

Orion Portable Fire Extinguisher Performance Testing against a Laptop Lithium-ion Battery Stored-energy Fire — Method, Magnesium Fires, and Combustion By-product Toxicity

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As part of the qualification of the International Space Station (ISS) fine water mist portable fire extinguisher (PFE), several test methods were developed to determine firefighting capability against stored-energy sources. The most challenging of these devised stored-energy fire test methods proved to be the Lithium-ion (Li-ion) battery fire test scenario. The Orion crew capsule will utilize a different PFE technology from ISS (water spray rather than water mist), which spurred the need for the same type of evaluation focused on the sources of stored energy slated for use on Orion. Laptops were identified as a realistic source for stored-energy fires, requiring a modified Li-ion battery fire test scenario. In addition to open test cell (ambient oxygen concentration) testing to evaluate new proposed PFE performance, sealed chamber (20.9% and elevated oxygen concentration) testing was also performed. Chamber testing included combustion product sampling at various fire progression points for analysis and application to Orion emergency equipment design and response planning. The PFE stored-energy fire test methodology was modified and testing performed. Initial tests indicated ignition of the laptop magnesium laptop cases was possible. Additional tests were performed to characterize the laptop magnesium case fire behavior in various configurations. The new water spray PFE technology proved effective in extinguishing laptop stored-energy fires, and much was learned in the way these types of fires progressed. Findings indicate potential laptop magnesium case ignition mitigation strategies need to be further investigated.

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I. Introduction

MANY fuel sources are present aboard current spacecraft including one especially hazardous source of stored energy: the Lithium-ion (Li-ion) battery. When overheated either by short, overcharge, or external heating, the Li-ion battery has the characteristic of self-sustaining heat, which can lead to a thermal runaway. Currently, Li-ion batteries are the preferred choice for use aboard international spacecraft, and therefore are a readily available fuel source if ever a fire should occur involving Li-ion stored energy. Previously carbon dioxide (CO₂) portable fire extinguishers (PFEs) had been used aboard international spacecraft as a means of mitigating fire events. Li-ion battery stored-energy fires have a great potential to re-ignite if sufficient heat is not removed by the PFE. As concerns arose about the effectiveness of CO₂ extinguishers against these tenacious stored-energy fires, it became clear that new PFE technologies would need to be developed. A gap was identified in test methods that could evaluate and compare the performance of various PFEs as an unbiased means for ranking and selecting new PFE technologies. The NASA White Sands Test Facility (WSTF) Flight Acceptance Standard Testing group was requested to lead the development of new fire extinguisher performance test methodology and used camcorder battery packs as the stored-energy fire source.¹ The developed test methodology was used to design, select, and qualify fine water mist portable fire extinguisher (PFE) technology for use on the International Space Station (ISS).^{1,2,3}

As the Orion Program works towards designing their own fire mitigation approach and selection of PFEs, the need was identified to customize the ISS PFE Stored-Energy Fire Performance (SEFP) testing methodology to address specific Orion Program scenarios. The objective of the Orion methodology continues to be the same as it was for the ISS methodology: to challenge the PFE's design to evaluate its ability to cool and to prevent fire re-ignitions and further propagation. This paper documents the details of the customized Orion PFE SEFP testing methodology.

II. Stored-energy Source Selection; Laptops & Magnesium Case-related Fire Concerns

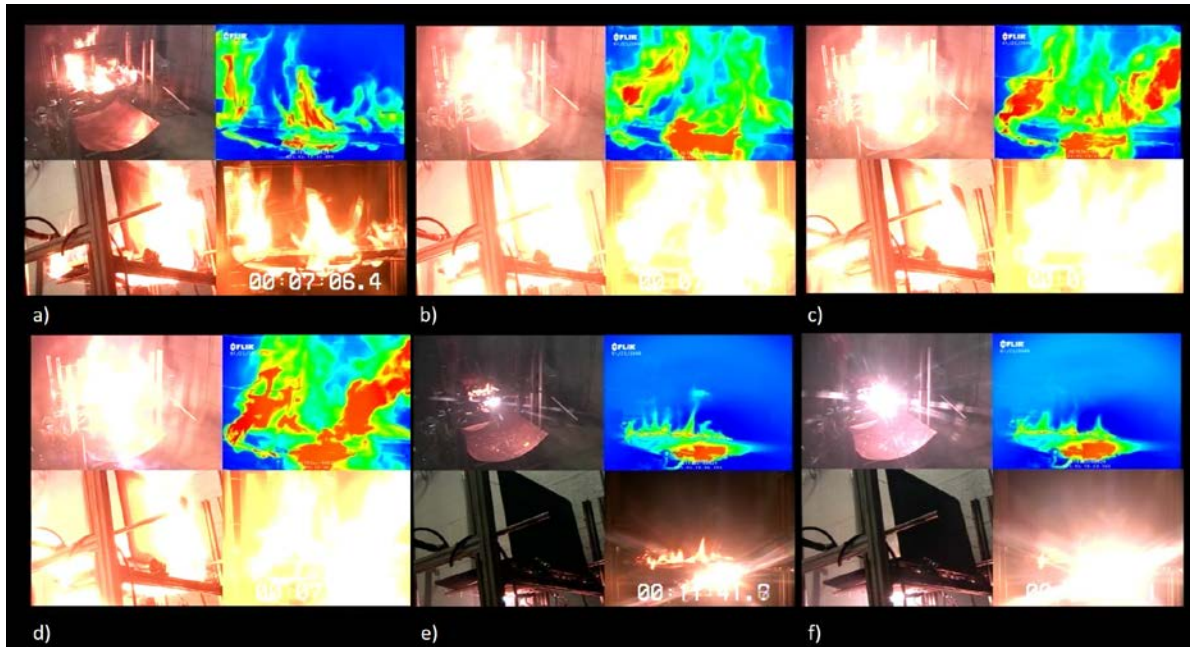
The PFE SEFP testing methodology was designed exclusively for space vehicles with known sources of stored energy that could be encountered onboard. It is impractical to test every Li-ion stored-energy configuration, as a variety of battery types are currently in use or planned for future use. One configuration must be selected to represent a challenging yet realistic stored-energy fire scenario. For the previous ISS SEFP testing, the Canon® BP-930 XL-1 Li-ion camcorder battery pack was chosen to represent ISS Li-ion stored energy. The Canon battery was selected because it is in use on the ISS, provides a challenging fire, and also allows for fire propagation evaluation between cells and between stackable packs.¹ The Orion Program set out to identify the largest realistic stored-energy source that may be found onboard, and settled on a full-size laptop for the fire challenge. Laptops met the criteria of realistic potential for use, presenting a challenging fire scenario, and a promise of providing insight on the PFE's ability to prevent propagation between cells.

