Development of a Standard Test Scenario to Evaluate the Effectiveness of Portable Fire Extinguishers on Lithium-ion Battery Fires

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Many sources of fuel are present aboard current spacecraft, with one especially hazardous source of stored energy: lithium ion batteries. Lithium ion batteries are a very hazardous form of fuel due to their self-sustaining combustion once ignited, for example, by an external heat source. Batteries can become extremely energetic fire sources due to their high density electrochemical energy content that may, under duress, be violently converted to thermal energy and fire in the form of a thermal runaway. Currently, lithium ion batteries are the preferred types of batteries aboard international spacecraft and therefore are routinely installed, collectively forming a potentially devastating fire threat to a spacecraft and its crew. Currently NASA is developing a fine water mist portable fire extinguisher for future use on international spacecraft. As its development ensues, a need for the standard evaluation of various types of fire extinguishers against this potential threat is required to provide an unbiased means of comparing between fire extinguisher technologies and ranking them based on performance.

Nomenclature

CO_2	=	Carbon Dioxide
EDU	=	Engineering Design Unit
FWM	=	Fine Water Mist
ISS	=	International Space Station
Li-ion	=	Lithium Ion
PFE	=	Portable Fire Extinguisher
PMMA	=	Poly(methyl-methacrylate)
WSTF	=	White Sands Test Facility
VDC		Volts, Direct Current

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I. Introduction

Many sources of fuel are present aboard current spacecraft, with one especially hazardous source of stored energy: the lithium ion (Li-ion) battery. Because of their nature, Li-ion batteries are a very hazardous form of fuel when, for example, external heat is applied. In general, batteries typically become extremely energetic fire sources when heat is applied, due to the potential for the self-sustaining effects of thermal runaway. Currently, Li-ion batteries are the preferred types of batteries aboard international spacecraft; therefore, they are a readily available stored energy source if ever a fire should occur. Currently NASA is developing a fine water mist (FWM) portable fire extinguisher (PFE) for future use on international spacecraft. As development ensues, a need for the evaluation of various types of fire extinguishers is required to provide an unbiased means of ranking and comparison between units.

External heating was determined to be the only realistic method of initiating thermal runaway in Li-ion batteries, considering the specific International Space Station (ISS) environment. External overheating represented a scenario in which other equipment overheating or another fire in close proximity could heat batteries to a point of thermal runaway. Other means of initiating thermal runaway (e.g., short circuiting and overcharging) were determined to be highly improbable due to the extensive measures taken aboard the ISS to prevent these types of failures.

The test described here was developed at NASA White Sands Test Facility (WSTF) around a known source of stored energy currently aboard the ISS. Design and materials reviews were employed to mitigate any inherent risks posed by on-board stored energy sources. However, considering the quantity and overall potential energy contained on the ISS, it is prudent to understand the efficacy of fire extinguishers against a stored energy fire incident. Battery fires have a great potential to re-ignite if the heat has not been adequately removed from the test article. This test method provides an excellent challenge to a PFE's cooling capability and ability to mitigate propagation.

II. Test Sample

This paper documents the development of a standard test method that evaluates experimental fire extinguishers and their ability to combat a fire initiated by overheating Li-ion battery cells. Though many Li-ion configurations can be found on the ISS, the Canon®[*] BP-930 XL-1 Li-ion camcorder battery pack was chosen to represent Li-ion stored energy in a standardized test method The Li-ion battery was determined to be a suitable source of stored energy, analogous to larger scale stored energy sources found on the ISS. Table 1 shows the overall dimensions to the test sample battery pack.

Four individual battery cells are contained within each battery pack. Each of these four battery cells carry a charge of ~ 3.6 VDC (volts, direct current). Two of the contained cells are wired in parallel and two are wired in series, for a total output voltage of ~ 7.2 VDC.

Early in development, it was defined that this test should characterize the involvement of multiple battery packs. It was decided that using two battery packs was ideal in obtaining a challenging fire size while not creating an event that was unrealistically large. To maintain the advantages of multiple battery packs while creating a predictable sequence of events and evaluating propagation, an optimum configuration was established as two battery packs oriented in a stacked configuration.

The stacked Li-ion battery pack configuration consists of two separate battery packs stacked horizontally one on top of the other. The lower pack serves as an igniter battery (Synergy®[†] SD-BP930 Li-ion battery pack; overall dimensions are listed in Table 1); the upper serves as the sample battery (Canon). The voltage output of the igniter battery is identical to that of the sample battery. This orientation allowed for analysis of the propagation path between cells within a battery pack. This configuration provided two essential test variables: (i) the igniter battery served as a realistic external heat source for the sample battery pack; and (ii) the stacked configuration provided a clear propagation path not only from cell to cell but from battery pack to battery pack. The potential for stopping propagation with the use of a fire extinguisher allowed for better assessment of fire extinguisher performance. Figure 1 shows the stacked battery pack configuration.

[*] Canon® is a registered trademark of Canon Kabushiki Kaisha Corp., Tokyo, Japan.
[†] Synergy® is a registered trademark of Synergy Digital Power Products, Brooklyn, NY.

Table 1. Li-ion battery pack dimensions.

Canon® BP-930 XL-1 (Sample Battery)	
Battery Width	3.7 cm
Battery Length	7.0 cm
Average Battery Thickness	3.8 cm
Average Battery Weight	186.1 g
Synergy SD-BP930 (Igniter Battery)	
Battery Width	3.7 cm
Battery Length	7.0 cm
Average Battery Thickness	3.8 cm
Average Battery Weight	180.5 g

(a) (b)

Figure 1. (a) Battery bundle, (b) Constrained cells.

During developmental testing, it was determined that the Synergy battery casing material was far easier to ignite than the casing of the Canon battery. These characteristics were exploited when attempting to create a sequence of events. The two batteries were stacked with the more easily ignitable battery beneath the more robust, so a clear propagation path was established. The final sample configuration is shown in Fig. 1 with the Canon battery (sample) positioned above the Synergy battery (igniter).

