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Fire Protection for the Shipment of Lithium Batteries in Aircraft Cargo Compartments

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16. Abstract

The Pipeline and Hazardous Material Safety Administration and the Federal Aviation Administration (FAA) are proposing a new regulation for the shipping of lithium-ion and lithium metal batteries and cells. Much of the regulation involves record keeping, package markings, cell size, and lithium content. Part of the regulation may restrict packaging, shipping mode, and cell type for shippers who elect to ship their devices on transport category aircraft.

The tests described in this report were designed to increase knowledge of the flammability of lithium-ion and lithium metal cells generated in earlier test efforts. Based on the previous work of the FAA William J. Hughes Technical Center Fire Safety Team, tests were conducted with larger number of cells and simulated self-ignition (thermal runaway) conditions. The effectiveness of Halon 1301 was evaluated from the perspective of open flame suppression as well as the ability to halt the propagation of thermal runaway within a shipment.

Preliminary tests were also conducted to characterize the flammability hazard of lithium polymer batteries that are used in some laptop computers.

The capability of existing shipping containers to contain lithium-ion and lithium metal cell fires was evaluated. A proposed performance standard for a shipping container or overpack for lithium-ion cells was developed.

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LIST OF ACRONYMS

CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
JAA	Joint Aviation Authority
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RSPA	Research and Special Programs Administration
TC	Thermocouple

EXECUTIVE SUMMARY

The Pipeline and Hazardous Material Safety Administration, in consultation with the Federal Aviation Administration (FAA), is proposing a new regulation for shipping lithium-ion (rechargeable) and lithium metal (nonrechargeable) batteries and cells. Much of the regulation involves record keeping, package markings, cell size, and lithium content. Part of the regulation may restrict packaging, shipping mode, and cell type for shippers who elect to ship their devices on transport category aircraft.

The tests described in this report were designed to increase knowledge of the flammability of lithium-ion and lithium metal cells generated in earlier test efforts and to address their safe shipment. Based on previous FAA William J. Hughes Technical Center Fire Safety Team work, tests were conducted with a larger number of cells and simulated self-ignition (thermal runaway) conditions. The effectiveness of Halon 1301 was evaluated from the perspective of suppression of open flames as well as the ability to halt the propagation of thermal runaway within a shipment.

Several preliminary tests were also conducted to characterize the flammability hazard of lithium polymer batteries that are used in some laptop computers.

The results from these tests confirmed that Halon 1301 is effective at suppressing open flames from lithium-ion cells in thermal runaway. The halon, as expected, was totally ineffective at stopping the progression of cell-to-cell thermal runaway. Even in the presence of Halon 1301, all cells in the shipment were consumed. Data was collected showing the propagation rate between adjacent cells as well as cell temperature while in thermal runaway.

The capability of existing shipping containers to contain a lithium-ion and lithium metal cell fire was evaluated. Currently available robust shipping containers, such as metal pails and drums recommended by the International Civil Aviation Organization, were not effective in controlling lithium metal cell fires, but they were effective in containing lithium-ion cell fires. A cardboard container designed to ship oxygen generator canisters was tested in a 100-cell lithium-ion cell fire and successfully contained the fire. A proposed performance standard for a shipping container or overpack for lithium-ion cells was developed, which is based partly on the oxygen generator overpack performance standard.

From the tests conducted, no safe method for shipping lithium metal cells is currently available.

1. INTRODUCTION.

Both lithium metal (nonrechargeable) and lithium-ion (rechargeable) batteries are a popular power source for many small electronic appliances. Most of the batteries used in the United States are manufactured in Japan, China, and South Korea. The batteries are packed in bulk corrugated cardboard containers, stacked on pallets, and shipped in the cargo holds of passenger and freighter aircraft.

An incident that involved a shipment of lithium metal batteries occurred at Los Angeles International Airport in April 1999. A pallet of batteries caught fire on the ramp while being handled between flights. There was no known external ignition source. The nature of metallic lithium fires makes them very difficult to extinguish with all common extinguishing agents ineffective in controlling the fire. As a result, in 1999, the National Transportation Safety Board (NTSB) recommended such batteries be prohibited on passenger flights as air cargo and a safety analysis be conducted to determine if such batteries are safe.

The safety analysis conducted by the Federal Aviation Administration (FAA) found that (1) lithium metal batteries could self-ignite (referred to as thermal runaway) during an unrelated aircraft cargo compartment fire, even after the fire was suppressed by the Halon 1301 used in aircraft cargo compartments; (2) when lithium metal batteries ignite, the fire would not be extinguished or suppressed by Halon 1301; and (3) a lithium metal cell fire would spew molten lithium that could penetrate aircraft cargo compartment liners [1].

The Research and Special Programs Administration (RSPA), which is now the Pipeline and Hazardous Materials Safety Administration (PHMSA), and the FAA issued an Interim Final Rule, HM-224E, "Prohibition on the Transportation of Primary Lithium Batteries and Cells Aboard Passenger Aircraft" on December 14, 2004. This rule prohibited the shipment of lithium metal batteries on passenger-carrying commercial aircraft. In addition, the rule states that "RSPA and the FAA will continue to study the hazards associated with the transportation of secondary (rechargeable) lithium batteries and will initiate additional actions as necessary." Specifically, the RSPA (now PHMSA) and the FAA will "Investigate flammability characteristics, extinguishing system effectiveness, battery charge state, and battery failure mode."

There have been many incidents involving lithium-ion cell fires onboard aircraft in carry-on luggage. These were generally minor due to the limited number of lithium-ion cells. The FAA has produced a training video "Extinguishing Lap-Top Computer Fires" that provides guidance in extinguishing these types of fires. This video is referenced in the FAA Safety Alert for Operators (SAFO) 09013, and is available on the Fire Safety Team website (www.fire.tc.faa.gov).

