level prototype was completed in December of 2014.

¹ Special thanks to the Wisconsin Space Grant Consortium (WSGC) who provided the necessary funding for student involvement in this project.

Fire Science Overview

There are three elements required for a combustion reaction to take place: a fuel source, oxidizer, and heat energy. Removal of just one of these three elements will cause a fire to collapse. Most portable fire suppression systems focus on the removal of the oxidizer or heat energy from the combustion system. This is done because removing the fuel source after the advent of a fire is typically not practical. The three components required for combustion are the same both on earth and in space. The behavior of fire in microgravity however, is different compared to earth.

The “teardrop” shape of a candle flame does not occur in orbit. On Earth, the flame’s shape is defined by the effects of gravity: the buoyancy of hot gases and movement of convection currents. Without gravity fire takes a much more spherical shape, as shown in Figure 1. There is no natural convection in microgravity. In the absence of an upward direction for a fire to burn, it burns in all directions. Typically microgravity fires burn slower as well; mainly because flames tend to be weaker without the aid of convection currents. New oxygen is not “swept” into the fire but needs to diffuse into the combustion area, which takes more time to accomplish (Friedman, 1999). Fires in space:

1. Burn at slower rates
2. Burn at lower temperatures, requiring less heat energy
3. Burn at lower oxygen levels, using 2-3% less oxygen compared to earth.

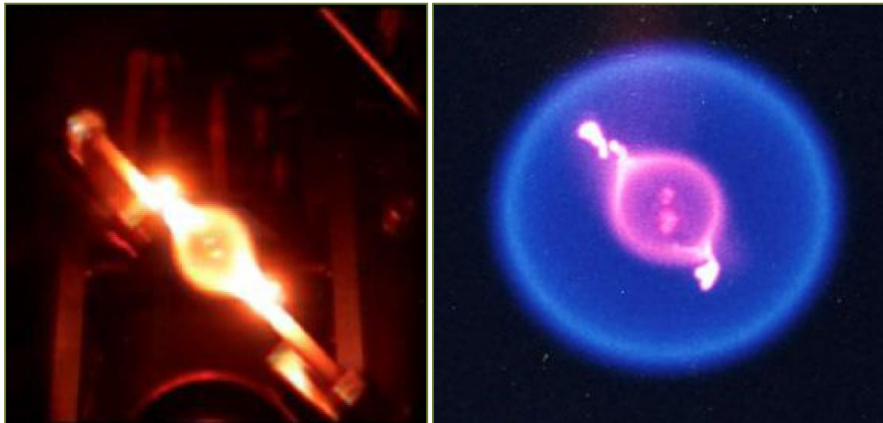


Figure 1: N-Heptane burning in micro-gravity, Credit: NASA.

These factors mentioned, fire in space can be both harder to detect and more persistent. Although we had previously mentioned the absence of natural convection in microgravity, there are other methods of airflow which occur in these environments. Human spaceflight requires ventilation systems to circulate and filter the enclosed atmosphere. These systems can be very effective at moving large volumes of gas and vapors over short periods of time. The ISS — having a pressurized internal volume of 388 cubic meters — could easily circulate smoke and harmful gases through the entire station in less than a half hour period (McKinnie, 1997). Additionally, airflow from the ventilation system has the ability to stoke potential fires, or give direction and speed to fires that already have started to burn.

Historical Overview

Over the course of 30 years from 1967 to 1997 there have been a least seven recorded incidents of fire onboard spacecraft and space stations (Barr, 2010; Sanchez, 2000). Figure 2 gives a

timeline of incidents along with the specific craft involved (red crosses denote loss of life or life threatening situation). Aside from the Apollo 1 fire in 1967 all incidents occurred during actual flight. The frequency of these incidents together with other risk assessment analysis led NASA to predict that over the lifespan of the ISS a minimum of two fires would occur on the station (McKinnie, 1997). With the operating life of the station now expected to extend past 2024, it is likely the probability of fire will increase as the station ages.