A 1300W/240VAC heating element was used to heat the battery pack bundle to ignition. The heating element was equipped with a hinged mount and an electrical solenoid that, when actuated, would drop the heater away from the bottom of the battery bundle. Removal of the heating element ensured that any reactions occurring after the full involvement determination were due to internal reactions rather than external energy input.

Finally, the battery packs were placed with the cylindrical axis oriented perpendicular to the direction of fire extinguisher discharge. This orientation was determined to offer the greatest challenge to the PFE. The battery pack bundle would create 'shielded' fires by preventing direct impingement of the PFE plume on the back row of battery cells. Figure 2 shows the direction of PFE plume impingement (blue arrow) and the orientation of the cylindrical cells relative to the plume on a side view.

Preliminary tests showed the potential for rapid and violent venting of battery cells, resulting in cell ejections. Each cell is equipped with a rupture disc that typically resulted in a jet expelling pressurized gases axially from one end of the cylindrical cell. Failures of these rupture discs resulted in flaming jets and projectiles tracking along the axis of the cell.

Figure 3 (a, b) displays the kinetic potential of an ejected battery cell. Figure 3a displays the scale of energy released when a cell is ejected. During preliminary testing, a steel containment cage was used to prevent damage to a flammability chamber by the ejection of cells, yet this containment cage was punctured by an ejected cell.

The ejection of cells during a test would eliminate a heat source, decreasing the total energy input into the remaining cells. This loss of energy potential was decreed an invalidation of a test due to the variation an ejected cell would present compared to other tests. Several steps were taken to mitigate the risk of rapid venting/projectile ejection. All four battery cells within each battery pack were constrained to each other by weaving stainless steel tie wire throughout. The battery packs were reassembled so as to utilize the fuel potential of the casing material. The two battery packs were then further constrained together by a series of externally interwoven stainless steel tie wires (Fig. 1a).

The mitigation of propagation to adjacent materials is also of interest. Preliminary tests[1] showed hanging poly(methyl-methacrylate) (PMMA) sheets in the vicinity of the battery packs to be a satisfactory propagation material in the evaluation of the PFE. Four PMMA plates were placed parallel to each other and in the PFE stream, 5.1 cm (2.0 in.) apart and 6.4 cm (2.5 in.) above the battery pack bundle. The ignition of these propagation plates by the battery fire was required to declare a test sample fully involved, as it indicated that the fire had reached a large enough size that it could induce propagation to surrounding materials.

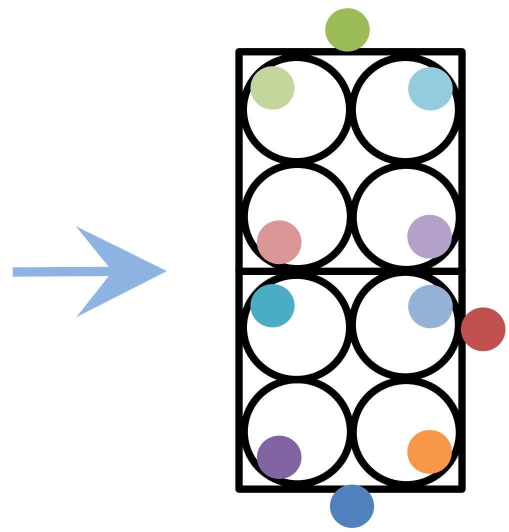

Figure 2. Side view cell/thermocouple orientation.

(a) (b)

Figure 3. (a) Damage to containment cage; (b) Ejected cells.

III. Fire Extinguishment Milestones Criteria

The involvement of all four bottom igniter battery cells and PMMA sheets was required prior to the initiation of the PFE. As mentioned previously, full involvement of the Synergy igniter battery pack served as a realistic overheat source for the sample Canon battery pack. All cells had to remain within the battery pack bundle for a test to be considered valid. This was to ensure that the maximum amount of energy was imparted from the igniter battery to the sample battery and that the maximum fire challenge was provided to the PFE. Adopting this acceptance criteria ensured the consistency and quality of data obtained from the testing.

Thermal runaway of each of the igniter battery cells was marked by the visual verification of flaming vents, aided by readings from the thermocouples located within the igniter battery pack (indicated by readings from the turquoise, blue-grey, purple and orange cells in Fig. 2). It was observed that temperatures in excess of ~ 400 °F were required to initiate thermal runaway.

Once the full involvement of the igniter battery pack and PMMA ignition was determined, a 15-s hold was initiated after which a firefighter was instructed to begin combating the fire, but only upon the Test Conductor's instruction. The goal of the 15-s wait time was to allow sufficient time after full involvement of the igniter battery to begin heating the sample battery and begin the thermal runaway process, but not so much time as to allow the sample battery to visibly ignite. This was done to evaluate the PFE's ability to stop thermal runaway and continued propagation within the sample battery pack. The heater was removed just prior to the fully involved point.

Passing criteria for the PFE was defined as all flames fully extinguished and re-ignition mitigated after full depletion of the fire extinguisher. Secondary evaluations included assessment of propagation minimization via posttest mass and charge evaluations as well as final thermocouple temperatures.

A. Firefighting Methodology

Automated fire extinguisher operation was considered; however, the manned operation offered the ability to analyze the technique and possibly direct recommendations based on observations. Therefore, a manned operation was chosen.

The involvement of all four of the igniter battery cells and PMMA sheets was required prior to initiating the PFE. The firefighter was positioned ~ 1.7 m (67 in.) away from the center of the event as a conservative distance when compared to the 1.2 m (48 in.) operational maximum currently available on the ISS. It was assumed an astronaut aboard international spacecraft would likely be restrained during use of a fire extinguisher and therefore would lack the ability to move positions to obtain a better vantage point of the fire. During test, firefighters were positioned in a stationary position with full range of motion in the torso and upper body in order to mimic conservative in-use conditions aboard the space station.

At the firefighter's discretion, the fire was fought until no flames were observed, with any subsequent flare-ups to be automatically combated. This method was deemed the "pulsing" method. The "pulse" technique is a possible realistic method of use aboard the ISS to preserve extinguishment media. After no flames had been observed for ~ 30 s, firefighters were instructed to empty the remaining contents of the PFE to further cool any residual heat within the individual battery cells. This method lengthened the effective use time of the PFE and ensured the extinguishment media was available throughout the duration of the fire.