At the time of this writing, the ISS flies the Hewlett-Packard (HP) ZBook®† 15 G2 laptop containing an 8-cell Li-ion battery (83 Wh). The HP Zbook 15 G4, with a 9-cell 90 Wh battery, was determined to be the largest-sized laptop anticipated to be flown on the Orion, providing a conservative stored-energy fire hazard battery (90 Wh) over the G2 (83 Wh). The HP ZBook 15 G3 Notebook (Product No. 818909R-999-FTF7, HP Long Life 9 cell 90 Wh Li-ion) could be found refurbished as a more affordable option to the G4 while continuing to deliver the worst-case stored energy battery size of 90 Wh and was therefore purchased and used for this testing.

When evaluating the laptop, it was determined that the casing was made of magnesium (Mg). When laptop Li-ion battery thermal runaway was induced, it was observed that sufficient heat was released to ignite the Mg. Figure 1 shows the progression of one Mg case ignition fire. Figure 1a shows the initial laptop fire prior to Mg ignition. Figure 1b -1d show an aggressive laptop battery fire with sufficient heat to induce Mg ignition (the bright white light of the Mg fire saturates the camera view). After the battery fire subsides, the Mg case fire continues (Figure 1e-1f). At some point, presumably when the battery fire has subsided and the area has cooled, the Mg fire self-extinguishes. It is generally understood that burning Mg reacts with water to produce hydrogen. Figure 1 does not show the introduction of water. In another test when a water PFE was discharged, the Mg fire was further aggravated, as was expected.

* Canon® is a registered trademark of Canon Kabushiki Kaisha Corp., Tokyo, Japan.

† ZBook® is a registered trademark of Hewlett-Packard Development Company, Houston, Texas.



Magnesium laptop case ignition was consistently observed for tests performed with the laptop in an open-lid configuration as shown in Figure 1. Notably, Mg case ignition was not observed in the three tests performed with laptop configured with the lid fully closed. It is possible that the closed-lid configuration both limited fresh oxygen from easily reaching the fire and provided additional thermal conductivity, dissipating heat and preventing the Mg case from reaching ignition temperatures. The severity of open-lid vs. closed-lid fire events can be seen when examining posttest laptops (Figure 2). The open-lid fire event laptop (top) has had a large portion of its case consumed, leaving internal components exposed and a white ring of magnesium oxide around the cavity. The closed-lid fire event laptop (bottom) shows superficial damage but little to no case consumption (Figure 2). Further testing would be necessary to confirm whether closed-lid configurations consistently mitigate Mg case ignitions. Nonetheless, these initial tests suggest that when faced with an overheating or smoking laptop, closing the lid may be a recommended best practice for helping to prevent Mg case ignition.



Figure 2. HP ZBook 15 G3 Notebook post stored-energy battery fire and Mg case ignition.

The Orion Program was now faced with a predicament. The best option for addressing a stored-energy fire is a water-based PFE, due to its remarkable capacity to remove heat.¹ However, this same water-based PFE option will also aggravate a potential Mg case fire. In the end, it was decided that the Orion Program would ensure that the laptop they choose to fly would not contain a Mg case, thereby eliminating the additional fire concern. Due to an expedited schedule, testing continued with the HP Zbook 15 G3 Notebook, a conservative Orion stored-energy fire challenge, until a decision was made on an alternate test laptop. As for the ISS Program, they are currently flying the HP ZBook 15 G2 Notebook containing a Mg alloy casing. NASA Materials and Processes has been made aware of the potential secondary fire concern.

The test community came to consensus on the alternate stored-energy fire-challenge laptop: the Dell Model No. XPS[®] 15[‡] 9560-5000SLV-PUS, 97 Wh and six cells. The Dell XPS 15 provided various advantages over the HP Zbook 15 G3, the first and most obvious being that it did not have a Mg case. The Dell laptop case was verified by the manufacturer and again at the White Sands Test Facility in the laboratory to be made up of 98% aluminum. Second, though the Dell XPS 15 contained only six cells, each was larger than the nine cells contained in the HP Zbook. Overall battery power for the Dell XPS 15 is 97Wh, compared to the 90Wh present in the HP Zbook 15 G3, making it a more severe and conservative stored-energy fire fuel source challenge. Last, as previously stated, the preferred stored energy source criteria included realistic potential for use, presenting a challenging fire scenario, and providing insight on the PFE's ability to prevent thermal fire propagation between cells. Once testing began on the HP Zbook 15 G3, it was discovered that it did not completely address the third criterion. The HP Zbook 15 G3 contains pouch style batteries that are not robustly separated from each other. When forced into thermal runaway, all batteries react in very close coupling (a result of thin stacked battery cells), leaving little to no opportunity to evaluate the PFE's ability to prevent fire propagation (Figures 3 and 4).