An incident involving a shipment of lithium-ion batteries occurred onboard a FedEx® aircraft parked on the ramp in Memphis, Tennessee. The individual cells were assembled into a battery pack for an electric car. The crate containing the battery pack was placed in a cargo container and loaded on the main deck of the FedEx aircraft. The cargo handlers smelled smoke and traced it to the container with the battery pack. The container was quickly off-loaded from the aircraft to the ramp where it burst into flames. An NTSB investigation determined that the source of the fire was the lithium-ion battery pack. Lithium-ion batteries are also suspected to be the cause of the loss of a United Parcel Service DC-8 in Philadelphia in 2006.

The FAA conducted a safety analysis that determined (1) lithium-ion cells are capable of self-ignition due to physical damage, internal shorts, external heating, and other means; (2) one cell in thermal runaway generates sufficient heat to cause adjacent cells to go into thermal runaway, propagating through the entire shipment; (3) the chemical reaction within a cell undergoing thermal runaway generates heat and pressure, resulting in a spray of flammable electrolyte; (4) Halon 1301 is effective in controlling the open flame and the spread of the fire to adjacent materials; and (5) Halon 1301 is not effective at stopping the propagation of thermal runaway within the shipment [2].

2. LITHIUM-ION FLAMMABILITY SUMMARY.

Lithium-ion cells and batteries are flammable and capable of self-ignition—a condition known as thermal runaway. Thermal runaway is a chemical reaction within the cell that generates high temperatures and pressures. Lithium-ion 18650 cells can reach measured surface temperatures of 1100°F, measured on the surface of the cell. This is sufficient to heat adjacent cells causing them to go into thermal runaway. A lithium-ion cell only needs to be heated to 450°F to induce thermal runaway. Once in thermal runaway, the 1100°F surface temperature can easily ignite any adjacent flammable materials. The internal pressure increases in a cell during thermal runaway until the pressure relief ports open. This results in a spray of highly flammable electrolyte. If a single cell in a typical bulk shipment box of 100 cells goes into thermal runaway, all the cells in that box will sequentially go into thermal runaway. The electrolyte fire can be controlled with Halon 1301 or Halon 1211. Although, halon will not stop the progression of thermal runaway within the shipment, it will prevent the external flame and ignition of adjacent flammable materials. Water is very effective at stopping the progression of thermal runaway due to its cooling properties.

Lithium-ion polymer batteries differ from lithium-ion cells. Lithium-ion cells are encased in a cylindrical metal enclosure and resemble standard household alkaline batteries. Lithium polymer batteries are comprised of flat cells arranged in a stack similar to pages in a book. Some are encased in a plastic outer covering and others have metal outer cases. Figure 1 shows the difference between lithium-ion cells and lithium-ion polymer cells.

Figure 1. Lithium-Ion Polymer (left) and Lithium-Ion Cells (right)

Lithium-ion polymer cells are also highly flammable and capable of thermal runaway due to physical damage, internal shorts, external heating, and other means. Past FAA tests showed that lithium-ion polymer cells can reach thermal runaway when heated to 330°F. However, there is no pressure buildup or spray of liquid electrolyte. Halon 1301 and Halon 1211 can extinguish the open flame in a lithium-ion polymer fire, but re-ignition can occur if the halon concentration dissipates [3].

3. SCOPE.

The PHMSA and the FAA are proposing a new rule that will regulate the shipping of all types of lithium batteries and cells. Previous lithium battery tests performed by the FAA focused on the flammability characteristics of individual and small groups of cells. Much of that work investigated the response of the cells to the conditions found in a suppressed cargo compartment fire. The tests described in this report were designed to fill in any gaps in the data in regard to shipping lithium-ion, lithium metal, and lithium-ion polymer cells.

To further understand the response of a full shipment of cells when one cell fails (i.e., resulting in thermal runaway), a method was developed to simulate a single cell in thermal runaway. Simulating the heat generated by a cell in thermal runaway was accomplished with an electric heater that conformed to the external dimensions of a lithium-ion 18650 cell. This 100-watt cartridge heater is capable of reaching a temperature of 1100°F, matching the thermal conditions of a lithium-ion cell in thermal runaway.

This report describes tests conducted to investigate

- the propagation within a shipment of cells when one cell fails and goes into thermal runaway.
- the effect of Halon 1301 on the resulting fire.
- the effect of Halon 1301 on cell propagation.

- the effect of improved packaging on cell propagation.

- the effectiveness of common shipping containers to withstand a lithium cell fire.

The purpose of the tests was to develop recommendations for effective and safe shipping for lithium-ion, lithium metal, and polymer cells.

4. THERMAL RUNAWAY PROPAGATION TESTS.

4.1 TEST DESIGN.

A single cell failure resulting in thermal runaway generates an external temperature of 1100+°F. The cell will also vent, causing a spray of flammable electrolyte. The heat generated is sufficient to (1) ignite the packing materials and (2) heat adjacent cells causing them to go into thermal runaway. Typically, a cell will undergo thermal runaway when heated to temperature of approximately 450°F. The propagation of thermal runaway from cell to cell is related to heat transfer by overheated cells as well as by the burning packaging.

Thermal runaway propagation tests were performed in a pressure chamber at the Pressure Modeling Facility at the FAA William J. Hughes Technical Center. The pressure chamber can withstand up to 1000 psi. The pressure chamber contains instrumentation to measure pressure and temperature. An internal video camera was used to monitor the test. The pressure chamber is shown in figure 2.