Preliminary techniques involved firefighters fully depleting the PFE immediately after the first observed extinguishment. Re-ignition of the samples after full depletion of the FWM PFE occurred on several preliminary tests. Residual heat remaining in some of the battery cells promoted re-ignition. Once re-ignition occurred after full depletion, no discharge media remained to fight the fire. As a result of these tests, a 30-s wait time was imposed following extinguishment without re-ignition of the battery pack bundle before full depletion of the PFE was performed.

It was determined that this 30-s wait time was sufficient for possible re-ignitions to occur and allowed internal heat to be conducted to the surface for additional cooling. These observations have the potential to help establish a technique for future firefighters when operating any experimental PFEs against Li-ion battery fires.

Because astronauts receive limited firefighting training, trained vs. untrained firefighter effects were evaluated. Results depicted in Table 2 show average weight loss for the entire bundles during free burn, trained firefighter, and untrained firefighter tests. Considering a free burn test as a control, it was observed that both trained and untrained firefighter tests mitigated the combustion event; comparing just the weight loss values indicates no appreciable difference between the two types of tests.

Table 2 Trained vs. untrained firefighters (FF) posttest averages.

	Free Burn[a]	Trained FF[b]	Untrained FF[c]
Posttest Weight Loss (g)	151.7	85.3	91.5
Posttest Sample Pack Weight (g)	118.9	153.7	161.8
Posttest Igniter Pack Weight (g)	96.0	121.9	107.6
Test Duration (mm:ss)	7:29	3:14	2:27
Spray Duration (s)	N/A	58	56
No. of Pulses	N/A	2	2
Extinguishment Time (s)	N/A	1.1	0.65

[a] Average of six tests, [b]Average of three tests, [c] Average of four tests

The test duration data points in Table 2 indicate the average amount of time required between ignition of the battery pack bundle and the final extinguishment of the bundle, aided or unaided by the extinguisher. Trained and untrained firefighters required approximately the same amount of time to extinguish the blaze. Several tests performed with the same PFE showed the untrained firefighters had a slightly shorter average extinguishment time. These results show no appreciable advantage is gained by utilizing professional operators. Though astronauts receive some level of firefighting training, they cannot be considered fully trained firefighters. These data are reassuring because they indicate that retention of training will likely not affect the outcome of the event.

V. Experimental Apparatus and Data Acquisition

The method for initiating failure of the Li-ion battery was determined to be through external overheating. Overheating of the battery pack was shown to induce thermal runaway within the cells of a battery pack. Other means of initiating thermal runaway (short circuiting and overcharging) were determined highly improbable in space due to the extensive measures taken aboard the ISS to prevent these types of failures.

An automotive ignition system was used in order to ensure repeatable and conservative ignition of the test samples. Two 'sparkers' were placed at the ends of the battery packs and wired to spark alternately at ~ 14 Hz. These sparkers ensured consistency in ignition of gases that were potentially pyrolized or vented out of the 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 sparkers were used for redundancy. Figure 4 shows a drawing of the sparkers in place over the sample.

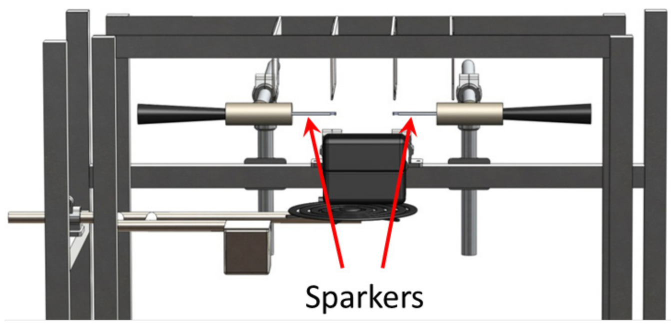

Figure 4. Sparker Placement.

Two keep out zone safety concerns emerged for ISS crew fighting potential fires. These were oxygen depletion and excessive environmental temperatures. Because crew may be limited in their ability to don protective equipment, these areas of concerns needed to be evaluated.

To evaluate excessive heat and burn concerns, calorimeters[‡] were used to measure the ambient room temperatures radiating from the test fire. Six calorimeters (Cu T ISO-17402) were placed in a "V" configuration emanating from the sample. Calorimeter readings can be related to human tissue second degree burn tolerance using the Stoll curve.[3]

To evaluate oxygen depletion keep out zones, oxygen sensors were placed at the same locations as the calorimeters. One oxygen sensor was placed on firefighter bunker gear to observe oxygen concentrations at the operators' positions. Oxygen concentration was monitored to determine if oxygen depletion could occur due to fire fumes and/or mist plume.

On the batteries themselves, eight internally mounted thermocouples were employed in addition to three externally mounted thermocouples Each of the eight thermocouples were placed one on each battery cell. The thermocouples were positioned to minimize the influence on the temperature measurement from adjacent cells within an individual battery pack. Figure 2 depicts the final thermocouple placement. Internally mounted thermocouples aided greatly in the analysis of individual battery cell involvement and fire extinguisher cooling capabilities. The internal effects caused by individual cells were only made apparent when the final thermocouple configuration was implemented. Prior to the implementation of this configuration, the mechanism for re-ignition was only speculative.

Firefighters were placed behind a Lexan shield for protection against ejected cells. A diagram of the entire test system setup can be seen in Fig. 5 and Fig. 6. Two screenshots of a typical test are shown in Fig. 7.

[‡] Calorimeters were used in anticipation of obtaining heat flux data. Upon initial analysis of the temperature measurements, further calculations were deemed unnecessary due to the relatively low temperatures in proximity to the test sample.