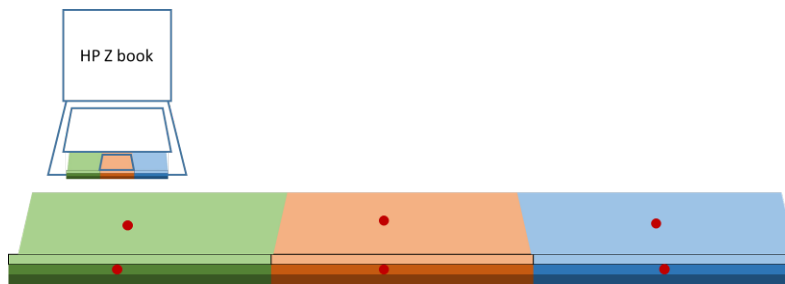


Figure 3. Simplified schematic of HP Zbook 15 G3 nine-cell battery configuration. *Three rows, each row containing three stacked batteries. Red dots indicate thermocouple placement for event monitoring.*



Figure 4. HP Zbook 15 G3 nine-cell battery configuration. *Three rows, each row containing three stacked batteries. Red dots indicate thermocouple placement for event monitoring.*

[‡] XPS[®] is a registered trademark of Dell, Inc., Round Rock, Texas.

On the other hand, the Dell XPS 15 contains six individually and robustly packaged battery cells (Figure 5, top). When the heater was placed external to the laptop case but aligned with Li-ion battery pack, the two center batteries were forced into thermal runaway. When engaged by PFE no further propagation to adjacent cells was observed (Figure 5, center). In a free burn test of the Dell XPS 15, where no effort was made to prevent fire propagation after initial external heating, the laptop did not self-extinguish and involved all six battery cells (Figure 5, bottom). The Dell XPS laptop battery pack configuration provided opportunity to evaluate the PFE's ability to prevent propagation to adjacent cells. The Dell XPS 15 laptop proved to fully meet all defined criteria (realistic potential for use, presenting a challenging fire scenario, and providing insight on the PFE's ability to prevent propagation between cells) and is recommended for continued use as the preferred Orion SEFP test stored-energy fuel source.



Figure 5. Dell XPS 15 six-cell battery configuration and thermal runaway propagation. Pre-test Li-ion battery pack configuration of six cells configured in-line (top), post-external heating and thermal runaway with Water Spray PFE engagement (center), post external heating and thermal runaway propagation to all battery cells (bottom)

III. Fire Engagement Milestones Criteria

Though each laptop fire progresses in a unique manner, an effort was made to standardize fire engagement criteria and maximize test repeatability (see Table 1). A definition for Full Involvement was required to indicate a uniform point for PFE Engagement. After extensive programmatic discussion (involving the NASA Fire, Operational, Orion Environmental Control and Life Support Systems (ECLSS) Government Furnished Equipment (GFE), and astronaut community), it was concluded that 30 s post visible flaming ignition (FI) represents the time frame of an awake crew member to recognize there is a fire event and immediately grab the PFE to suppress the fire event. In addition to correlating to realistic operational engagement times, engagement 30 s post FI provided a challenging PFE fire challenge. At 30 s post FI, laptop fires were found to be highly aggressive while providing sufficient time for initial battery cells in thermal runaway to conduct heat to adjacent cells and serve as a means to challenge and evaluate the PFE’s ability to prevent continued propagation.

Table 1. Timeline for Orion crew engagement using a water-based portable fire extinguisher (PFE).

Event	Description	Associated Timing
Laptop Smoking	<i>Realistically, laptop smoking may trigger vehicle alarms prior to flaming ignition (FI) providing additional response time, but due to its variable nature was not used as a fire engagement milestone.</i>	Variable
Flaming Ignition (FI)	<i>Visible flames observed, worst-case conservative initial alarm activation.</i>	FI = Time 0
Full Involvement/PFE Engagement	<i>Astronauts wake from deep drowsy sleep, one astronaut obtains PFE and immediately engages and all don emergency masks ASAP.</i>	FI+ 30 s
Pulsing Fire Engagement Technique	<i>Discharge until no visible flames (NVF) observed, pause, re-engage at the sight of additional flames.</i>	As Needed
Full PFE Discharge	<i>Discharge PFE until full depletion, to provide maximum cooling.</i>	NVF + 30 s

