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Flammability Assessment of Lithium-Ion and Lithium-Ion Polymer Battery Cells Designed for Aircraft Power Usage

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16. Abstract

Tests were performed at the Federal Aviation Administration William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Research and Development Division to examine the fire safety hazards that cylindrical- and polymer-type lithium-ion batteries may pose onboard aircraft. Tests were conducted on individual, manufacturer-supplied battery cells to determine how the cells would react in a fire situation, as well as what potential fire hazard the battery cells themselves may pose and the effectiveness of a typical hand held extinguisher on a fire involving the battery cells. The battery cells that were tested were all commercial off-the-shelf products that are being considered by manufacturers for aircraft power-related usage.

The results of the tests showed that the lithium-ion and lithium-ion polymer battery cells can react violently when exposed to an external fire. Under test conditions, when the battery cells failed, flammable electrolyte was released and ignited, which further fueled the existing fire. This release and ignition of the electrolyte resulted in significant temperature and pressure increases within the test fixtures.

Tests conducted with a hand-held Halon 1211 fire extinguisher showed that the halon was able to extinguish all three battery-type fires. However, even after several attempts, the halon extinguishing agent was not able to prevent the lithium-ion polymer battery cells, which are of a different chemistry, as well as a much higher energy density and power capacity, from reigniting.

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LIST OF ACRONYMS

Ah	Ampere-hour
FAA	Federal Aviation Administration
Li-ion	Lithium-ion
Li-Po	Lithium-ion polymer
mAh	Milliampere-hour
PED	Personal electronic devices
SOC	State of charge

EXECUTIVE SUMMARY

Rechargeable lithium-ion batteries offer many advantages over current battery technologies. They possess a high-energy density per unit volume, relatively constant voltage during discharge, low maintenance, good low-temperature performance, and a long shelf life. There is, however, a certain amount of hazard associated with the use of these batteries due to their high-energy content and potential thermal instability. Their proposed use onboard aircraft as power sources for starting aircraft engines or auxiliary power units, as well as other avionics, emergency, and standby systems, require the examination of the safety of their design. How these batteries will react in a fire situation and what type of fire hazard they pose themselves must be examined. Tests must be performed to ensure the batteries provide an appropriate level of safety. Current regulatory and test requirements may need to be updated to address the hazards associated with this new technology.

Tests were performed at the Federal Aviation Administration William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Safety Research and Development Division to examine the fire safety hazards that cylindrical and polymer type lithium-ion batteries may pose onboard aircraft. Tests were conducted on individual, manufacturer-supplied battery cells to determine how the cells would react in a fire situation. Tests were also conducted to determine what potential fire hazard the battery cells themselves may pose and to determine the effectiveness of a typical hand-held extinguisher on a fire involving the battery cells. The battery cells that were tested were all commercial off-the-shelf products that are being considered by manufacturers for aircraft power-related usage.

The results of the tests showed that the lithium-ion and lithium-ion polymer battery cells can react violently when exposed to an external fire. The cylindrical cells vented in a manner by which the electrolyte would spray out forcefully and ignite, increasing both temperature and pressure. The lithium-ion polymer battery cells had 3.5 to 7 times the capacity of the cylindrical cells and did not have vent locations. Instead, they were designed with a seam around the perimeter of the cell that would open, thereby exposing the flammable electrolyte. The failure of these battery cells greatly fueled the existing fire as the full amount of the electrolyte was exposed instantaneously to the fire source. In both single- and multiple-cell tests, the lithium-ion polymer battery cells, which are of a different chemistry and had a much higher energy density and power capacity (8 ampere-hour (Ah) per cell versus 1.2 and 2.3 Ah for the cylindrical cells), resulted in significantly higher temperature and pressure increases compared to the cylindrical cells.

Attempts to cause the battery cells to reach their thermal runaway point via short circuiting were unsuccessful on all three battery types.

Autoignition tests showed that battery cells failed, venting their flammable electrolyte at temperatures ranging between 330° and 527°F.

Tests conducted with a hand-held Halon 1211 fire extinguisher showed that the halon was able to extinguish all three battery type fires. However, for the lithium-ion polymer battery cells, even after several attempts, the halon extinguishing agent was not able to prevent the cells from reigniting.

1. INTRODUCTION.

1.1 BACKGROUND.

Rechargeable lithium-ion (Li-ion) batteries offer many advantages over current battery technologies. They possess a high-energy density per unit volume, relatively constant voltage during discharge, low maintenance, good low-temperature performance, and a long shelf life. There is, however, a certain amount of hazard associated with the use of these batteries due to their high-energy content and potential thermal instability. Their proposed use onboard aircraft as power sources for starting aircraft engines or auxiliary power units, as well as other avionics, emergency and standby systems, require the examination of the safety of their design. How these batteries will react in a fire situation and what type of fire hazard they pose themselves must be examined. Tests must be performed to show that they provide an appropriate level of safety. Current regulatory and test requirements may need to be updated to address the hazards associated with this new technology.

1.2 PREVIOUS RESEARCH AND REGULATIONS.

The Federal Aviation Administration (FAA) previously conducted research regarding the bulk shipment of both primary (i.e., nonrechargeable) lithium [1] and rechargeable Li-ion batteries [2]. The results stated that a relatively small fire source was sufficient to cause the battery cells to vent flammable electrolyte. In addition, it was determined that Halon 1301 did not prevent the further release of electrolyte from the heated cells, and a fire involving a bulk-packed Li-ion shipment may in fact compromise the integrity of the cargo compartment, due to the pressure increase that is observed when the cells begin to vent.

As a result of these findings, large, palletized shipments of primary lithium batteries are no longer permitted onboard passenger aircraft. In addition, the Pipeline and Hazardous Materials Safety Administration (PHMSA) released a rule in January 2008, which among other things, prohibits the transportation of loose Li-ion batteries used for personal electronic devices (PED) in checked baggage.

In addition to these tests, the FAA also determined the most effective method of extinguishing a cabin fire involving Li-ion batteries in PEDs. These tests resulted in a training video that provides guidance to flight crew on how to respond to such a fire. The training video is available online at http://www.fire.tc.faa.gov.