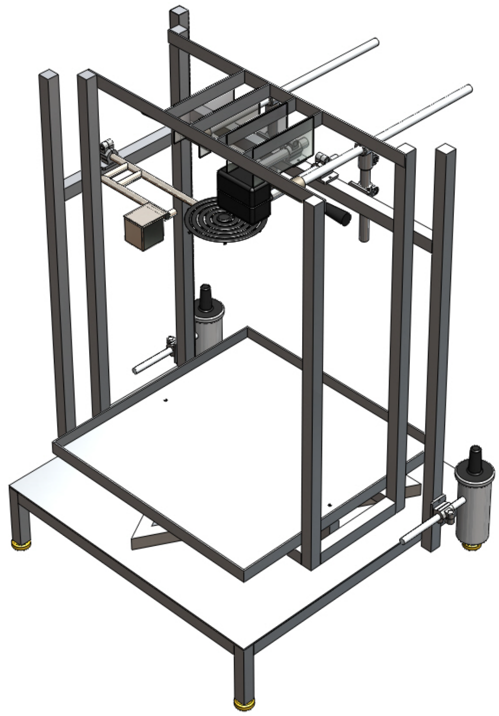

Figure 5. Battery test fixture.

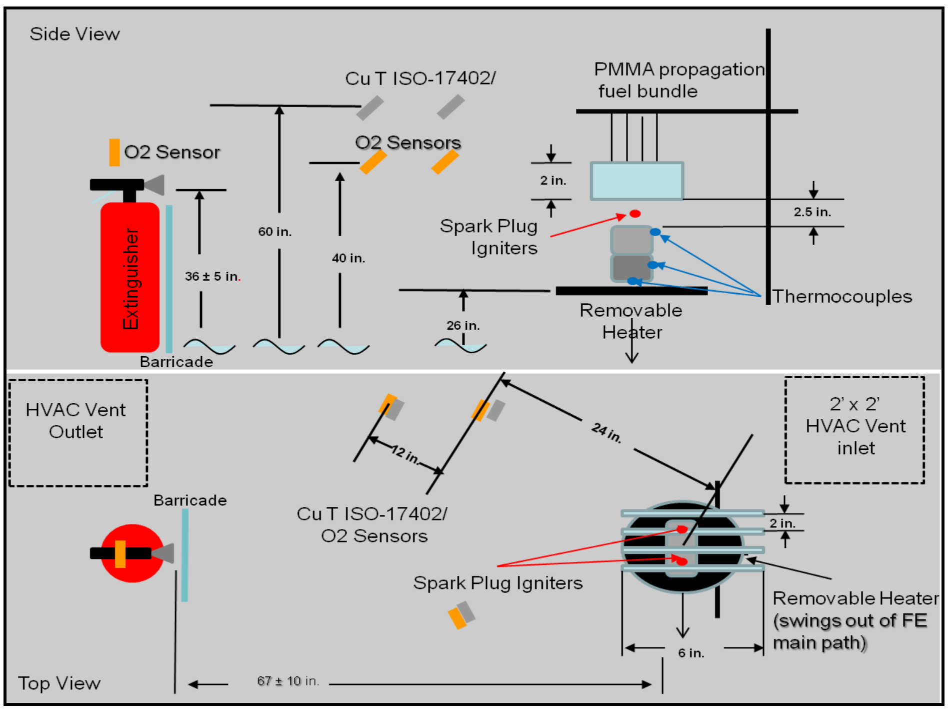

Figure 6. Li-ion battery test setup schematic.

Figure 7. Battery test video screen captures.

VI. Results and Discussion

To characterize the performance of a PFE against the Li-ion battery stored energy fire, three types of tests were performed. Free burn tests were performed in which the battery pack bundle was allowed to burn unhindered by the PFE. These free burn tests were performed as a way to characterize the fire and provide a control for comparison to PFE tests. The FWM PFE Engineering Design Unit (EDU)[2] was used in the tests discussed in this section; four nozzle configurations of the EDU were tested for firefighting efficacy. Also, results for tests performed using a commercially available 10 lb carbon dioxide (CO_2) PFE is discussed in this section as a means of comparison with the FWM PFE configurations. Currently, CO_2 PFEs are utilized aboard the ISS. The 10 lb CO_2 PFE tested here is conservative compared to the 6.5 lb CO_2 PFE currently in use on the ISS.

A. Discriminating Between Configurations: FWM PFE Engineering Design Unit Tests

The following section describes the different tests performed to evaluate the effects of the different component configurations when combating the Li-ion battery stored energy fire. Four nozzle configurations were evaluated. This section shows typical data generated from this method and the method's sensitivity in differentiating between configurations even within the same fire extinguisher technology.

No oxygen depletion was observed. Oxygen measurements did not fluctuate as a result of the test, most likely due to the ventilation within the cell. No fluctuations were observed as a result of PFE discharge.

The following paragraphs present a typical test performed using one of the nozzle configurations. Figure 8 is the temperature plot of Test No. 22.

Pre-ignition heating element temperatures were measured at just below 700 °F by the royal blue thermocouple attached to the outside bottom surface of the battery pack bundle. Ignition occurred at ~ 7 min 55 s. Temperatures recorded from the red thermocouple, most likely measuring direct flame temperature, indicated a rapid increase as a result of ignition. Temperatures throughout the battery packs increased after ignition. A vent marked the thermal runaway of the bottom purple cell at ~ 9 min 20 s; the ignited purple cell appears to initiate the heating of the turquoise cell located directly above. The PMMA ignited ~ 15 s later. Another vent occurred marking the thermal runaway of the bottom orange battery cell. At 9 min 30 s, both battery cells located at the bottom of the igniter battery pack had reached thermal runaway.

A vent dislodging the purple thermocouple at ~ 10 min 15 s was followed by a vent indicating thermal runaway within the turquoise battery cell; the light blue thermocouple cell directly above the orange cell reached thermal runaway immediately afterwards. At this point all four battery cells within the igniter battery pack were fully involved, and the PMMA was ignited at ~ 10 min 30 s, when full involvement was declared by the Test Conductor. The heater was removed or turned off after all four cells in the igniter battery pack were observed to be fully involved.