Once the Full Involvement/PFE Engagement criteria were met (FI +30 s), the established sequence was followed at the test conductor’s discretion: fire was fought until no flames were observed; pause discharge; immediately engage any subsequent flare-ups until no flames observed; and the cycle repeated. This method has been referred to as the “pulsing” method. During previous ISS SEFP testing, the pulsing method had been observed to be more effective in extinguishing camcorder battery pack fires vs. immediate full discharge of the PFE.¹ The pulsing method allows time for internal heat to conduct to outer surfaces between pulses while conserving media during that conduction period. It was assumed that this same phenomenon would be observed in laptop stored-energy fires, and the same pulsing technique was implemented. During laptop testing it was qualitatively observed that the pulsing technique was in fact an important factor in effective stored-energy fire mitigation. In some aggressive fires, even when flames were difficult to fully extinguish over an extended discharge, it was observed to be most effective to cease the initial discharge and pulse in order to achieve successful flame suppression. After no flames had been observed for approximately 30 s, the test conductor remotely discharged the remaining contents of the PFE to further cool any residual heat within the individual battery cells. This method lengthens the effective use time of the PFE and ensures extinguishment material is available throughout the duration of the fire. It was presumed an astronaut aboard Orion spacecraft would likely be restrained during use of a fire extinguisher and, therefore, would engage a fire from a stationary position. Though direct human firefighter involvement was preferred to include realistic PFE articulation during engagement of the fire, the previously mentioned HP Zbook 15 G3 Mg fire safety concerns as well as PFE pressure vessel certification safety concerns led to the decision to operate the PFE remotely from in a fixed position. In previous testing, remote operation of the PFE in a fixed position and orientation proved to be as effective as (either equivalent to or more conservative than) direct firefighter involvement (utilizing sweeping or angling technique) as long as the pulsing technique was applied (as opposed to a non-pulsing continuous PFE discharge to full depletion).¹ Previous evaluation showing no appreciable advantage was gained by utilizing trained vs. untrained firefighters was reassuring, as astronauts currently receive limited firefighter training on a one-time basis.¹ One key feature recommended to be emphasized in training and operational guidance tools is the importance of the pulsing technique in engaging stored energy fires for most successful outcomes vs. immediate and full discharge.

IV. Testing Methodology: Experimental Apparatus and Data Acquisition

The test methodology used for the Orion PFE SEFP testing was largely the same one developed for the ISS SEFP testing,¹ but with three key modifications to address the specific Orion vehicle scenario. These modifications can be seen as program-specific test variables that were modified for the Orion test and would likely be tailored for future program PFE SEFP Testing (Table 2). Orion Program modifications included: 1) the use of a laptop as the stored-energy fuel source challenge instead of camcorder battery packs; 2) the implementation of stationary remote PFE discharge instead of firefighter involvement; and 3) shorter firefighting distances of 0.9 m and 0.6 m (3 ft and 2 ft) vs. ~1.8 m (~6 ft).

Table 2. Stored-energy fire performance (SEFP) testing methodology program-specific test variables.

Variable	Description
Stored-energy Fuel Source	<i>Realistic, challenging, propagation evaluation.</i>
Fire Fighting	<i>Conservative remote stationary vs. realistic human firefighter intervention.</i>
Fire Engagement Distance	<i>Tailored to vehicle maximum anticipated dimensions.</i>

As addressed earlier, a laptop was selected for Orion test methodology as a worst-case realistic stored-energy fuel source that will be present onboard. The Dell XPS 15 laptop provided all preferred criteria: realistic potential for use, presenting a challenging fire scenario, and a configuration that would allow for the evaluation of the PFE’s ability to prevent propagation between cells. Also previously discussed, stationary remote PFE discharge provided a conservative discharge scenario while mitigating Mg fire and PFE pressure vessel certification safety concerns. Though the PFE was located in a stationary position, it was angled in such a way as to aim the PFE plume toward the laptop trackpad. The angle of the PFE was adjusted to approximate a 75/25% split of the plume, with 75% engaging the keyboard and trackpad of the laptop and the other 25% providing cooling below the laptop. Some testing was performed at ambient conditions in an open test cell. Other tests at elevated oxygen conditions of 30% O₂. Elevated oxygen tests were conducted in initial quiescent environments in an 8 m³ flammability chamber connected to vacuum, oxygen and nitrogen supplies. The size and conditions of the chamber were selected to simulate as closely as possible conditions present in the Orion capsule. For testing performed inside a chamber, oxygen concentration was monitored using a BW Technologies Max XT II Gas Monitor located within the chamber (0-30.0% O₂ range with 0.1% resolution). Photos of the elevated-oxygen-concentration Orion PFE SEFP test chamber and PFE angle are shown in Figures 6 and 7.

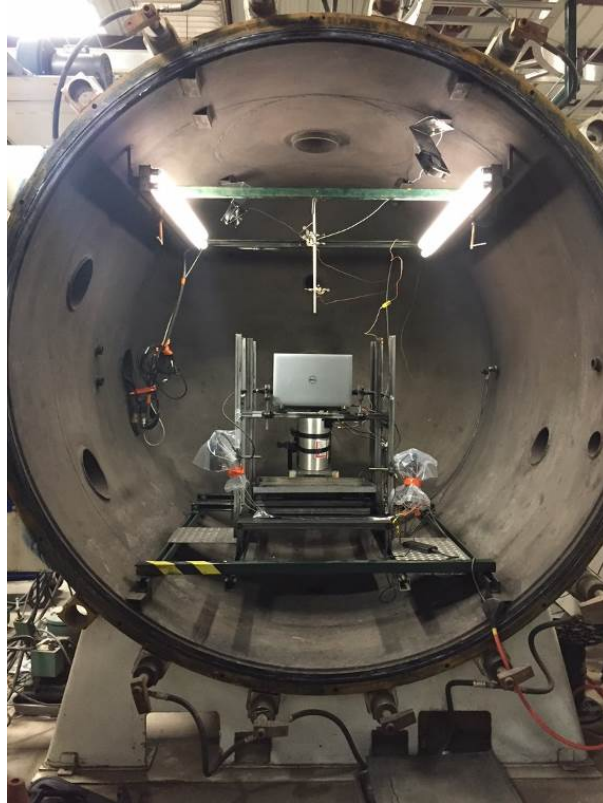


Figure 6: Elevated-oxygen-concentration Orion PFE SEFP test chamber.