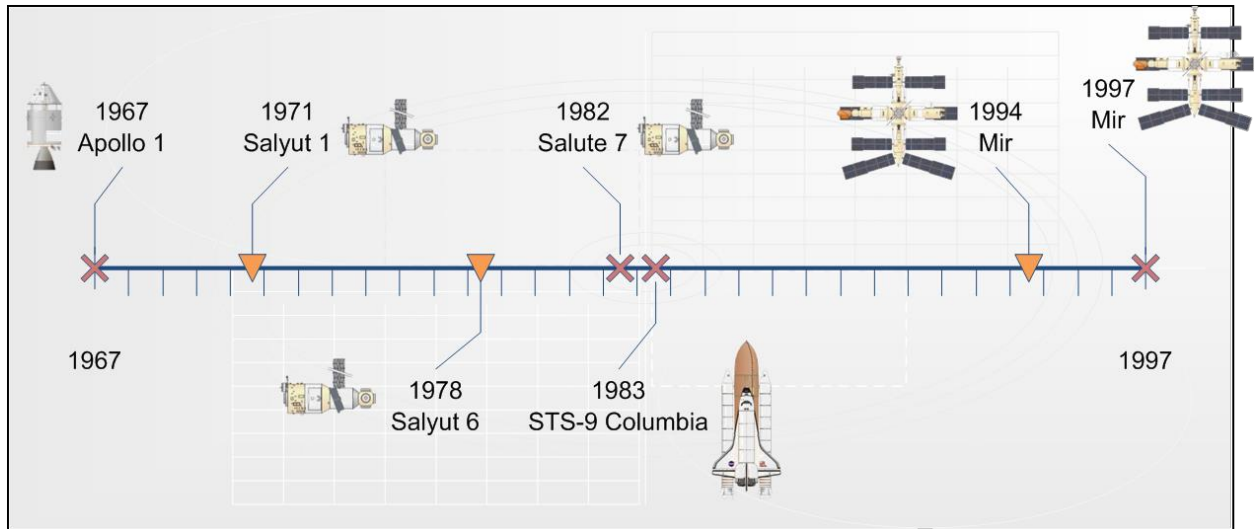


Figure 2: Timeline of fire occurrences. Red crosses denote life threatening situations.

The most serious of the orbital fires occurred on space station Mir. The station caught fire twice both in 1994 and 1997. The '97 event was the most serious, where a failure in one of two oxygen generation systems onboard caused a fire which burned for 15 minutes before finally self-extinguishing (Figure 3). The crew was not able to suppress the reaction because the foaming-agents used in the station's PFEs were designed to blanket and suffocate fire. Because the system which had caught fire was designed to generate oxygen, blanketing the fire to eliminate oxygen was ineffective. The system created oxygen by burning what is commonly called "oxygen candles". Similar candles to those onboard the station are commonly used throughout the commercial airline industry to generate emergency oxygen for passengers.



Figure 3: Fire-damaged panel onboard Mir, Credit: NASA.

Fire Modes in Microgravity

Fire is taken very seriously onboard the ISS. The USOS alone houses thirteen fire extinguishers, and many studies have been done to determine the most likely causes of fire. Besides oxygen candles, various spaceflight applications (including astronaut EVAs) require elevated oxygen as part of the ambient atmosphere, which heightens the risk of fire. There is also growing concern regarding the amount of lithium-ion (Li-ion) batteries currently being used on the ISS in laptops and other electronics. Looking forward it is likely that commercial spaceflight will continue to rely heavily on these batteries. Precedence can be set by the 2013 Boeing 777 electrical fires, which were caused in part from newly integrated lithium-ion batteries. These batteries can also burn in the absence of atmospheric oxygen as well. This property eliminates one possible mode of defense against spacecraft fires, which would include depressurizing the cabin to remove the oxygen.

Liquid chemical fires are possible as well, although less likely to occur in habitable segments of a spacecraft. Hydrazine is a common fuel source for both power and propulsion in the space industry. A hydrazine leak from several of space shuttle Columbia's auxiliary power units caused a fire which could have crippled the craft's hydraulic systems needed for re-entry (Barr, 2010).