1.3 SCOPE.

Tests were performed at the FAA William J. Hughes Technical Center by the Fire Safety Team of the Airport and Aircraft Safety Research and Development Division to examine the fire safety hazards that Li-ion batteries may pose onboard aircraft. Tests were conducted on individual, manufacturer-supplied battery cells to determine how the cells would react in a fire situation. Tests were also conducted to determine what potential fire hazard the battery cells themselves may pose and to determine the effectiveness of a typical hand-held extinguisher on a fire involving the battery cells. The battery cells that were tested were all commercial off-the-shelf products that are being considered by manufacturers for aircraft power-related usage. The results of these cell-level tests are to be used to determine the necessary safety and test requirements of a battery system designed for aircraft usage. These safety systems may include vent hole sizing and positioning, thermal protection circuits, hardened casings, and physical barriers placed between adjacent cells. It should also be noted that battery technology is constantly evolving. There are several different chemistries used in these batteries. Two of the major chemistries, those with oxide- or phosphate-based cathodes, were examined in this research.

2. TEST EQUIPMENT.

2.1 BATTERY CELLS.

Three battery cell types were obtained for testing purposes, all with varying chemistries, dimensions, and power characteristics. Two cells were cylindrical in shape and varied in size. The first was 18 mm in diameter, and the second was 26 mm in diameter. Both were 65.0 mm in height. Typical notation for a cylindrical battery cell consists of a five-digit code, where the first two digits represent the diameter of the cell, and the last three digits represent the height. As such, these two cells are considered to be 18650- and 26650-sized cells, respectively. The third battery cell type was a lithium-ion polymer (Li-Po) battery, which instead of being cylindrical, was a nearly flat rectangular-shaped cell measuring 3.5″ by 4″ by 1/4″.

The 18650 cell had a lithium iron phosphate-based chemistry with a capacity of 1150 milliampere-hours (mAh). The nominal voltage per cell for this battery type was 3.3 V, and the recommended charge voltage was 3.85 V.

The 26650 cell also had a lithium iron phosphate-based chemistry with a capacity of 2300 mAh. The nominal voltage per cell for this battery type was 3.3 V, and the recommended charge voltage was 3.6 V.

The Li-Po cell had a lithium cobalt dioxide-based chemistry with a capacity of 8000 mAh. The nominal voltage per cell for this battery type was 3.7 V, and the recommended charge voltage was 4.2 V.

Table 1 summarizes the characteristics of each cell, and figure 1 shows the battery cells that were tested.

Table 1. Summary of Battery Specifications

	Battery Cell 1	Battery Cell 2	Battery Cell 3
Battery type	Cylindrical Li-ion	Cylindrical Li-ion	Li-ion Polymer
Battery size	18650	26650	3 1/2″ x 4″ x 1/4″
Chemistry	Lithium Iron Phosphate	Lithium Iron Phosphate	Lithium Cobalt Dioxide
Capacity (mAh)	1150	2300	8000
Nominal voltage	3.3	3.3	3.7
Charge voltage	3.85	3.6	4.2

(a) (b) (c)

Figure 1. Battery Cells Used in the Tests (a) 18650, (b) 26650, and (c) Li-Po Cell

2.2 FIRE TEST CHAMBER.

A 64-ft^3 fire test chamber was constructed to evaluate the flammability of the test cells. The fire test chamber was constructed of 1/8″ steel and measured 4′ by 4′ by 4′. The front side of the fire test chamber was fitted with a hinged door to provide access to the inside of the chamber. This door had a large Plexiglass window to view and videotape the test in progress. The fire test chamber was equipped with variable 3″ vent holes located on the centerline of the sidewalls, 2″ above the floor. Horizontal slots, 3″ by 30″, were cut near the top of the sides and back wall. These slots were sealed with aluminum foil to act as blowout panels to prevent any overpressure from damaging the structure. The fire test chamber was also fitted with a nozzle at the top center of the structure to allow for the injection of Halon 1211 for extinguishing purposes.

A steel angle frame was constructed to support a basket made from 0.5″ wire mesh. This mesh basket was used to support the cells at a height of 4″ over a 5.25″ square fire pan. Four type-K thermocouples were placed along the centerline of the fire test chamber. The first was placed at a height of approximately 12″ from the floor of the fire test chamber, with each subsequent thermocouple spaced vertically approximately 12″ apart from each other. Figure 2 shows a diagram of the fire test chamber.

Figure 3 shows the results of the baseline fire conditions to which the battery cells were exposed, which consisted of 50 ml of 1-propanol ignited with a propane torch. The peak temperature recorded was approximately 450°F, measured 12″ above the fire pan, roughly 3 minutes into the test. The temperature at the ceiling of the fire test chamber rose only to approximately 215°F.