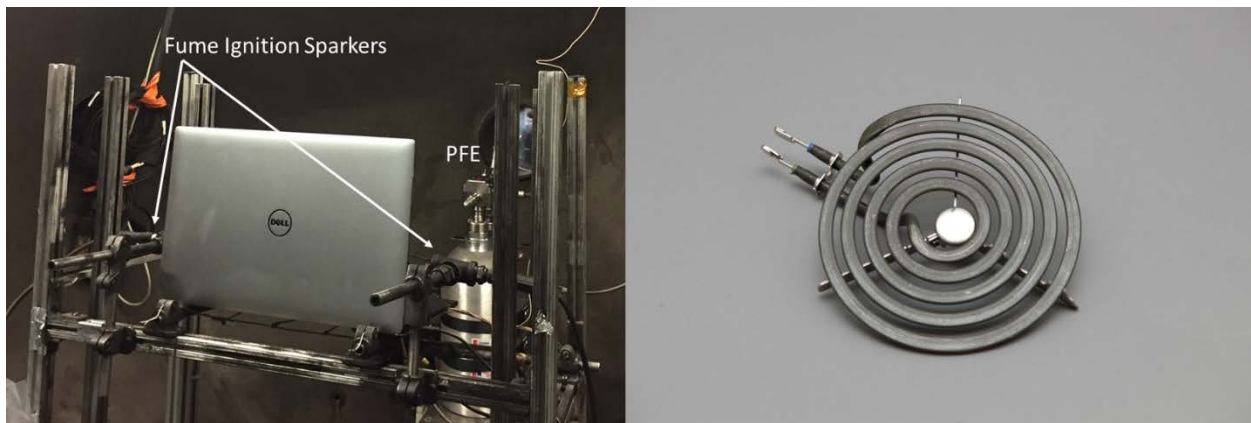


Figure 6: Elevated-oxygen-concentration Orion SEFP PFE Angle and External Heater. (Left) Spark plugs are shown on either side of laptop, and PFE angled to split plume 75% on keyboard and 25% below laptop. Range top heating element cannot be seen but is located external and below laptop case aligned and centered with internal Li-ion battery pack. (Right) Range top heating element

The Orion vehicle cabin is significantly smaller than ISS modules. The ISS SEFP testing methodology was designed to provide a conservative fire engagement distance of ~1.8 m (~6 ft) as compared to the 1.2 m (2 ft) operational maximum that could be achieved on the ISS.¹ For the smaller Orion vehicle, the ISS ~1.8 m (~6-ft) distance was excessively conservative and it was decreased to 0.6 m (2 ft). In distance evaluation testing it was found that the closer proximity significantly increased extinguishment performance by concentrating the cooling plume onto the test article.⁴ Because of the higher efficiency at close proximity, smaller volume PFEs could be considered for use while

maintaining reliable extinguishment capability. It is a notable observation suggesting that even in ISS fire scenarios it would be a good practice to approach the fire at closer proximity than 1.8-m (6-ft) if possible to increase effectiveness.

To summarize the test methodology and implementation details, the battery stored-energy fuel source was induced into thermal runaway using external heating of the laptop case but aligned and centered with internal Li-ion battery pack. The heating element is a commercially obtainable electric range surface heating element capable of outputting 1300W of power @ 220VAC. The heating element is a 6 inch, 5 turn ceramic coated surface element on which the laptop is placed in direct contact to the bottom case oriented with the two center batteries directly above the element. A variable transformer was used to limit the output to approximately 1060W by controlling the input voltage to 180VAC. The heating element was equipped with a hinged mount and an electrical solenoid that, when actuated, would drop the heater away from the stored-energy source (laptop or battery bundle) after full involvement was obtained. Removal of the heating element ensured any reactions occurring after the full involvement determination (FI +30 s) were due to internal battery thermal runaway and heat propagation rather than external energy input.

An automotive ignition system was used to ensure repeatable and conservative ignition of the test samples. Two spark plugs were placed above and towards the outside edges of laptop battery packs. Spark plugs were wired to spark alternately at ~14 Hz. Spark plugs were in place to ensure consistency in ignition of gases that were potentially pyrolyzed or vented out of the laptop battery packs as a result of the heating. Ignition of gases emitted from test samples often propagated back to the test sample itself and represented a likely worst-case scenario for re-ignition of the test sample. Two spark plugs were used for redundancy. During ISS testing there were concerns about dangerous astronaut oxygen depletion or extremely high temperature keep-out zones. To address these concerns, temperature calorimeters and oxygen meters were used. Because ISS testing demonstrated that no safety keep-out zones existed, further evaluation was not required during Orion testing.¹