Historically through to the present, electrical fires have always been a great concern when regarding human spaceflight. Due to the size and volume constraints placed on Earth-launched vehicles, electrical wiring is typically packed as tight as possible inside a spacecraft. These wires are many times hidden away behind panels where it would be very difficult to visually identify the source of any smoldering or combustion taking place in the wire bundles. It is important to note that reaching the necessary heats for combustion is much easier in microgravity. Overheated motors, bearings, wires and other components will remain hot longer due to a lack of convective heat transfer in microgravity (Friedman, 1999).

Current Systems

The US orbital segment's PFE represents the most modern system currently available for space (Wieland, 1999). It is a compressed CO₂ extinguisher, designed to be discharged completely in the event of a fire over a 60 second period. A diagram of the PFE can be seen in Figure 4. It carries 6 lbs (2.7 kg) of CO₂ with a net weight of 12 lbs (5.35 kg). The discharge pressure is around 850 psi (8.56 MPa). The design intent behind this device was the elimination of fires which cannot be directly observed, occurring behind electrical panels or inside experiment racks onboard the ISS. In many ways it is a brute force tool, meant to indiscriminately fill a large volume quickly and remove breathable air from the combustion reaction. For this reason it is also required for astronauts to use portable breathing equipment while operating the PFE, else they may be injured by the large concentrations of CO₂. During operation, rapid expansion of the enclosed gas will cause the tank surface temperature to drop as low as -37 degrees C. Once the fire is extinguished the additional carbon dioxide is scrubbed by environmental controls, and excess pressure is vented from the cabin to space.

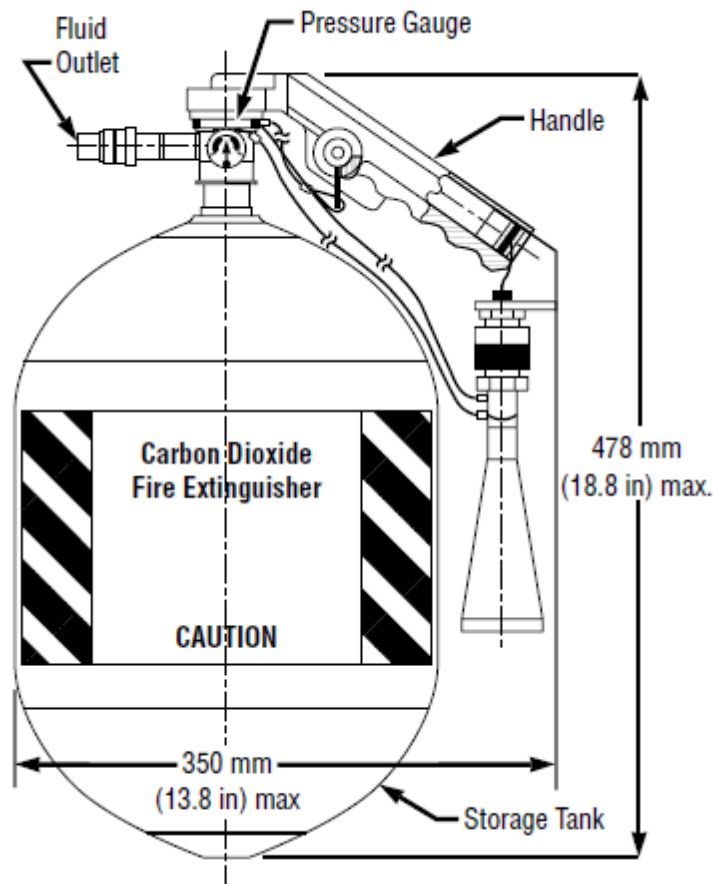


Figure 4: USOS PFE Diagram, Credit: NASA.

Analyses of the present options for space-application fire extinguishers lead us to conclude they are not acceptable for commercial spaceflight. For instance, they are far too expensive. The sales price for just one USOS unit is approximately one million dollars. They are also heavy, cannot be easily operated single-handed, and take up a large volume of usable storage space. A PFE

suitable for commercial spaceflight needs to be highly mobile, effective at removing most if not all of the fire hazards previously discussed, and cost effective. This is why ORBITEC will develop a more acceptable alternative for spaceflight applications. Doing so will require several important decisions to be made regarding the function of the device. Mainly, the type of fluid used as a fire suppressant will need to be determined.