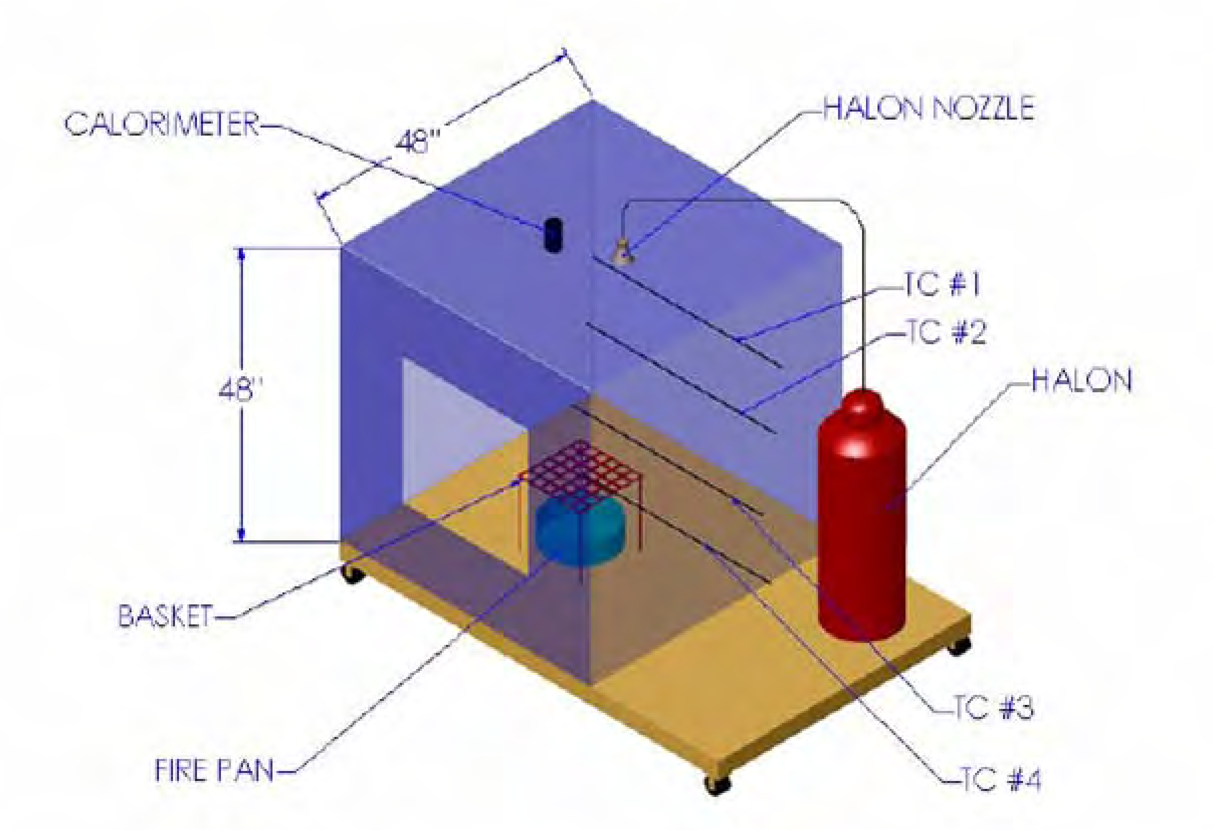

Figure 2. Fire Test Chamber

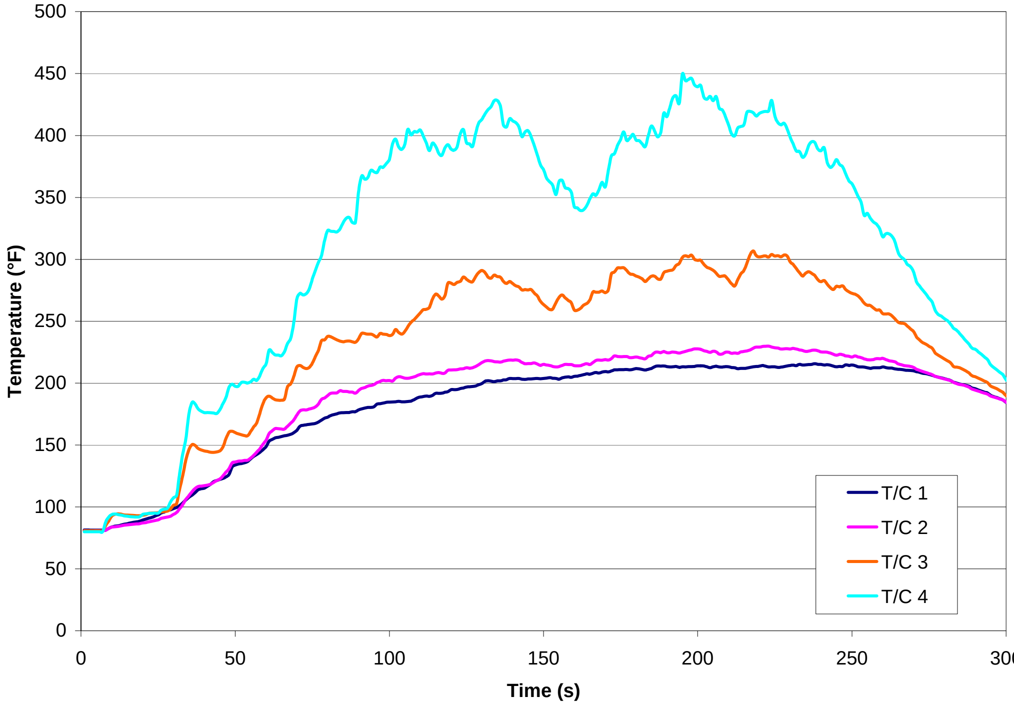

Figure 3. Baseline Fire Source Data in the Fire Test Chamber

2.3 PRESSURE FIRE MODELING FACILITY.

The pressure fire modeling facility houses a 5-ft-diameter, 350 ft^3 pressure vessel capable of withstanding a maximum working pressure of 650 psi. A steel angle frame was constructed to support a basket made from 0.5″ wire mesh. This mesh basket was used to support the cells at a height of 4″ over a 5.25″ square fire pan. This fire pan and support basket were placed in the center of the pressure vessel. Three type-K thermocouples were placed in the vessel to record temperature throughout the test. One was placed at the location of the fire pan, and one was approximately 42″ away from the fire pan in either direction. Each thermocouple was placed at a height of 18″ above the support basket. In addition, a pressure transducer was used to record the pressure pulse within the pressure vessel. Figure 4 shows an external view of the pressure fire modeling facility.

Figure 4. External View of the Pressure Fire Modeling Facility

Figure 5 shows the results of the baseline fire conditions to which the battery cells were exposed. The peak temperature recorded was approximately 310°F, measured 18″ above the location of the battery support basket. The temperature readings at the front and rear of the pressure vessel reached just over 110°F, and the pressure rose by roughly 0.4 psi.