Temperature data were monitored by Type K thermocouple (TC) placement internal to the laptop on each individual battery cell. A Type K TC was also located on the external casing directly above the heater element to verify adequate heat input. Figure 8 presents a depiction of Laptop and thermocouple placement, each of the 6 individual batteries were equipped their own TC which can be differentiated by color coding in the Laptop diagram and corresponding colored thermocouple data in the chart. In Figure 8 environmental and heater TCs are indicated by color coded dots in depiction and corresponding colored thermocouple data. Thermocouples provide excellent event monitoring. Initial thermal runaway and propagation information is generated. TC data also documents PFE cooling capacity when discharged. Beyond evaluating PFE capacity to stop a fire from progressing, TC data can aid in comparing subtler differences between various PFE performances by comparing cooling capacity. An example of the data results generated in a PFE SEFP test can be seen in Figure 8. Full burn data chart (Figure 8, top) represents a Laptop Li-ion stored fire and how it would progress without PFE intervention. In this chart you can see that all TCs corresponding to Li-ion batteries rise well above 1000 °F. The temperatures indicate thermal runaway and full fire involvement of all 6 battery cells. Subsequent tests introduced Water Spray PFEs to evaluate their effectiveness in extinguishing Li-ion stored energy fire and to prevent further propagation. Water Spray PFEs were evaluated containing 2.5lbs of water, using nozzle style 3004, and containing 300 and 200 psi gaseous nitrogen fill pressures. 300 psi fill pressure Water Spray PFE introduction test (Figure 8, bottom) shows a rapid rise in TC data for the two center batteries in closest proximity to the external heat source, indicative of thermal runaway. Following PFE introduction, a dramatic drop in previously elevated TC temperatures is observed and maintained. This demonstrated effective cooling by the Water Spray PFE and capacity to prevent continued thermal runaway and propagation to neighboring battery cells. Ignition of laptop keyboard and plastic materials helped to provide realistic fire event and combustion product profiles but were rapidly extinguished with PFE introduction.

In addition, two Type K thermocouples were placed 0.609 m (24 in.) and 0.864 m (34in.) above the laptop to monitor potential worst-case cabin temperature conditions during a fire event (Figure 8). Whenever testing was performed inside of a chamber (in order to simulate elevated oxygen concentrations), chamber pressure was also monitored using a Heise Model 710A Pressure transducer (Tolerance 0.1 % of Full Scale, 0-50.00 psia range with 0.01 psi resolution).² Pressure data were valuable to program stakeholders who were concerned about cabin overpressure implications. Internally mounted TCs aided greatly in the analysis of individual battery cell involvement and fire extinguisher cooling and propagation prevention capabilities.

Various video cameras were employed: up to two standard definition cameras at varied aperture settings when practical, one infrared (IR) video camera when available for additional information, and one GoPro when available. Camera goals were to verify the operation of the spark plugs throughout the test, and to document progress the entire event, and the IR camera to provide additional temperature profile information.

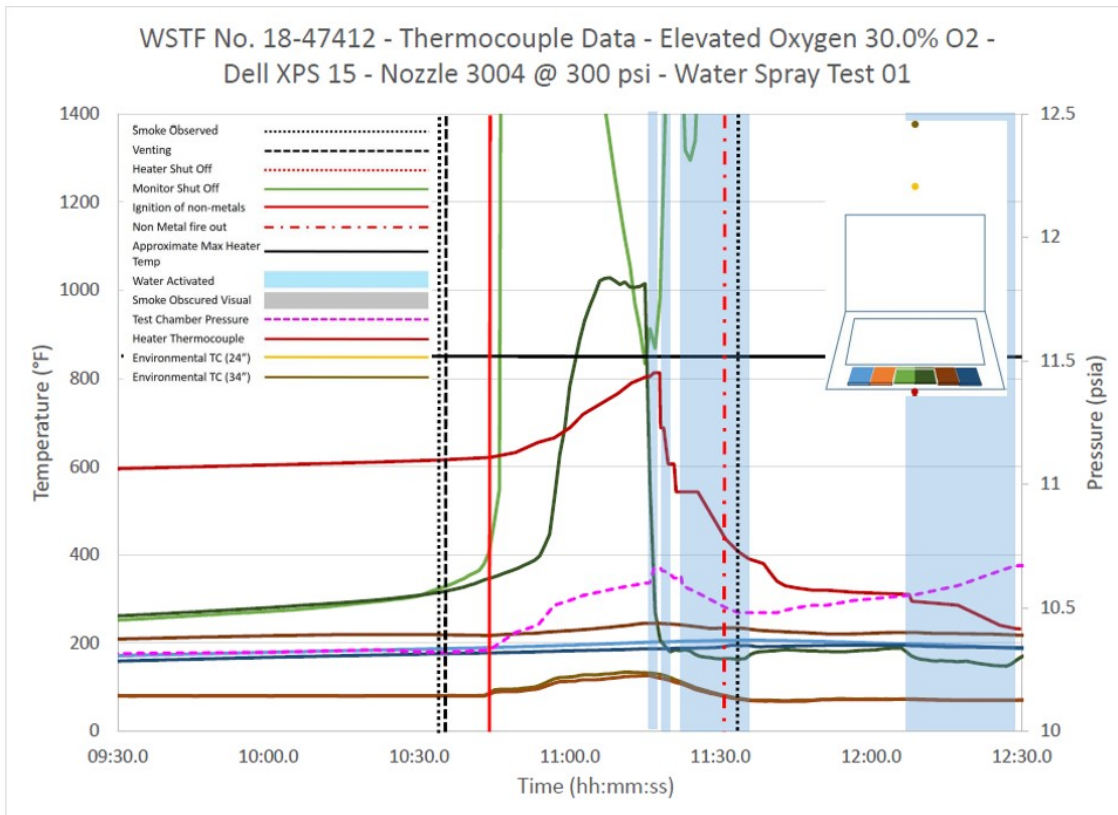
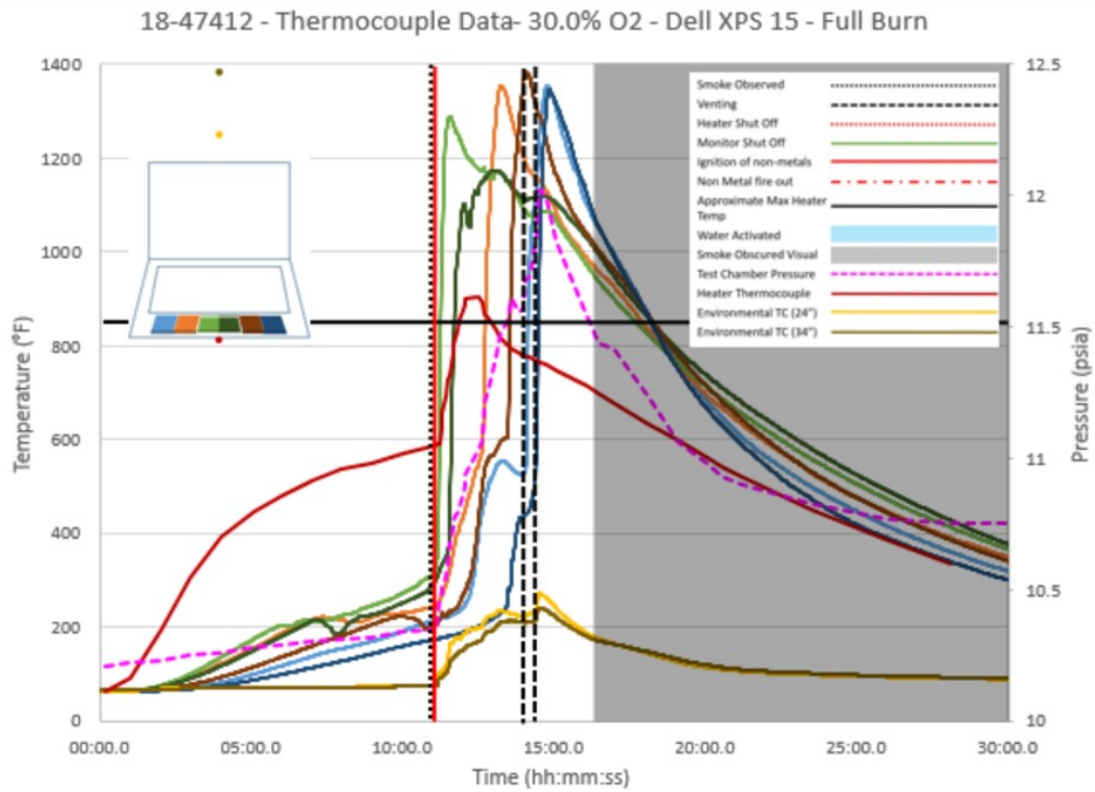