The use of gas as a suppressing fluid is a good choice for microgravity environments because of its ability to fill three-dimensional space. Liquid suppressants travelling through free space tend to “ball up” due to surface tension effects and “wander around” instead of canvassing the combustion event (Butz, Carriere, Abbud-Madrid, & Easton, 2011) (Butz, Carriere, Abbud-Madrid, & Easton, 2011). Liquids however do have other properties which could apply very well to microgravity applications, provided the delivery mode is effective at concentrating the fluid to where the fire actually occurs.

New Technologies

Over the past decade studies have been conducted on the effectiveness of water-based fire suppression systems for microgravity. Studies led by researchers at the Colorado School of Mines used atomized water droplets to fight microgravity fires (Angel & McKinnon, 2003). The findings from these studies have been subsequently applied to the development of delivery methods for these highly atomized droplets referred to as FWM (fine water mist) systems (Butz & Abbud-Madrid, 2010). FWM allows liquid to behave in open areas like gases, operating three-dimensionally and creating a dense fog rather than a continuous stream of fluid. This gas-like behavior is enhanced by the microgravity environment of a spacecraft.

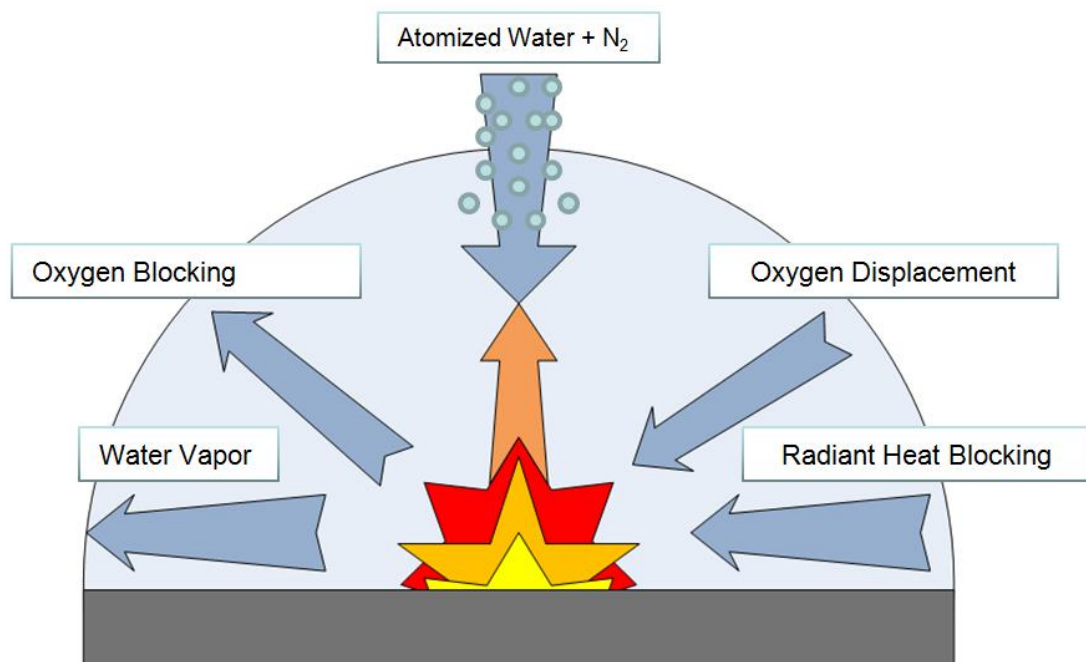


Figure 5: Diagram of PFE spray/combustion interaction.