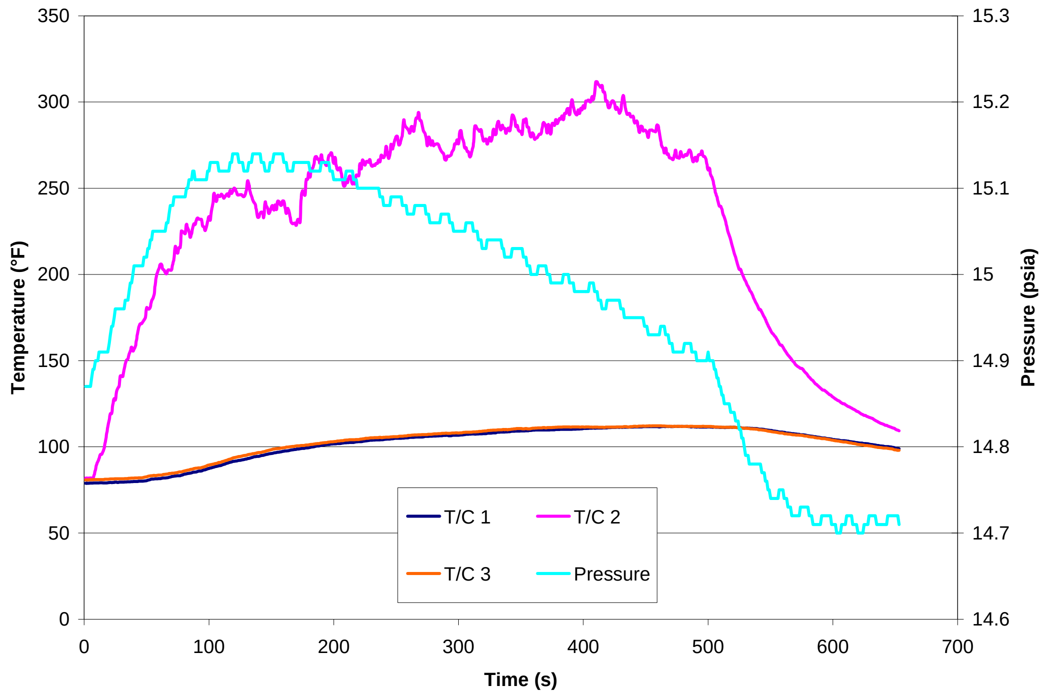

Figure 5. Baseline Fire Source Data in the Pressure Fire Modeling Facility

2.4 AUTOIGNITION TEST CHAMBER.

The autoignition test chamber was a 1-ft^3 insulated, steel box. A steel angle frame was constructed to support a basket made from 0.5″ wire mesh, which was used to support the battery cells in the center of the test chamber. Two type-K thermocouples were placed inside; one near the top of the autoignition test chamber and one in the direct vicinity of the battery cell. An oxy-acetylene torch, fitted with a rosebud nozzle, was attached to a support structure to provide an external heat source for the autoignition test chamber. Figure 6 shows the test chamber and torch setup.

Figure 6. Autoignition Test Chamber

3. TEST PROCEDURES.

3.1 FIRE EXPOSURE TESTS.

The fire exposure tests were designed to evaluate the results that occur when a battery cell or a group of battery cells is exposed to an external fire. For each battery type, the fire exposure test was conducted with a single cell, a group of four cells, and a group of eight cells. In the multiple-cell tests, the cells were packaged in a tight configuration and secured with safety wire. All cells were charged to 100% state of charge (SOC) and placed in the mesh basket inside the fire test chamber. The cylindrical battery cells were positioned with the vent locations pointing in an upward direction. The Li-Po battery cells were positioned vertically with the positive and negative terminals pointing upward. All the battery cells were positioned directly above the center of the fire pan.

The test was initiated by loading 50 ml of 1-propanol into the fire pan and igniting it with a propane torch. The fire test chamber door was then closed and sealed. The behavior of the battery cell(s) was monitored throughout the test, along with temperature readings from the four fire test chamber thermocouples.

3.2 PRESSURE PULSE TESTS.

The pressure pulse tests were designed to determine and evaluate the pressure pulse resulting from the failure of a battery cell or groups of battery cells. For each battery type, the pressure pulse test was conducted with a single cell, a group of four cells, and a group of eight cells. In the multiple-cell tests, the cells were packaged in a tight configuration and secured with safety wire. All cells were charged to 100% SOC and placed in the mesh basket inside the pressure vessel.

The test was conducted similar to the fire exposure tests and was initiated by loading 50 ml of 1-propanol into the fire pan. The pressure vessel door was then closed and sealed. A remotely triggered oil burner spark igniter was used to ignite the 1-propanol. The behavior of the battery cell(s) was monitored throughout the test, along with all temperature and pressure readings within the sealed pressure vessel.

3.3 HALON 1211 SUPPRESSION TESTS.

The Halon 1211 suppression tests were designed to evaluate the effectiveness of a typical hand-held fire extinguisher in extinguishing and suppressing a fire involving Li-ion battery cells. For each battery type, the suppression tests were conducted with a group of eight cells packaged in a tight configuration and secured with safety wire. All cells were charged to 100% SOC and placed in the mesh basket inside the fire test chamber. The tests were conducted in the exact same manner as the fire exposure tests.

At the point of failure of a single battery cell, Halon 1211 was discharged into the fire test chamber until the fire was extinguished. The behavior of the battery cells was monitored throughout the test, along with temperature readings from the four fire test chamber thermocouples. In the event that subsequent cells either ignited or vented, additional Halon 1211 was discharged into the fire test chamber. At the end of the tests, the battery cells and the fire test chamber were allowed to cool to ensure no further ignition or venting would occur.

3.4 EXTERNAL SHORT-CIRCUIT TESTS.

The external short-circuit tests were designed to evaluate the effect of a short circuit on an individual cell. For each battery type, a single cell was charged to 100% SOC and was placed in in the mesh basket inside the fire test chamber. A 14-gauge wire was used to connect the positive and negative terminals of the battery cell. In addition to the thermocouples inside the fire test chamber, a thermocouple was placed on the external casing of the battery cell itself to monitor the actual cell surface temperature. The test was conducted to observe if any fire, explosion, or venting of the battery would occur. If no fire, explosion, or venting was observed, the test was continued until the battery cell temperature peaked and began to decline, which indicated the battery cell had fully discharged without resulting in a fire or explosion.

3.5 AUTOIGNITION TESTS.

The autoignition tests were designed to evaluate the risk of a battery cell reaching thermal runaway and either venting or exploding due to an external heat source such as a suppressed smoldering cargo fire. For each battery type, an individual battery cell at 100% SOC was placed in the mesh basket inside the autoignition test chamber. An oxy-acetylene torch fitted with a rosebud nozzle was used as the heat source. The torch was positioned so the flame impinged on the bottom surface of the autoignition test chamber, creating a steady temperature rise within the autoignition test chamber. The autoignition test chamber temperature was increased until the battery cell either ignited or vented. The temperature within the autoignition test chamber was monitored and recorded until battery failure.

4. DISCUSSION.

4.1 FIRE EXPOSURE TEST RESULTS.

The fire exposure test was conducted with a single cell, a group of four cells, and a group of eight cells for each battery type. In the multiple-cell tests, all cells were packaged in a tight configuration and secured with safety wire. The cylindrical battery cells were positioned with the vent locations pointing in an upward direction. The Li-Po battery cells were positioned vertically with the positive and negative terminals pointing upward.

Figure 7 shows typical temperature versus time curves resulting from the single-cell fire exposure tests. These are plots of the thermocouple closest to the battery cells, located approximately 12″ from the floor of the test chamber. These are not representative of the actual battery cell temperatures. The full results from the single-cell, four-cell, and eight-cell battery tests are summarized in tables 2-4.