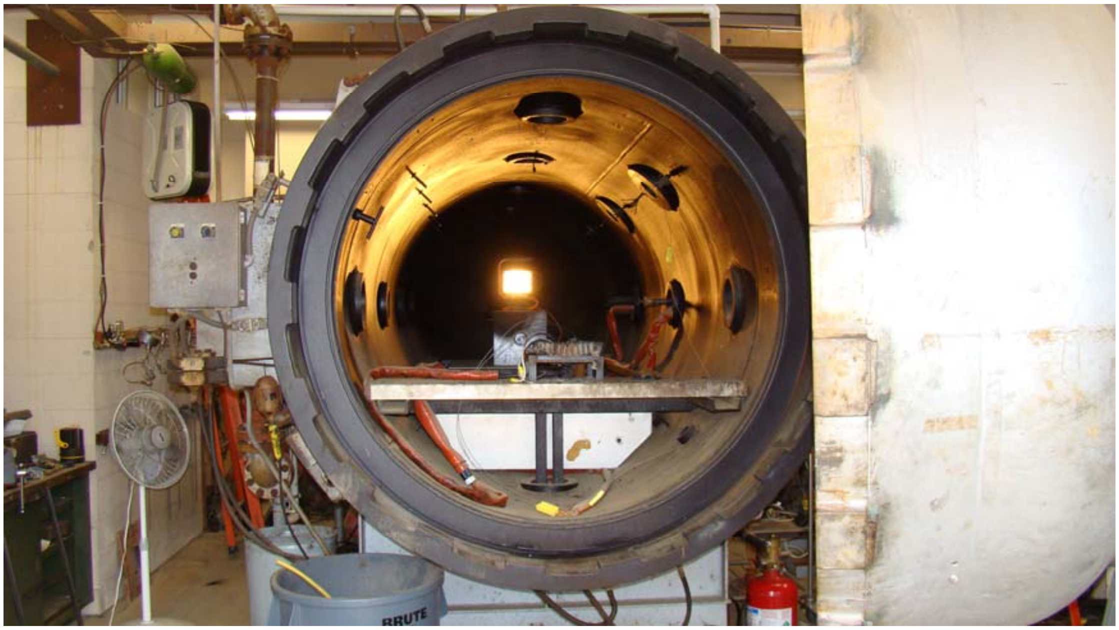

Figure 2. Pressure Chamber in the Pressure Modeling Facility

Lithium-ion 18650 cells are shipped in cardboard boxes containing 100 cells. The cells are separated from each other by interlocking cardboard separators, as shown in figure 3. A single cell was removed from the box near the center and replaced with a 100-watt cartridge heater. Thermocouples were attached to the cartridge heater, the middle cell (two rows from the cartridge heater), and the outer cell (four rows from the cartridge heater). Thermocouples were also attached to the cells in each corner of the box. The box was then closed and resealed. All tests in this series were performed using lithium-ion 18650 cells as shipped. The cells are shipped at a 50% state of charge. The test was initiated by activating the heater. Temperature data was collected as well as air pressure. Video documentation of the test was successful until obscured by smoke.

Figure 3. Shipping Box With Interlocking Cardboard Separators for 100 Battery Cells

4.2 PROPAGATION TEST RESULTS.

4.2.1 Baseline Test.

Three thermocouples (TC) were installed for this test. TC 1 measured the cartridge heater temperature and TCs 2 and 3 measured the temperature of the middle and outer cells. The box was closed and placed in the pressure chamber (figure 4). The cartridge heater was activated at time zero. The cartridge heater temperature reached 1000°F at the 9-minute mark, peaking at 1250°F at approximately 19 minutes. The power to the cartridge heater was shut off at this time. The cardboard box began to smoke 8 minutes into the test. The box caught fire at the 11-minute mark. As cells went into thermal runaway, strong torch flames erupted from the box as electrolyte was vented and ignited by the burning cardboard. The fire continued to burn vigorously until the 45-minute mark. Data was collected until all thermocouples returned to near ambient temperature. The middle cell (TC 2) reached thermal runaway at 18:46 (minutes:seconds). The outer cell (TC 3) went into thermal runaway at 30:25. The pressure within the air-tight chamber rose 0.43 psi during the test. Figure 5 shows a graph of the temperature and pressure. The posttest photograph in figure 6 shows that all the cells were consumed.