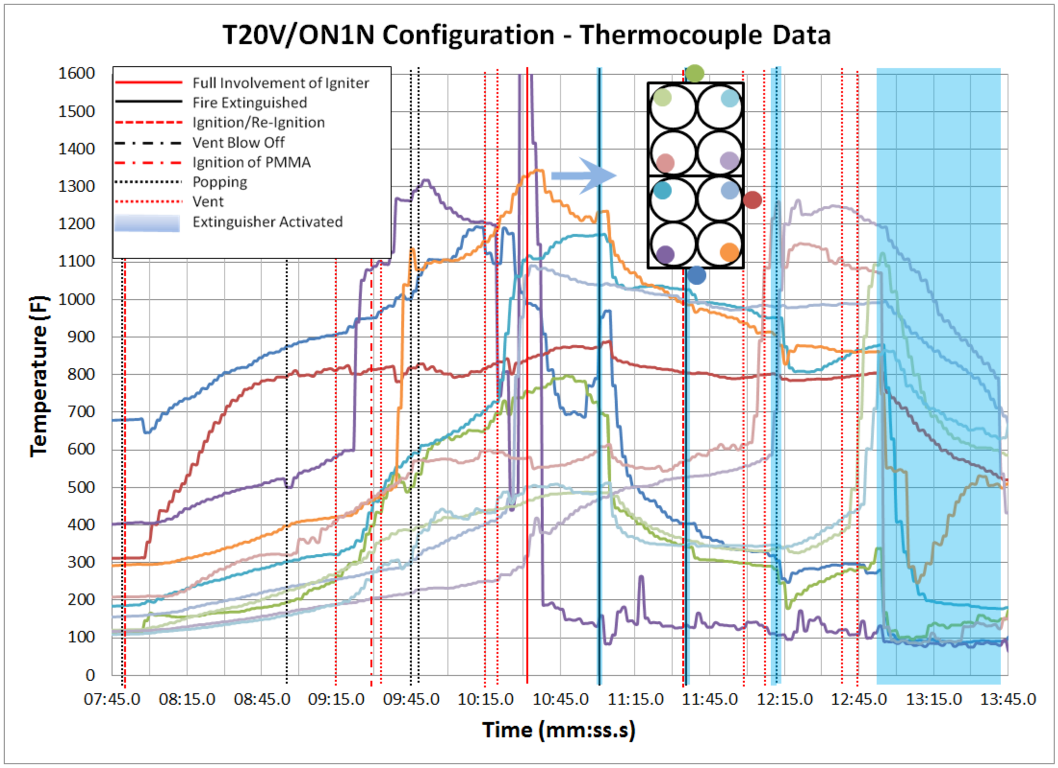

Figure 8. Test No. 22: T20V/ON1N EDU test, thermocouple data.

At 11 min, the FWM PFE was discharged and the fire was extinguished. As a result, the orange, light purple, and turquoise cell temperatures decreased steadily until ~ 11 min 35 s when re-ignition occurred. Firefighters immediately addressed the re-ignition, extinguishing it for a second time. Two vents occurred ~ 15 s later, indicating thermal runaway occurring in the pink and pale purple cells (the bottom two cells within the sample battery pack). The firefighter discharged the FWM PFE for a third time without instruction from the test team due to observed venting. The 30-s hold prior to full discharge was initiated; and ~ 20 s into the hold two more vents and temperature spikes occurred, signaling the thermal runaway of the top two batteries within the sample battery pack. Actual ignition of vent fumes was not observed. Shortly thereafter the FWM PFE was fully discharged, cooling the cells and preventing further reactions within the battery cells. The FWM PFE was powerful enough to halt steep temperature increases in the light green and light blue cells, which were both in the middle of thermal runaway. Cooling cells in the middle of thermal runaway can be seen as the optimal challenge for any fire extinguisher. Once again the pale purple cell was the hottest cell after full and final discharge, confirming the additional challenge its shielded position provided to the FWM PFE. Despite all cells undergoing some level of reaction during this test, the PFE was able to prevent re-ignition of the test sample, which saved the remainder of the sample battery casing material, as well as mitigated venting and consumption of the top light green and light blue cells.

Figure 9 shows the environmental temperatures within the test cell throughout Test No. 22. Significant temperature increases were not observed until the bottom purple cell reached thermal runaway at ~ 9 min 15 s. Peak temperatures occurred at ~ 11 min, occurring shortly after the peak temperatures recorded within the bottom orange cell. A stratification of temperatures according to the proximity of the calorimeters existed. An increase of a maximum of ~ 12 °F was observed. Maximum temperatures, measured at 24 in. from the battery fire, were ~ 83 °F, well below the 112.2 °F recommended temperature pain limit.[3]