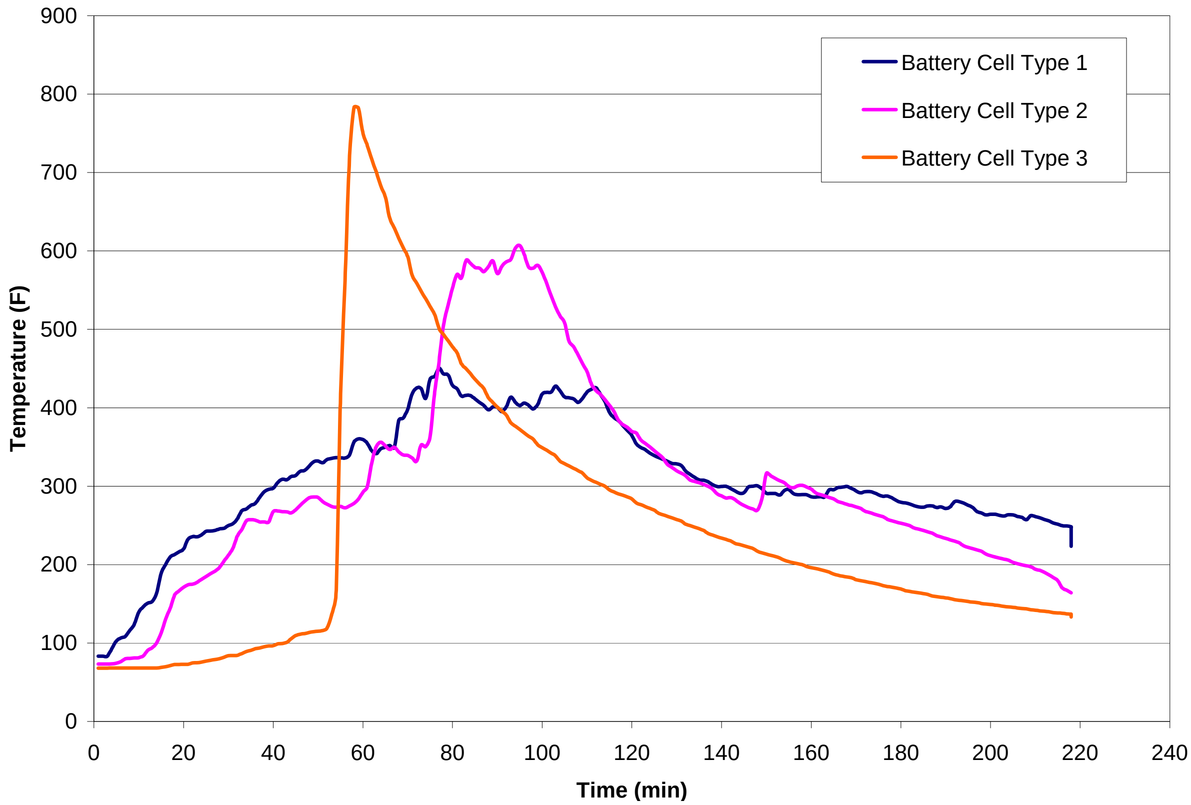

Figure 7. Typical Temperature vs Time Curves Resulting From Single-Cell Fire Exposure Tests

Table 2. Fire Exposure Test Results—Single Cell

Battery Cell Type	Approximate Time to First Event (min)	Peak Temperature (°F)	Approximate Time to Reach Peak Temperature (min)	Fire Duration (min)
1	1.00	450	1.25	4.00
2	1.00	605	1.50	3.25
3	0.75	780	0.75	2.75

Table 3. Fire Exposure Test Results—Four Cells

Battery Cell Type	Approximate Time to First Event (min)	Peak Temperature (°F)	Approximate Time to Reach Peak Temperature (min)	Fire Duration (min)
1	0.75	560	1.5	4.5
2	2.00	700	2.00	4.5
3	0.75	900	1.00	1.75

Table 4. Fire Exposure Test Results—Eight Cells

Battery Cell Type	Approximate Time to First Event (min)	Peak Temperature (°F)	Approximate Time to Reach Peak Temperature (min)	Fire Duration (min)
1	1.00	545	2.00	5.25
2	2.50	580	2.50	3.25
3	0.75	750	1.00	2.25

Typically, the cylindrical cells exhibited similar failure characteristics when exposed to the 1-propanol flame source. As the battery cell heated, pressure buildup within the cells caused the vent location to open, resulting in a forceful spray of flammable electrolyte. The vented electrolyte ignited, resulting in an associated pressure pulse and temperature rise within the test chamber.

During the battery type 2 single-cell test, the vents failed to open, resulting in an explosion. It is believed that this is a result of the cell's internal pressure increasing at a rate that exceeded the capability of the cell's relief mechanism. This did not occur for the multiple-cell tests for either cylindrical battery type, because the increase in overall thermal mass resulted in a slower rate of temperature and pressure rise for each individual battery cell.

Figures 8 through 11 show the postignition damage of the cylindrical battery cells.

Figure 8. Results From the Single-Cell Test of Battery Type 1

Figure 9. Results From the Single-Cell Test of Battery Type 2

Figure 10. Results From the Eight-Cell Test of Battery Type 1

Figure 11. Results From the Eight-Cell Test of Battery Type 2

The Li-Po battery cells do not have pressure release vent locations. Instead, they are designed such that under overpressure conditions, the seam around the perimeter of the cell opens up, releasing the flammable electrolyte. Due to the large surface area of the opening, there was no observable pressure pulse as with the cylindrical batteries. These cells however, did greatly fuel the existing fire once they failed as the full amount of the electrolyte was exposed all at once to the fire source. This resulted in higher peak temperatures as well as an increased burn rate of the pan fire. It is also important to keep in mind however, that these battery cells also had a much higher power capacity than the other cells, which also contributes to the high temperatures that were observed.

Figures 12 and 13 show the postignition damage of the Li-Po battery cells.