Figure 7. Dell XPS 15 Orion PFE SEFP Testing Results. The PFE discharge is indicated by blue bars.

V. Evaluation of Toxic Combustion Products

When addressing risks associated with any fire, and especially when addressing a complete and large event, discussion on toxic combustion by-products (TCBs) generated during the fire is necessary. The Orion Program requested WSTF to customize the PFE SEFP test methodology to allow for TCB sampling and analysis. To do this, the test was configured inside of a 1.4 m³ (50 ft³) chamber to contain combustion by-products. It was found that the use of fans in the smaller chamber was critical to ensuring ignition and propagation⁵.

A gas sampling manifold was designed and built to remotely sample the chamber at program-specified key milestone points across the fire duration (Table 3). The gas sampling manifold was equipped with four evacuated 4-L cylinders, each connected via individual remote operated valves for actuation at the test conductor's command. After the fire test was completed, the gas sample cylinders were immediately taken to the NASA WSTF Molecular Desorption Analysis Laboratory (MDAL) for full evaluation using NASA-STD-6001 Test 7 constituent identification and quantification methodology.⁴ The MDAL team was on standby during testing to perform immediate analysis, as time is critical in ensuring constituent reaction, recombination, and degradation are minimized after the sampled event. The purpose of the data was to inform emergency cleanup equipment design and development.

Two test runs were executed. For the 1st test run the HP ZBook laptop was induced into thermal runaway in 20.9% oxygen and 14.7-psia conditions and allowed to burn freely while gas samples were drawn at target operational milestones (see Table 3). For the 2nd run, the HP ZBook laptop was again induced into thermal runaway but now in 30% oxygen and 12.4-psia conditions. In this 2nd run, water spray was introduced using a weed tank sprayer nozzle to evaluate how water interacts with combustion products and if the water aids in "scrubbing" the environment.

In addition to gas sampling for detailed combustion product analysis, the test chamber was equipped with particulate instruments (DRX aerosol condensation particle counters and witness plates for a NASA Glenn Research Center combustion particulate analysis; and CO and CO₂ gas monitors for a NASA Johnson Space Center gas analysis) to further correlate a laptop fire event with other key areas of environmental control and monitoring. Outcomes of the gas sampling toxicity portion of the evaluation are complex and deserve their own publication to be presented at a later time. Nonetheless it is mentioned here because coupling test article thermal runaway flammability testing with rigorous TCB analysis to inform emergency equipment design is an innovative approach that was implemented as part of this program evaluation.