Water has a very large latent heat capacity; meaning its ability to absorb heat energy is substantial. By delivering water to the fire as micron-sized droplets the liquid can readily absorb

conducted and radiated heat, rapidly decreasing the thermal energy in the system below what is necessary for sustained combustion. As the water droplets begin to vaporize, the resulting steam displaces ambient oxygen to quicken the extinguishing process (Figure 5). The FWM valve assembly works to atomize the water droplets by mixing a continuous water stream with nitrogen (an inert gas) prior to expulsion from the nozzle (Figure 6). Under ultra-high pressure (UHP), the nitrogen and water mix effervescently and travel in tandem towards the fire. By using compressed nitrogen as part of the PFE system, the mean diameter of the water droplets is reduced to sizes otherwise unobtainable using only mechanical fluid separation (Butz & Abbud-Madrid, 2010). The use of nitrogen also works to further reduce the amount of available oxygen in the combustion area. Research done onboard space shuttle Columbia in 2003 showed that water droplets between 20 and 50 microns in diameter were most effective at absorbing the heat energy of fire (when produced by hydrocarbon droplets). This level of atomization is possible with the FWM system.

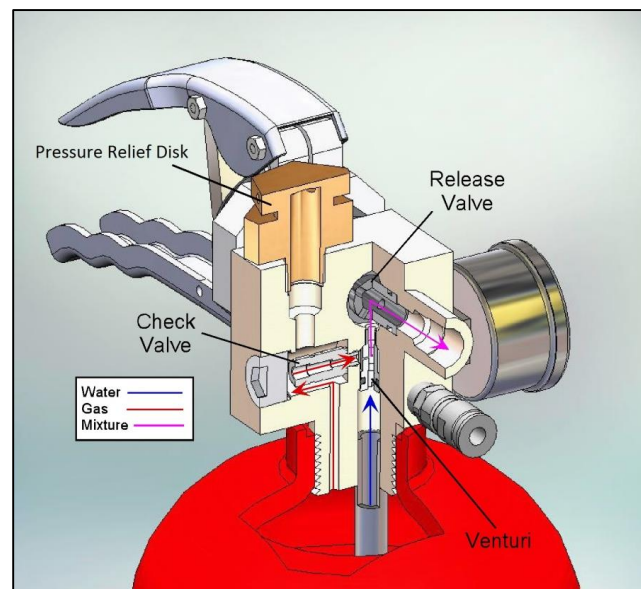


Figure 6: FWM PFE fluid flow path, Credit: ADA Technologies.

Because operation of the PFE will require the storage and pressurization of both nitrogen and water, a novel two-phase fluid management system was developed for use with the FWM nozzle assembly. Leading design alternatives involved the use of an elastic bladder housed in the PFE's tank. The water-filled bladder would be kept under pressure by compressed nitrogen which fills the remainder of the tank's volume. The tank and bladder assembly needs to withstand pressures in excess of 1000 psi for nominal atomization to take place.

Other fluid storage methods were also explored. Another design would include taking advantage of the unique physics of micro-gravity and capillary-actions to deliver the fluids into the FWM assembly. This method would work without needing to physically separate the gas and liquid phases inside the tank, but would also make operation of the PFE under normal gravity much more difficult. For reasons including cost, the simpler bladder design was chosen for early prototype development.

Prototype Testing

The first PFE prototype was completed in early December, 2014; standing 18in tall with a tank diameter of 5.25in. Fully loaded with water and nitrogen, the system has a weight of approximately 12lb (5.3kg). The finished prototype along with a graphical cross section of the interior can be seen in Figure 7.