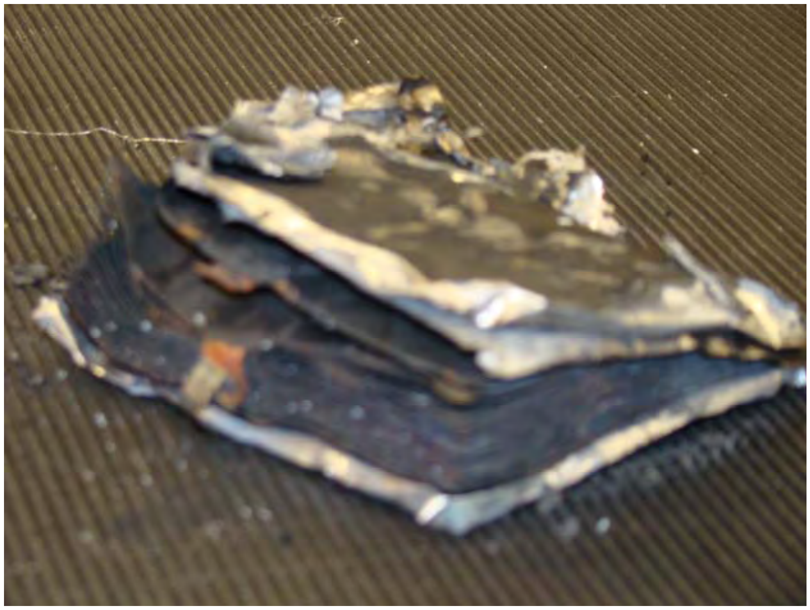

Figure 12. Results From the Single-Cell Test of Battery Type 3

Figure 13. Results From the Eight-Cell Test of Battery Type 3

4.2 PRESSURE PULSE TEST RESULTS.

The pressure pulse test was conducted with a single cell, a group of four cells, and a group of eight cells for each battery type. In the multiple-cell tests, the cells were packaged in a tight configuration and secured with safety wire. The cylindrical battery cells were positioned with the vent locations pointing in an upward direction. The Li-Po battery cells were positioned vertically with the positive and negative terminals pointing upward.

The results of the data obtained from these tests are summarized in tables 5-7, which show results for the single-cell, four-cell, and eight-cell battery tests, respectively. It should be noted that there is no peak temperature recorded for the eight-cell test of battery type 3, due to a failed thermocouple.

Table 5. Pressure Pulse Test Results—Single Cell

Battery Cell Type	Peak Pressure Rise (psi)	Approximate Time to Reach Peak Pressure (min)	Peak Temperature (°F)
1	0.70	3	420
2	1.40	4	500
3	2.15	1.75	770

Table 6. Pressure Pulse Test Results—Four Cells

Battery Cell Type	Peak Pressure Rise (psi)	Approximate Time to Reach Peak Pressure (min)	Peak Temperature (°F)
1	1.10	5	470
2	1.50	4.5	585
3	4.10	2	1065

Table 7. Pressure Pulse Test Results—Eight Cells

Battery Cell Type	Peak Pressure Rise (psi)	Approximate Time to Reach Peak Pressure (min)	Peak Temperature (°F)
1	1.35	6.5	480
2	1.10	5	515
3	5.30	3.5	N/A

From this data, it can be observed that the two cylindrical batteries (types 1 and 2) behaved in a somewhat similar manner, resulting in somewhat comparable increases in temperature and pressure. The Li-Po battery (type 3) however, resulted in much more severe increases of temperature and pressure. In addition, the Li-Po battery cells failed more rapidly, thus leading to a faster rise in pressure. It should again be noted that these battery cells have a much higher power capacity than the other cells, which contributes to the high temperatures and pressures that were observed.

4.3 HALON 1211 SUPPRESSION TEST RESULTS.

The Halon 1211 suppression tests were conducted with a group of eight cells packaged in a tight configuration and secured with safety wire for all battery types. All cells were charged to 100% SOC and placed in the mesh basket inside the test chamber. The cylindrical battery cells were positioned with the vent locations pointing in an upward direction. The Li-Po battery cells were positioned vertically with the positive and negative terminals pointing upward. The cells were exposed to the small alcohol fire, and at the point of failure of a single battery cell, Halon 1211 was discharged into the fire test chamber until the fire was extinguished.

Figures 14 and 15 show the temperature data from these tests for the two cylindrical battery cells. The initial venting event for both battery type 1 and 2 occurred at a temperature of approximately 125°F, measured 12″ above the fire pan. After this initial event, the temperature at this location rose rapidly to just over 180°F until the fire was extinguished with the halon agent. Once the fire was extinguished, no further ignition or venting of the battery cells was observed.