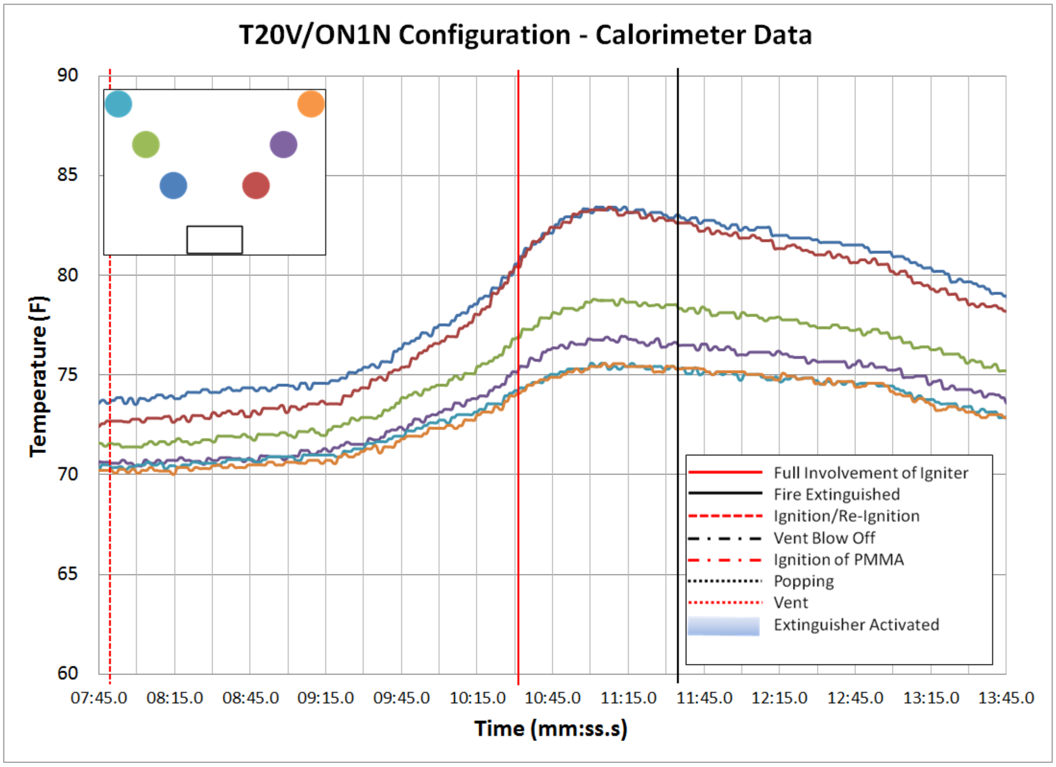

Figure 9. Test No. 22: T20V/ON1N EDU test, calorimeter data.

When comparing data from the four configurations tested, clear differences could be easily noted between nozzle options. Testing confirmed that the developed Li-ion battery test method was sensitive enough to discriminate between configurations of the same technology. A more detailed discussion of data analysis will be presented later in this section.

B. Discriminating Between Technologies: CO_2 PFE Tests

In the previous section, FWM technology tests were presented. To compare the test method's sensitivity in discriminating between technologies, tests were also performed using a commercially available CO_2 PFE as a means to simulate the standard PFE currently used on the ISS. A CO_2 fire extinguisher suffocates a fire, while an FWM extinguisher cools a fire. The CO_2 PFEs used for testing provided additional conservatism as they held 10 lb of CO_2 compared to the 6.5 lb flight units. In Fig. 10, the first and most striking observation is that the CO_2 PFE failed to extinguish the fire without re-ignitions.

Following the initial extinguishment, the pink and light purple thermocouples (located in the sample battery) increased in temperature, most likely heated by the adjacent cells located in the igniter battery (Fig. 10). At 13 min, the final discharge of the PFE was initiated. During the final discharge, a vent was observed most likely due to the cell measured by the pink thermocouple. Re-ignition of the test sample occurred at ~ 13 min 20 s.

Figure 11 displays oxygen sensor measurements from a battery test with a CO_2 PFE discharge. The "X"s indicate oxygen concentration and can be interpreted using the axis to the right. Immediately after discharge, several oxygen sensors indicated a drop of ~ 1.5 percent oxygen from ambient conditions. A small decrease in oxygen concentration was observed during fire extinguishment despite forced flow within the facility and buoyant convection flow, indicating that some oxygen depletion was occurring due to CO_2 displacement. It should be noted that oxygen depletion on the ISS would likely be more significant than seen on the ground tests due to the smaller cabin volume and lower ventilation. Diffusion would be the only driver for dilution in a fire scenario on the ISS, where ventilation has been shut off as part of standard fire protocol. If CO_2 levels were to reach above 3 percent, effects would begin to be noted; and levels above 5 percent would be considered directly toxic.

Clear differences can be seen in extinguishing performance when comparing data between the FWM and the CO_2 PFE technologies. Testing confirmed that the developed Li-ion battery test method was sensitive enough to discriminate between configurations of the same technology. A more detailed discussion of data analysis will be presented later in this section.

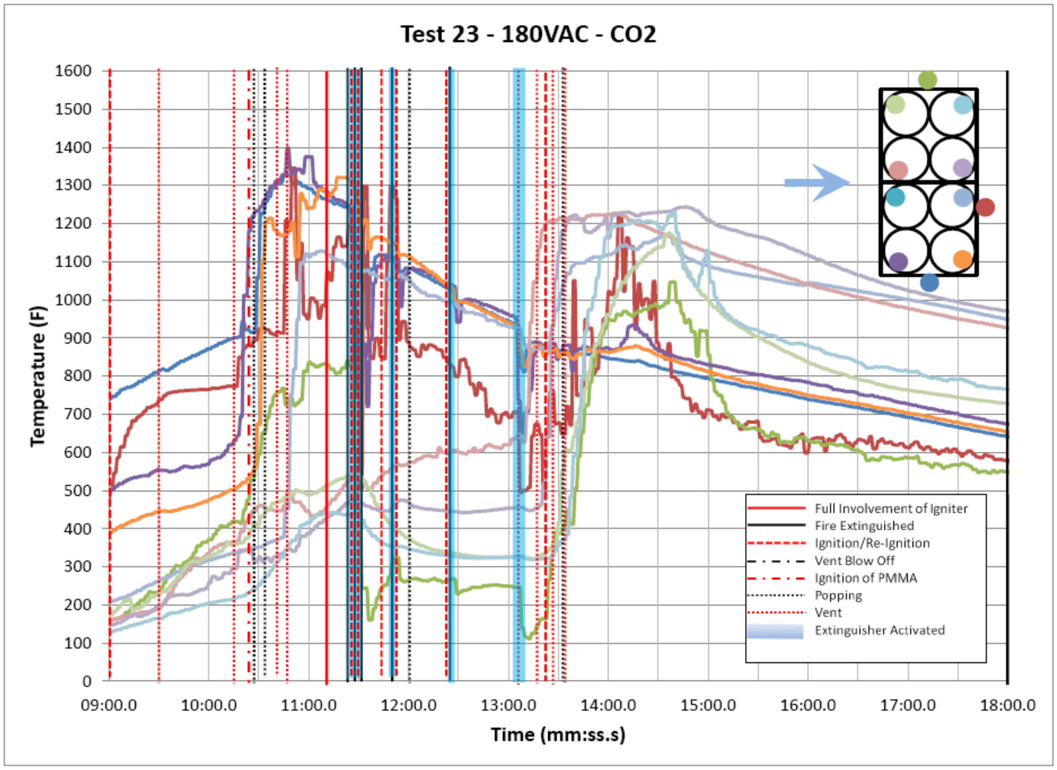

Figure 10. Typical CO_2 PFE battery test: Thermocouple data (tight).