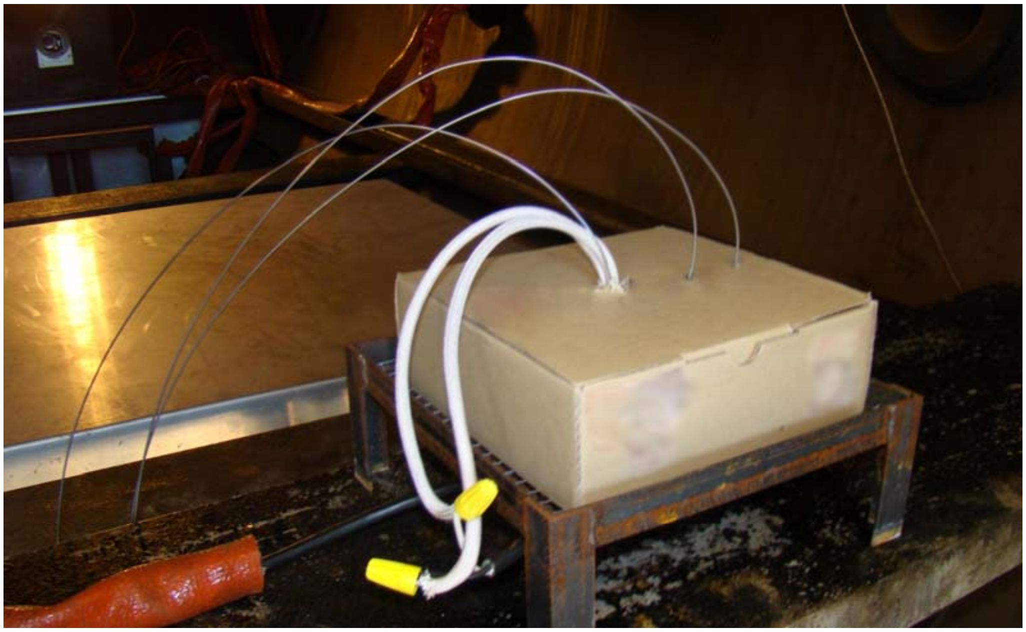

Figure 4. Lithium-Ion Baseline Propagation Test

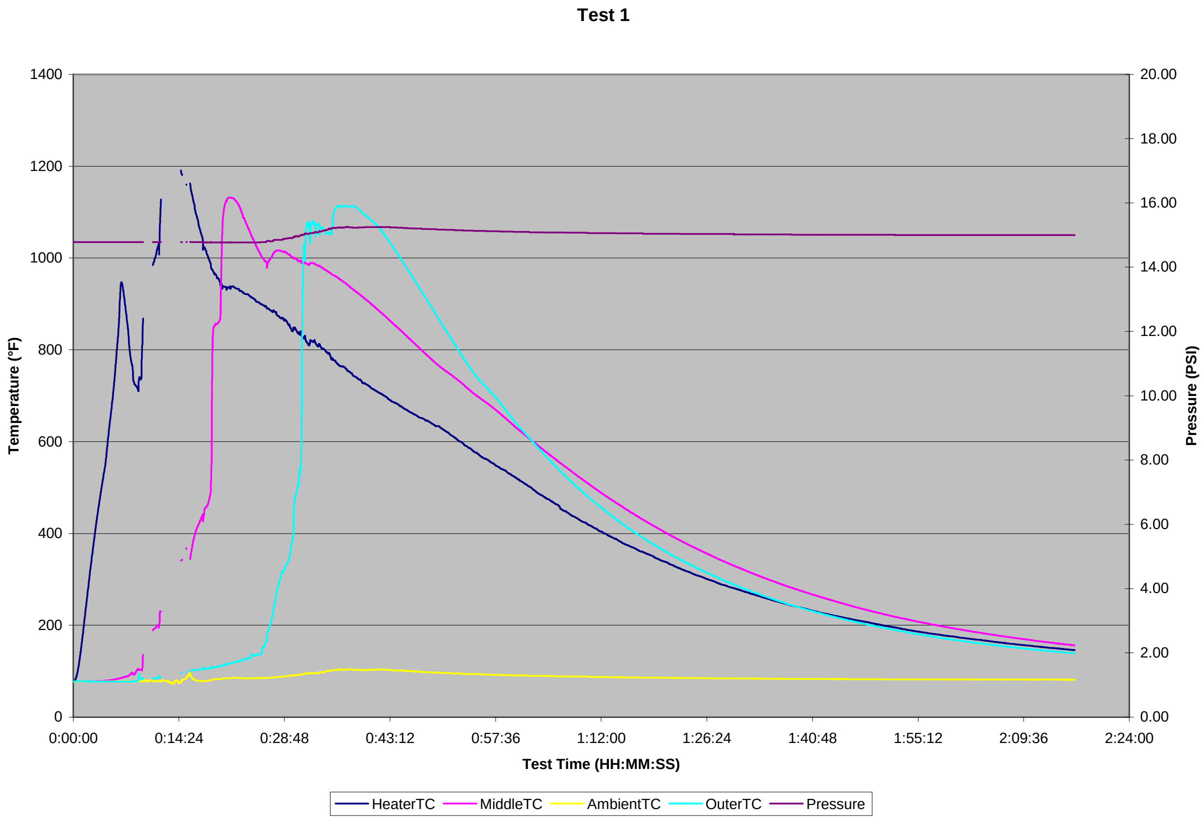

Figure 5. Lithium-Ion Baseline Propagation Test Cell Temperature and Pressure Data

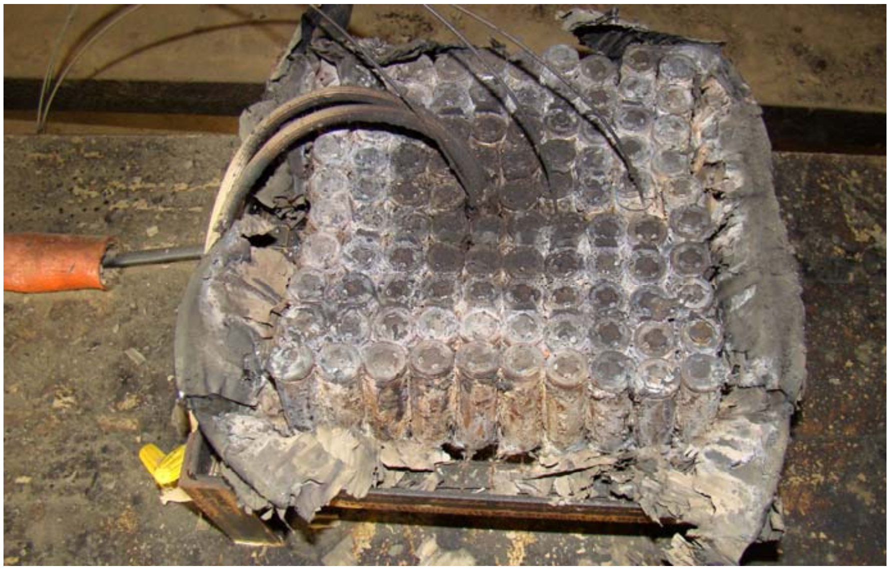

Figure 6. Lithium-Ion Baseline Propagation Posttest

4.2.2 Halon 1301 Effectiveness Test.

For this test, the box of cells was prepared in the same manner as the baseline test, except four additional thermocouples were added. The additional thermocouples were installed in each corner of the box, enabling additional propagation measurements. Figure 7 shows the instrumentation configuration.