VI. Conclusions

Stored-Energy Fire Performance (SEFP) testing methodology can be tailored to program-specific variables for customized testing. Key variables for program specific customization were found to be stored energy fuel source and fire engagement distance. Key stored energy source criteria was found to be; realistic potential for use, presenting a challenging fire scenario, and providing insight on the PFE's ability to prevent propagation between cells. The Dell XPS 15 laptop was found to meet all key stored energy source criteria and is recommended for continued use as the preferred Orion SEFP test stored-energy fuel source. This test methodology can be used to aid in design by comparing variables such as PFE initial discharge pressure, discharge media volume, and nozzle options as well as for verification of final configuration performance. Test method is capable of evaluating not only fire extinguishment but PFE ability to inhibit further fire propagation. One key recommendation in training and operational guidance, is the importance of the "pulsing" fire extinguishment technique when discharging PFE for most successful outcomes vs. immediate and full discharge. It is also recommended, as a good practice, to approach stored energy fires at closes proximity to increase extinguishment effectiveness. For laptops containing Mg casing, initial tests suggest that closing the lid may help to prevent Mg case ignition. Further testing would be necessary to confirm whether closed-lid configurations consistently mitigate case ignitions in a stored energy fire scenario. Coupling stored-energy fuel source thermal runaway flammability testing with rigorous toxic combustion product analysis to inform emergency equipment design is an innovative approach that was implemented as part of this program and may be a valuable approach for future programs.

Acknowledgments

The authors would like to acknowledge the support provided by members of the NASA WSTF test team (John Bouvet, Luis Alday, George Quezada, Bertha Garcia, Alejandro Cuaron, Ilse Alcantara, Vanessa Buchanan, Emmanuel Silva, George Aldrich, and George Vines) and the JSC Orion Program Customers and project engineers (Mary Coan-Skow, Ph.D., Chris Nagel, Stephanie Casper, Sterling Tarver) as well as GRC combustion particulate analysis expert Marit Meyer, Ph.D. and JSC gas analysis expert Paul Mudgett, Ph.D. for their contributions to the fire evaluations.

Notes

*Any use of trade names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Table 3. Orion stored-energy fire event critical milestones and gas sampling for evaluation of toxic combustion by-products.

Operational Orion Event Timeline in the Case of a Laptop Stored-energy Fire	Milestone Time	Gas Sampling	Toxic Combustion By-products (TCB) Test Notes
<u>Laptop Smoking</u> : Realistically, laptop smoking may trigger vehicle alarms prior to flaming ignition, providing additional response time.	Variable		
<u>Flaming Ignition (FI)</u> : Visible flames, worst-case initial alarm sounding.	FI = Time 0	Yes	Sampled for both the 1 st run (no water) and the 2 nd run (water introduction) tests.
<u>Scenario 1: Portable Fire Extinguisher (PFE) Engagement</u> : Astronauts wake from deep drowsy sleep; one astronaut obtains PFE and immediately engages fire while others don emergency masks.	FI +30 s	Yes	Sampled for both the 1 st run (no water) and the 2 nd run (water introduction) tests.
<u>Pulsing PFE Fire Engagement Technique</u> : Discharge until no visible flames (NVF) observed, pause, re-engage at the sight of additional flames.	Variable, as needed		During TCB testing, PFE discharge was delayed to allow for further event progression.
<u>Scenario 2: PFE Engagement</u> : Astronauts wake from sleep promptly; astronauts obtain and don contained breathing apparatus (CBA) assemblies. One astronaut obtains PFE and immediately engages fire. Timestamp most realistic toxicity profile for the environment that will be captured inside the CBA assemblies. Observation of progression of fire toxicity will definitely capture flaming “vents” in addition to flaming ignition.	FI +2 min	Yes	Sampled for both the 1 st run (no water) and the 2 nd run (water introduction) tests.
<u>Scenario 3: PFE Engagement</u> : Astronauts wake from deep drowsy sleep, astronauts obtain and don CBA assemblies. One astronaut obtains PFE and immediately engages fire. If astronauts in deep sleep, this timestamp will be most conservative toxicity profile for the environment that will be captured inside the CBA assemblies. Observation of progression of fire toxicity will definitely capture flaming “vents” in addition to flaming ignition.	FI +3 min	Yes	Sampled during the 1 st run (no water) introduction test as a pre-water introduction evaluation point.
	FI +3 min 15 s		During TCB 2nd test run, water was introduced to evaluate TCB scrubbing.
<u>Full PFE Discharge</u> : Discharge PFE until full depletion, to provide maximum cooling.	NVF +30 s		
<u>Post-Full PFE Discharge</u> : It is anticipated that by FI +5 min the PFE would have been fully discharged.	FI +5 min	Yes	Sampled during the 2 nd run (water introduction) test as a post water introduction evaluation point.

References

¹A. Juarez, S.A. Harper, David B. Hirsch, B. R. Rodriguez, G. M. Young, and S. B. Tarver, "Development of a Standard Test Scenario to Evaluate the Effectiveness of Portable Fire Extinguishers on Stored Energy Fires: Li-Ion Battery Scenario," *43rd International Conference on Environmental Systems*, Vail, Colorado, July 2013.

²A. Juarez, S.A. Harper, J.M. Stoltzfus, D.B. Hirsch, B.R. Rodriguez, G.M. Young, and S.B. Tarver, "Development of a Standard Test Scenario to Evaluate the Effectiveness of Portable Fire Extinguishers in an Elevated Oxygen Environment," *43rd International Conference on Environmental Systems*, Vail, Colorado, July 2013.

³A. Juarez, S.A. Harper, H. Beeson, D.B. Hirsch, B.R. Rodriguez, G.M. Young, and S.B. Tarver, "Evaluating the Effectiveness of Portable Fire Extinguishers on Stored Energy Fires: International Space Station Self Contained Oxygen Generators," *43rd International Conference on Environmental Systems*, Vail, Colorado, July 2013.

⁴WSTF 15-46648 MPCV FWM PFE Minimum Volume Threshold and Distance Testing, June 12, 2015

⁵WSTF 17-47230 Laptop Chamber Flammability Toxicity Test 2B, August 01, 2017