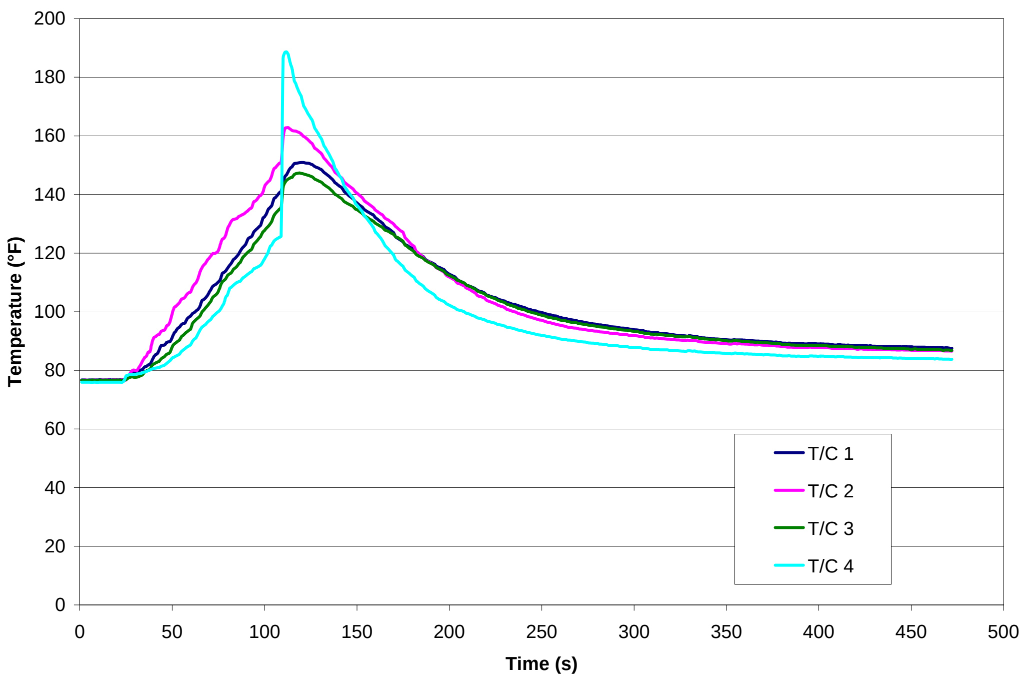

Figure 14. Halon 1211 Suppression Test Results—Battery Type 1

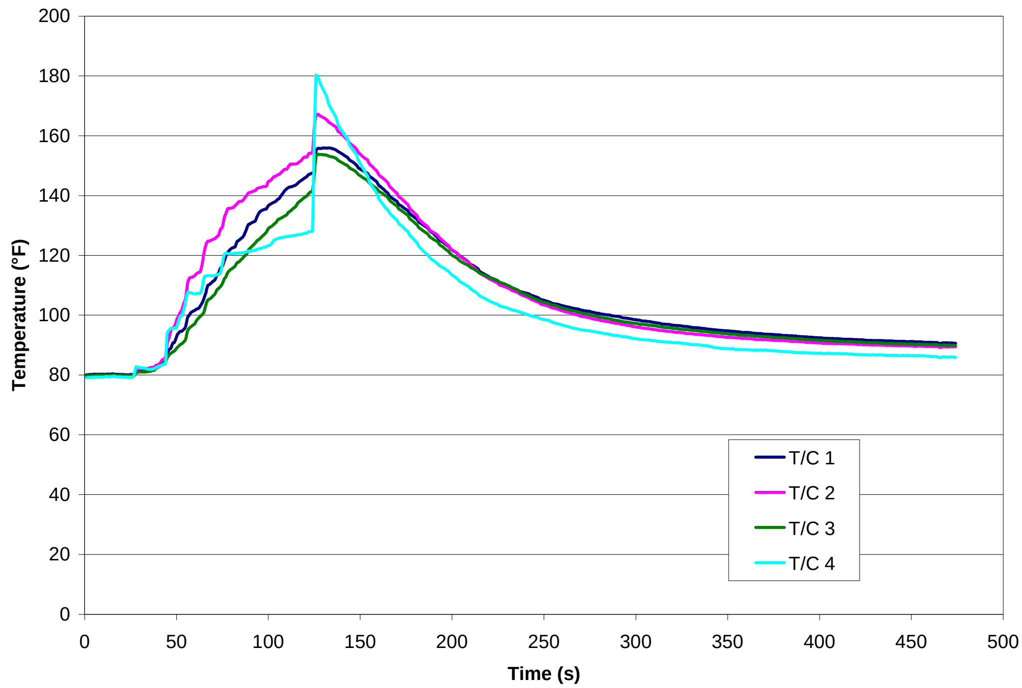

Figure 15. Halon 1211 Suppression Test Results—Battery Type 2

Figure 16 shows the temperature data from this test for the Li-Po battery cells. The initial venting event occurred at a fire test chamber temperature of approximately 95°F. After this initial event, the temperature in the fire test chamber continued to rise rapidly to just over 210°F, at which point the fire was extinguished with the halon agent. Once the fire was extinguished however, there were multiple reignitions that occurred within the fire test chamber. At each point of reignition, additional Halon 1211 agent was injected into the fire test chamber until the fire extinguished. The reignition events continued for 4 minutes past the time of the initial injection of the extinguishment agent. At this time, the full contents of the 2.5-lb hand-held fire extinguisher were discharged into the fire test chamber. Due to decreased visibility caused by the smoke in the fire test chamber, it was difficult to ascertain whether the reignition events were subsequent battery cells venting or if they were due to a reignition of the remaining 1-propanol in the fire pan.

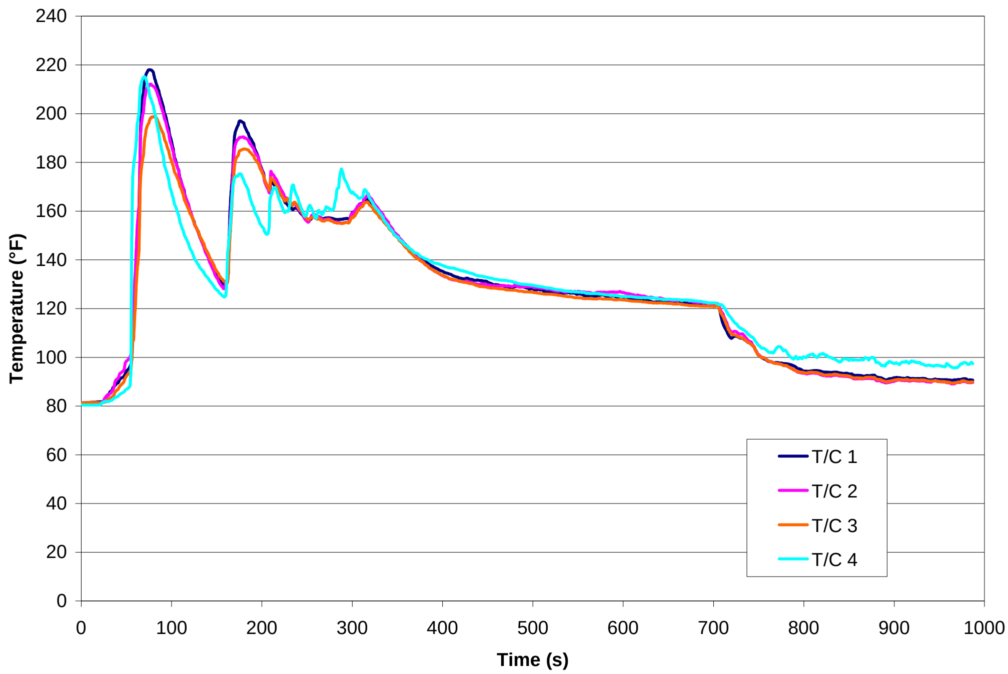

Figure 16. Halon 1211 Suppression Test Results—Battery Type 3

<u>4.4 EXTERNAL SHORT-CIRCUIT TEST RESULTS</u>.

The external short-circuit tests were conducted with a single-cell battery, charged to 100% SOC. The battery cell was placed in the mesh basket located within the fire test chamber. A 14-gauge wire was used to connect the positive and negative terminals of the battery cell.

None of the battery cells tested resulted in any venting or explosion. In the case of all three battery types, the temperature, measured on the outside casing of the cell, rose steadily throughout the test until the battery was fully discharged and then gradually began to cool to room temperature. The peak temperature reached for battery type 1 was 200°F. Battery type 2 reached a temperature of 167°F, and battery type 3 reached a temperature of 110°F.