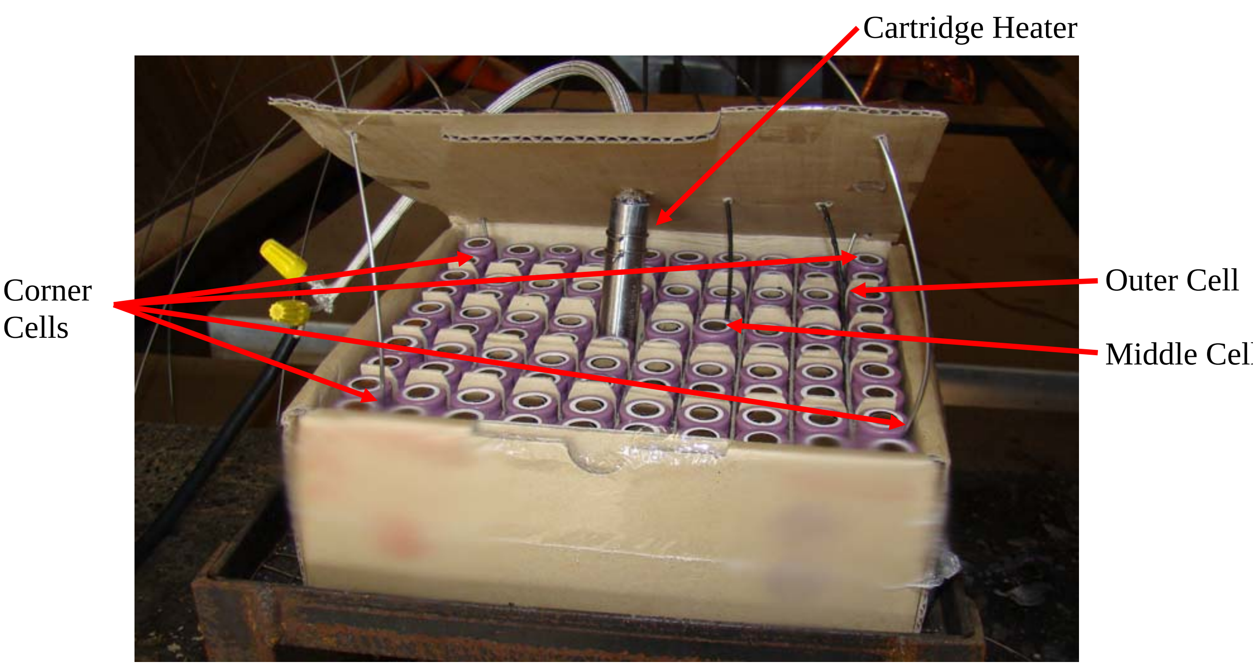

Figure 7. Halon 1301 Effectiveness Test Instrumentation

The test was initiated by powering the cartridge heater. The box caught fire at 11.5 minutes. At this time, Halon 1301 was discharged into the pressure chamber. The amount of agent was calculated to achieve an initial concentration of 6%. The open flames were immediately extinguished. Thermal runaway continued to propagate throughout the box. The middle cell reached thermal runaway at 19:01 and the outer cell at 30:16. These times are statistically identical to the baseline test. The rear left corner cell reached thermal runaway at 31:40 and the rear right corner cell at 33:00. The front left corner cell reached thermal runaway at 33:39. The front right corner cell, which was the farthest from the cartridge heater, reached thermal runaway at 37:15. All cells experienced thermal runaway. Figure 8 shows a graph of the cell temperature and pressure data.

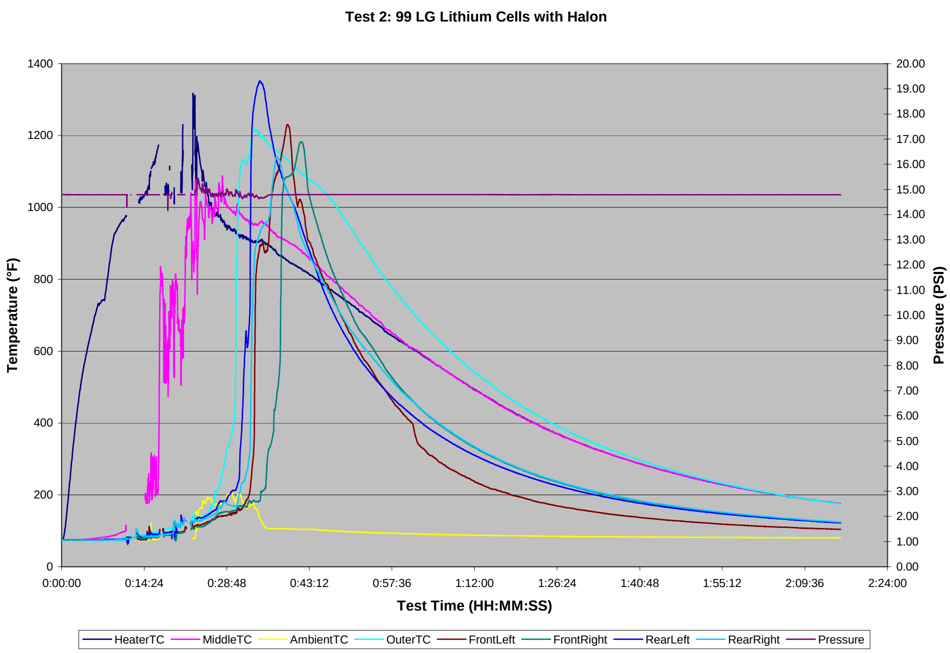

Figure 8. Halon 1301 Effectiveness Test Cell Temperature and Pressure Data

The propagation rate of thermal runaway with Halon 1301 suppression was identical to the baseline test without suppression. It can be concluded that the primary means of propagation within a single box is heat transfer from adjacent cells in thermal runaway. The burning electrolyte and packaging in the baseline test did not change the propagation rate between cells.