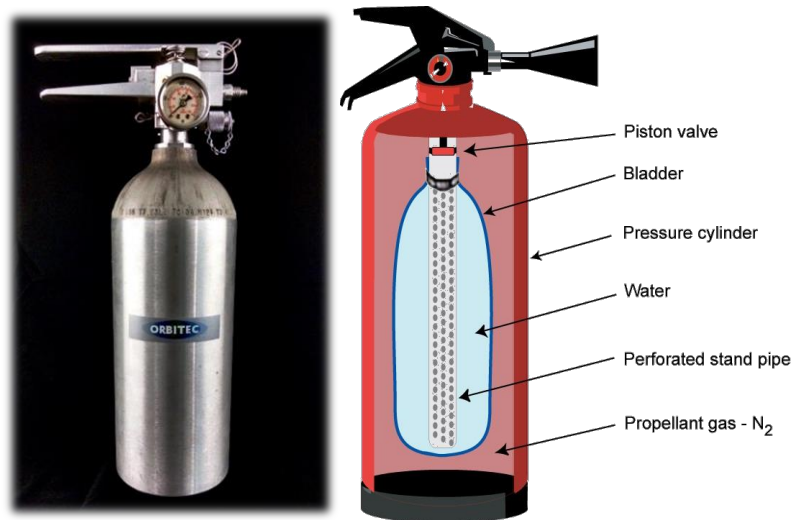


Figure 7:UHPFE Prototype with Cross Section Graphic

Time constraints limited preliminary testing to several simple criteria. Namely the effects of starting pressure and PFE orientation on discharge duration, and the effectiveness of the system against a lithium ion battery fire. All testing was video recorded for future review and evaluation.

The PFE can be held consistently at any orientation using the developed test stand shown in Figure 8. Although simulating microgravity conditions was not possible for this early stage testing, the ability to discharge the PFE in multiple orientations (vertically, inverted, etc.) allowed for the elimination of result bias based on the direction of gravity. Testing showed consistent discharge times regardless of orientation, lasting approximately 10 seconds at maximum pressure. At maximum pressure, the PFE also showed consistent throw distances in excess of 25 feet. With decreasing initial pressure, discharge durations increase as shown in Figure 9. Higher pressures are required for more effective atomization of the suppressing fluids however, and the critical point at which droplet size becomes ineffective has yet to be established.



Figure 8: Discharging UHPFE on test stand

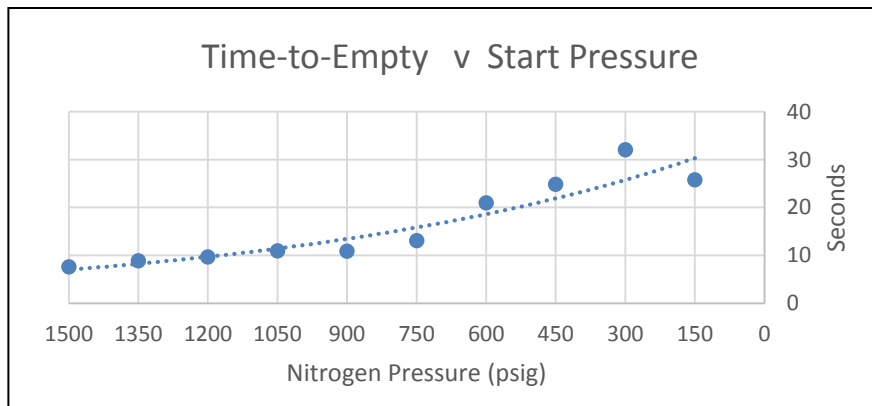


Figure 9: Graph showing relationship between discharge duration and tank pressure

The Canon BP-930 lithium ion battery was chosen for testing the effectiveness of the PFE prototype. This battery was selected because it is known to be currently used onboard the ISS in critical applications, including portable oxygen monitors used in EVA preparation. The batteries were enclosed in a protective cage, and combusted using a hotplate. The applied heat causes degradation of the anode-cathode barriers within the battery, and creates electrical shorts which sustains the production of heat energy. This process is also known as “thermal runaway”. The batteries were allowed to burn with a sustained flame for several seconds prior to PFE discharge, as shown in Figure 10.



Figure 10: Battery fire (left) and UHPFE discharge (right)

In two separate tests, the PFE was able to extinguish the battery fires. In the second battery fire test, a re-ignition of the battery occurred; after which the remaining fluid in the PFE was discharged to successfully extinguish the fire a second time.

Conclusion

The results produced over the course of this design and testing period show great promise for the future applications of the ORBITEC UHPFE. Simple and cost effective, the system is shown in preliminary testing to function appropriately regardless of orientation. More exciting was the prototype's performance against live lithium ion battery fires; against which the PFE functioned as hoped and extinguished both fire events.

Over the coming months, ORBITEC will continue to work with both university partners and the Wisconsin Space Grant Consortium (WSGC) to build, test, and validate ultra-high pressure portable fire extinguishers suitable for commercial spaceflight applications. By building this PFE we will be closer to the creation of a great commercial product, which in turn will help protect the lives of astronauts.

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