<u>4.5 AUTOIGNITION TEST RESULTS</u>.

For each battery type, an individual battery cell at 100% SOC was placed in the mesh basket located in the 1-ft^3 autoignition test chamber. An acetylene torch fitted with a rosebud nozzle was used as the heat source. The torch was positioned so the flame impinged on the bottom surface of the autoignition test chamber, creating a steady temperature rise within the autoignition test chamber. Failure of the battery cell was detected by a rapid rise in the autoignition test chamber temperature, as shown in figure 17.

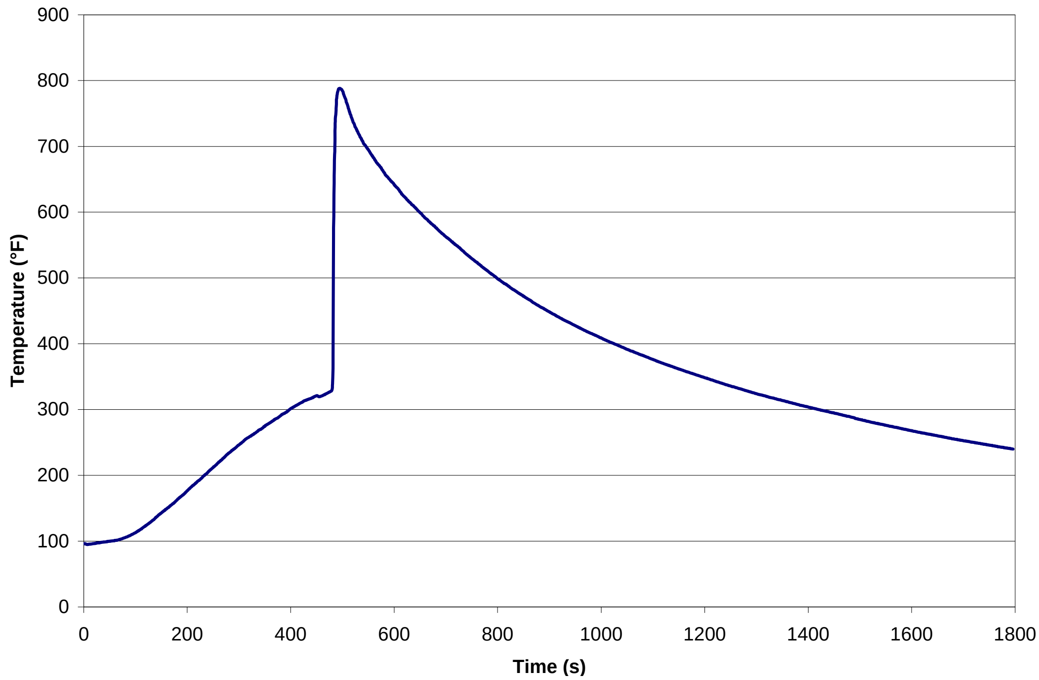

Figure 17. Typical Failue Results for Autoignition Tests

Two test trials were conducted for each battery type, and the results shown in table 8 display reasonable agreement between the tests, with the ignition temperature of the battery cells varying, at most, by 50°F. Ignition temperatures for the two cylindrical battery cells ranged from 440° to 527°F, while ignition temperatures for the Li-Po battery cell were at 330° and 340°F for the two tests.

Table 8. Autoignition Test Results

Battery Cell Type	Trial 1			Trial 2		
	Ignition Temperature (°F)	Peak Temperature (°F)	Resulting Temperature Increase (°F)	Ignition Temperature (°F)	Peak Temperature (°F)	Resulting Temperature Increase (°F)
1	440	572	132	490	649	159
2	480	664	184	527	639	112
3	340	741	401	330	788	458

Peak temperatures for battery type 1 were 572° and 649°F. These temperatures compare similarly to the results of battery type 2, which were recorded as 664° and 639°F. The Li-Po battery cells achieved somewhat higher temperatures of 741° and 788°F. This, again, can be attributed to the significantly higher power capacity of these battery cells.

5. SUMMARY.

The results of the tests show that the Li-ion and Li-Po battery cells can react violently when exposed to an external fire. During the single-cell test for battery type 2, the vents failed to open, resulting in an explosion of the battery cell. It is believed that this is a result of the cell's internal pressure increasing at a rate that exceeded the capability of the cell's relief mechanism. All other tests resulted in venting the highly flammable electrolyte, as expected. The cylindrical cells vented in a manner by which the electrolyte would spray forcefully and ignite, resulting in increased temperature and pressure. The cylindrical batteries test results are consistent with previous data that was obtained by examining batteries that are used in PED applications [2].

The Li-Po battery cells did not have vent locations; instead, they were designed so the seam around the perimeter of the cell would open, thus exposing the flammable electrolyte. The failure of the Li-Po battery cells greatly fueled the existing fire as the full amount of the electrolyte was exposed all at once to the fire source. In both single- and multiple-cell tests, the Li-Po battery cells, which have a much higher energy density and power capacity (8 Ah per cell versus 1.2 and 2.3 Ah for the cylindrical Li-ion cells), resulted in significantly higher temperature and pressure increases when compared to either of the two cylindrical cell types.

Attempts to cause the battery cells to reach their thermal runaway point via short circuiting the terminals were unsuccessful on all three battery types. The autoignition tests showed that battery cells reached thermal runaway and failed at temperatures ranging between 330° and 527°F. The Li-Po battery cells autoignited at lower temperatures and created far greater temperature increases than the Li-ion battery cells.

Tests conducted with a hand-held Halon 1211 fire extinguisher showed that the halon was able to successfully extinguish the fires resulting from all three battery types. However, for the Li-Po battery cells, even after several attempts, the halon extinguishing agent was not able to prevent reignitions in the fire test chamber. Due to decreased visibility, however, it was difficult to ascertain whether the re-ignition events were subsequent battery cells venting or if they were due to a re-ignition of the remaining 1-propanol in the fire pan.

6. REFERENCES.

1. Webster, H., "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft," FAA report DOT/FAA/AR-04/26, June 2004.

2. Webster, H., "Flammability Assessment of Bulk-Packed, Rechargeable Lithium-Ion Cells in Transport Category Aircraft," FAA report DOT/FAA/AR-06/38, September 2006.