<u>4.2.3 Improved Packaging Test</u>.

The standard bulk packaging for lithium-ion 18650 cells consists of a cardboard box with interlocking cardboard separators. One possible way to reduce the radiant heat transfer from a cell in thermal runaway to adjacent cells is to replace the cardboard separators with a heat-resistant material. For this test, the cardboard separators were replaced with a fiberglass material used as a flame barrier in aircraft thermal acoustic insulation. The fiberglass was cut to the same dimensions as the cardboard separators. The installed fiberglass separators are shown in figure 9.

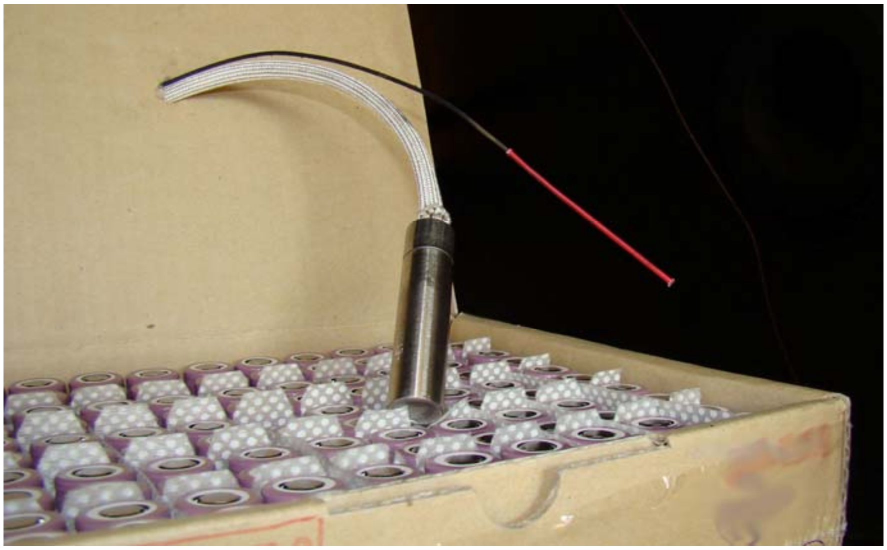

Figure 9. Installation of Fiberglass Separators

The test was conducted in the same manner as the baseline test without Halon 1301 suppression. The cartridge heater reached 1000°F at 8:54 and peaked at 1257°F at 18:56. The cartridge heater was shut off at this time. The box began to smoke at 8:34 and flames were observed at 11:56. The middle cell went into thermal runaway at 19:19 and the outer cell at 25:59. The rear left cell went into thermal runaway at 28:26 and the rear right cell at 29:04. The front left cell went into thermal runaway at 27:47 and the front right cell at 32:13. Figure 10 shows the temperature traces for each cell.

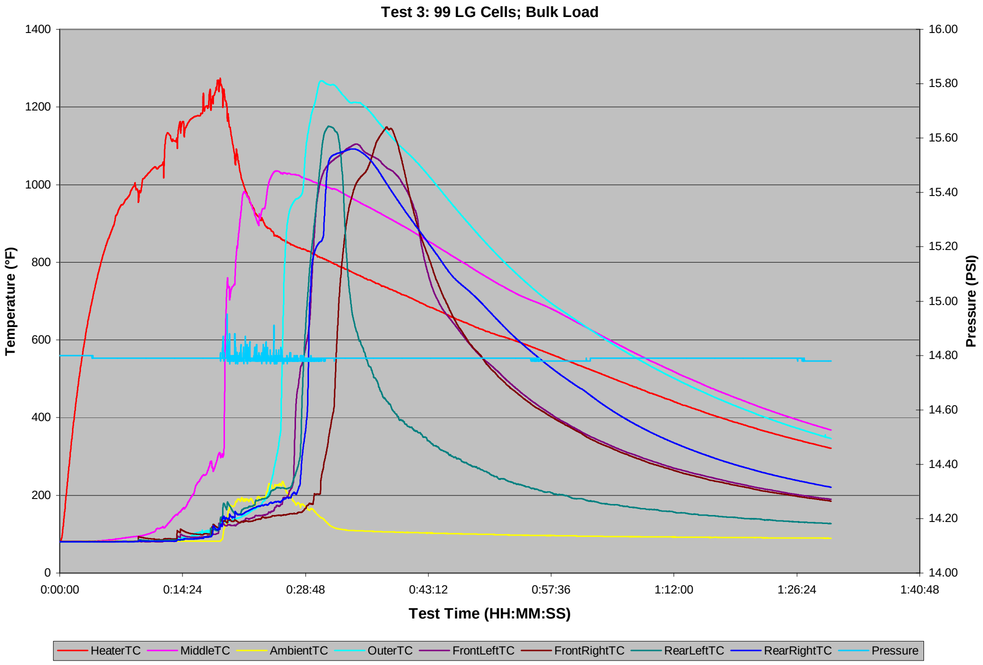

Figure 10. Fiberglass Separator Cell Temperature and Pressure Data

Comparing the propagation rate of this test to the baseline test, the middle cell went into thermal runaway 33 seconds later. The outer cell, however, went into thermal runaway almost 5 minutes earlier. Since the baseline test did not have corner thermocouples and the Halon 1301 test did, it may be reasonable to compare the corner cells to the Halon 1301 test to this test. In each case, the corner cells went into thermal runaway 3 to 5 minutes faster than in the Halon 1301 test.

Based on these results, the fiberglass material was less effective in controlling the propagation of thermal runaway between cells than the standard cardboard separators. The concept, however, is promising, and further tests are planned with other materials.