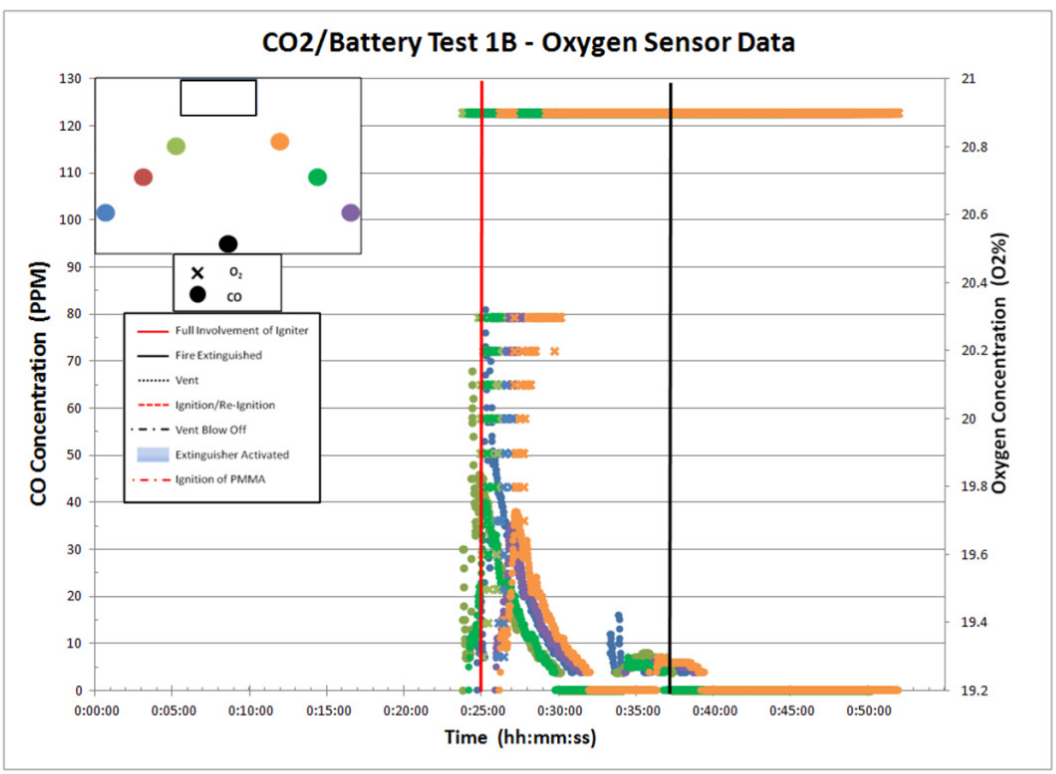

Figure 11. Typical CO_2 battery test: Oxygen sensor data.

C. Interpretation and Application of Data

Posttest analysis of the battery packs consisted of visual inspection, mass measurements, and voltage measurements. Posttest analysis also included verification of acceptance criteria, analysis of test footage, and extinguisher performance analysis. Remaining casing mass as well as remaining voltage assisted in assessing how effective a given fire extinguisher configuration mitigated propagation.

The casing material was apparently consumed for all of the free burn tests; however, some if not most of the sample battery casing remained after tests performed with the FWM PFE. The CO_2 PFE failed to extinguish the test sample; posttest samples appeared similar to the free burn posttest samples. Evidence of mitigation of propagation could be seen by simply examining the FWM PFE posttest photos. Table 3 shows a summary of the mass and voltage measurement results for the preliminary tests, showcasing the effects of free burn tests compared to PFE tests. Testing performed using a commercially available 10 lb CO_2 PFE resulted in failures to extinguish the test fire in every attempt. Tests performed using the 10 lb CO_2 PFE were conservative when compared to the 6.5 lb ISS units. For all CO_2 PFE tests, posttest mass and charge analysis coincided with battery packs retrieved from full burn tests.

Table 3. Comparison of average posttest measurements.

Test	Igniter Battery Pack				Sample Battery Pack			
	Weight (g)	# of cells Charge = 0	# of cells Charge >0	# of cells Charge >75%	Weight (g)	# of cells Charge = 0	# of cells Charge >0	# of cells Charge >75%
Pretest[a]	180.47	0	4	4	186.09	0	4	4
Free Burn[b, h]	124.88	4	0	0	130.18	4	0	0
Free Burn[c, g]	96.04	4	0	0	118.85	4	0	0
FWM PFE[b, j]	136.48	4	0	0	175.83	2.0	2.0	0.8
FWM FF[c,d, h]	124.39	4	0	0	166.87	0.67	3.33	1.0
FWM UT FF[c,e, i]	105.75	4	0	0	173.68	1.0	3	1.5
CO_2 PFE[c,f, h]	100.76	4	0	0	115.82	4	0	0

[a] Average of 4 igniter and 4 sample battery pack values; [b] Initial thermocouple configuration test performed w/ 140VAC; [c] Final thermocouple configuration, test performed w/ 180VAC; [d] Test performed by trained firefighting professional; [e] Test performed by test personnel; [f] Commercially available 10 lb CO_2 PFE; [g] Average of 2 tests; [h] Average of 3 tests; [i] Average of 4 tests; [j] Average of 5 tests

In addition to extinguishment/non-extinguishment criteria, mass and voltage measurements were particularly useful in comparing the PFE technologies. Mass and voltage did not offer as much insight in comparing configurational differences within one technology.

Fine water mist technology works on the principle of heat removal as a means to mitigate a fire event. Re-ignitions generally occurred as a result of shielded battery cells reheating adjacent cells and forcing thermal runaway to resume. Considering the efficacy of the cooling effect on the test samples, a high post-final discharge thermocouple temperature indicates less cooling had taken place as a result of the full PFE discharge. Because pulsing duration and number vary from test to test, only the final temperature after the full depletion of a PFE can provide true insight into how well a given PFE performed. Posttest cell temperatures serve as a good indication of the amount of cooling provided by a PFE during discharge and allow comparison between configurations and technologies in performance. Figure 12 shows the highest temperatures of any single thermocouple measurement after full discharge of the FWM PFE during EDU configurational comparison testing. Highlighted with a red dashed line is the failure of the T12V/HF4N FWM PFE configuration in one of four tests (Test No. 58) and with a black dashed line the similar but passing test scenario using the T20V/ON1N FWM PFE configuration (Test No. 22) described previously. The blue bars indicate measured maximum temperature immediately after final and full discharge, and the red bars indicate the calculated averages for each of the FWM PFE configurations.

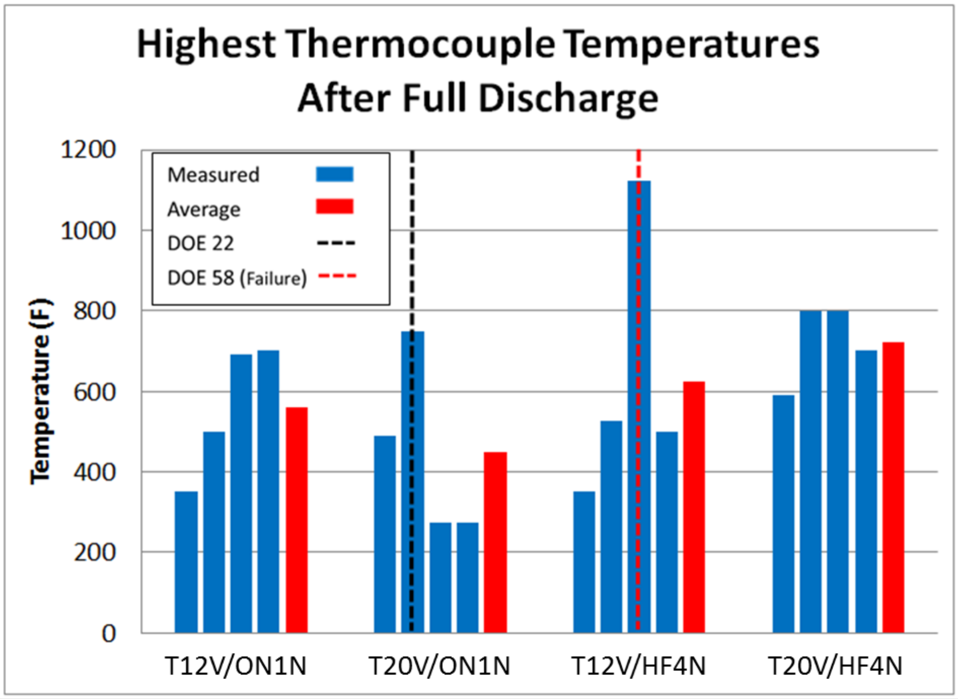

Figure 12. Highest EDU posttest temperatures.

As one would expect, the test that experienced a failure resulted in the highest post-final discharge temperature among all the tests performed. After final discharge, the temperatures measured showed significant cooling; nonetheless, they were still high enough to heat adjacent cells and reinstate thermal runaway reactions. The battery cell that consistently displayed the highest post-final discharge temperatures was the back lower battery cell within the sample battery pack (light purple). This battery cell was in the most shielded position, posing the greatest challenge to the PFE and therefore the greatest risk for sample reheating. Located in the lowest row of the sample battery pack, this row received the most heat and the least cooling within the sample battery pack because of its close proximity to the fully involved battery cells (turquoise and blue grey). This cell was also shielded from direct PFE plume impingement.

Regardless of the FWM PFE configuration used, Fig. 12 indicates configurations utilizing the HF4Ncomponent resulted in higher post-final discharge temperatures on average than tests utilizing the ON1N component. The failure of the test using the T12V/HF4N configuration, and the average extinguishment times coupled with the final thermocouple temperatures, lead to the conclusion that the ON1Ncomponent performed better. In addition to extinguishment/non-extinguishment criteria, the highest final thermocouple temperature after final and full discharge proved to be a sensitive indicator for evaluating and comparing PFE performance.

VII. Conclusions

The development of a repeatable test method simulating a realistic yet challenging ISS stored energy fire scenario, unbiased with regard to the type of PFE used, was the primary goal of these experiments. Reproducibility was paramount, and measures were taken to achieve this goal by means of a standardized test sample as well as a standardized test method. The success of the containment of the battery cells throughout the test was mostly due to the development of the cell containment wiring technique. Not only were the negative effects of the test mitigated but also the safety concerns. Measurement of various parameters, as well as adjustment of test method when observations dictated the need for changes, proved necessary to achieve this goal.

Cooling proved to be the mitigating factor for this type of fire. The FWM PFE performed well in this test scenario for that reason. Suffocation as the main means of extinguishment (for example, with CO_2) in the case of a Li-ion battery fire showed to be insufficient due to the internal thermal mechanism driving this type of fire.

Shielded battery cells offered another challenge in the cooling process. Testing showed that these shielded battery cells were often the source of reheating, resulting in re-ignitions of the test sample. Shielded cells have the ability to retain heat and act as a heating element, causing adjacent cells to reach thermal runaway more easily.

The method of implementing the extinguisher using the pulsing technique lengthened the effective use time of the PFE and ensured extinguishment media was available throughout the duration of the fire. This realistic technique may provide guidance for the eventual use on spacecraft.

The Li-ion batteries test method provided a very energetic fire that proved to be challenging. Testing showed the method's ability to differentiate between PFE technologies (FWM and CO_2) as well as between configurations of a single technology (FWM PFE). In addition to extinguishment criteria, the test method allowed assessment of propagation minimization via evaluation of posttest sample mass and charge measurements. Final temperatures after full and final discharge of PFE proved to be a sensitive parameter by which to evaluate and compare PFE performance. This method also provides adequate evaluation of temperature and oxygen keep out zones.

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Notes

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

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