5. CONTAINER TESTS.

Lithium metal cells are banned from cargo shipment on U.S. passenger aircraft, but they are allowed to be shipped on cargo aircraft. The International Civil Aviation Organization (ICAO) allows a small quantity of lithium metal cells to be shipped on passenger aircraft when packed in metal containers.

5.1 TEST DESIGN.

Containers in two different sizes and two different materials were procured for these tests.

- 5-gallon steel pail with a gasketed crimp-on lid
- 30-gallon steel drum with a bolt-closed ring seal and gasketed metal lid
- 30-gallon plastic drum with a metal ring seal

The containers were tested by initiating thermal runaway in a small group of cells. The number of cells was increased until the container failed. The cells were placed in close proximity to the cartridge heater. Tests conducted with a larger number of cells were placed in wire cages to maintain proximity to the cartridge heater. Packaging materials were not part of this test design.

5.2 LITHIUM METAL CELL CONTAINER TESTS.

The lithium metal container tests were conducted using CR2-size cells. The following tests were designed to evaluate the effectiveness of commonly available containers to control and contain a lithium metal or lithium-ion cell fire.

5.2.1 Five-Gallon Steel Pail Tests.

Two tests were conducted in this series. A new pail was used for each test.

- Test 1: Two CR2 cells were wired to a cartridge heater. The cartridge heater and the cells were suspended inside the pail by the cartridge heater wires. The wires penetrated the lid through close-fitting holes. Approximately 6 minutes from cartridge heater activation, smoke was observed venting around the perimeter of the lid. The lid remained intact, and there was no bulging.

- Test 2: Six CR2 cells were wired to a cartridge heater (figure 11) and placed in the pail. At 6:30, which was minutes after the cartridge heater activation, the lid blew off and propelled 10 to 12 feet in the air, landing 10.5 feet from the pail (figure 12). The cells separated from the cartridge heater and landed next to the pail, where they continued to burn and expel flammable electrolyte and molten lithium until all cells were consumed.

The catastrophic failure of the 5-gallon pail with only six CR2 cells ended this test series.

Figure 11. Five-Gallon Pail Test, Six CR2 Cells Wired to the Cartridge Heater

Figure 12. Test 2—Five-Gallon Pail Lid Failure

5.2.2 Thirty-Gallon Steel Drum Tests.

Eight types of tests were conducted in this series. A new drum was used for each test. The following is a summary of the test results.

- Test 1: Six CR2 cells were wired to the cartridge heater. At 6 minutes, smoke was venting from the perimeter of the lid. The lid bulged upward, but remained intact (figure 13). The drum was very warm to the touch.

- Test 2: Twelve CR2 cells were wired to the cartridge heater. Because the cartridge heater failed, the test was halted.

- Test 3: Twelve CR2 cells were wired to the cartridge heater. At 6:23, smoke vented from the perimeter of the lid. The ends of the drum expanded, and the drum rocked back and forth. The drum sides were hot to the touch.

- Test 4: Thirty-six CR2 cells were vertically stacked in two groups of 18 around the cartridge heater. The group of cells was contained in a wire mesh enclosure. At 7:25, large volumes of smoke forcefully vented around the perimeter of the lid. The temperature near the center of the cell stack peaked at over 1600°F. The air temperature in the drum reached 600°F. The drum rocked back and forth, but contained the fire.

- Test 5: Thirty-six CR2 cells were vertically stacked in two groups of 18 around the cartridge heater. The group of cells was contained in a wire mesh enclosure. At 7:15, the lid deformed and blew off. The lid was propelled 50 to 75 feet into the air and landed 100 feet from the drum. The drum fell over onto its side. The cells remained in the drum, where they continued to burn, expelling molten lithium, until all the cells were consumed.

- Test 6: Six CR2 cells were wired to the cartridge heater. Smoke vented around the perimeter of the lid. The drum contained the fire.

- Test 7: Six CR2 cells were wired to the cartridge heater. Smoke vented around the perimeter of the lid. The drum contained the fire.

- Test 8: Six CR2 cells were wired to the cartridge heater. At 6:15, the lid blew off the drum. The lid was propelled 20-25 feet in the air and landed 45 feet from the drum. (figure 14).

Figure 13. Test 1—Lid Bulge After the Six CR2 Cell Test

LID

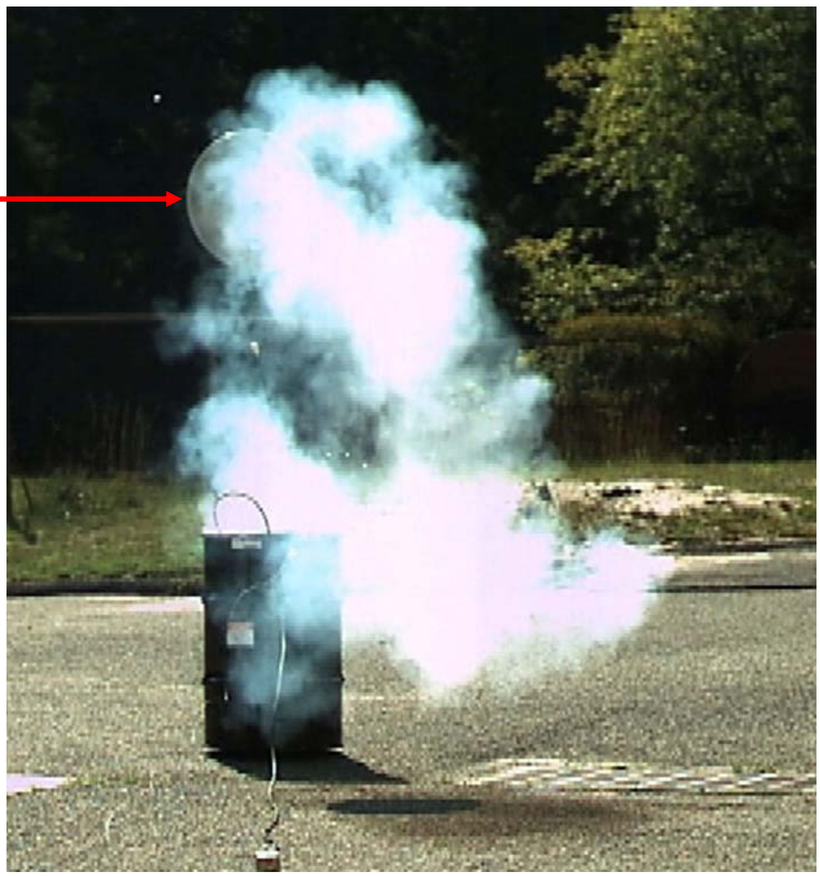

Figure 14. Test 8—Exploding Drum, Six CR2 Lithium Metal Cells

The initial total failure occurred with 36 CR2 cells. However, the large number of cells that went into thermal runaway after the explosion indicated that only a few cells were involved in the initial explosion. Therefore, additional tests were conducted, which reproduced the failure with six CR2 cells. Based on the violent nature of the failure, it is evident that steel containers are not effective in containing a lithium metal cell fire from as few as six cells.

5.2.3 Oxygen Generator Overpack Lithium-Ion Cell Test.

A performance standard was developed for outer package (often called an overpack) designed for safely shipping compressed oxygen and chemical generators on passenger aircraft. This performance standard is defined in PHMSA Rule HM224B. The oxygen generator overpack is designed to protect against both exterior and interior threats, i.e., protection of oxygen containers from an external fire and prevention of hazards from an activated generator from spreading outside the overpack. The same exterior threats apply to a bulk shipment of lithium-ion cells exposed to a Halon 1301 suppressed cargo compartment fire. A test was designed to determine if the overpack performance standard would protect against an internal lithium-ion cell fire caused by thermal runaway.

A cardboard container with a foil/ceramic insulator, which met the requirements of PHMSA Rule HM224B, was used for this test. A full box of 99 lithium-ion 18650 cells was prepared with a cartridge heater and thermocouples in the same locations as in the propagation tests described in section 4.2. An additional thermocouple was installed in the overpack to measure the air temperature. The overpack was assembled as per the manufacturer's instruction. The box of cells was placed in the bottom center of the overpack, as shown in figure 15. The wires for the instrumentation were carefully routed through the insulation folds and the flaps of the overpack. The seams were sealed with high-temperature fiberglass tape.

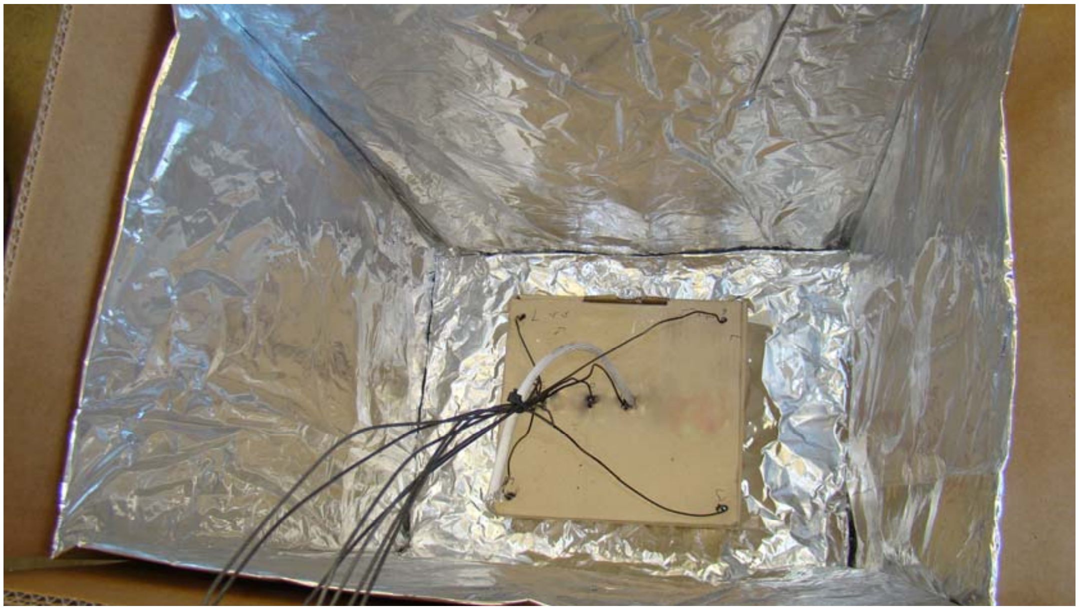

Figure 15. The Box of 99 Lithium-Ion Cells Installed in the Oxygen Generator Overpack

The test was initiated by energizing the cartridge heater, inducing thermal runaway in the adjacent cells. Once the chain reaction was initiated, the cartridge heater was shut off. The pass/fail criteria for this test were as follows:

- Smoke leaking through the seals is acceptable
- Fire or flames escaping through the seals or sidewalls or top or bottom is not acceptable
- The overpack must maintain its structural integrity, i.e., must keep the cells within the overpack

Eight minutes into the test, a small amount of smoke came through the top of the overpack where the flaps were taped shut (figure 16). The volume of smoke increased as the test continued, coating the top of the overpack with soot. The middle cell went into thermal runaway at 17:20, and the last corner cell went into thermal runaway at 38:40. These times are consistent with the thermal runaway propagation tests. The temperature of the last cell to go into thermal runaway peaked at 40:40 and began to decline. The air temperature in the overpack peaked at 41:45, reaching a temperature of 587°F. At 2 hours and 52 minutes, the air temperature within the overpack was 187°F (figure 17).

Figure 16. Smoke Venting Through the Flap Seal

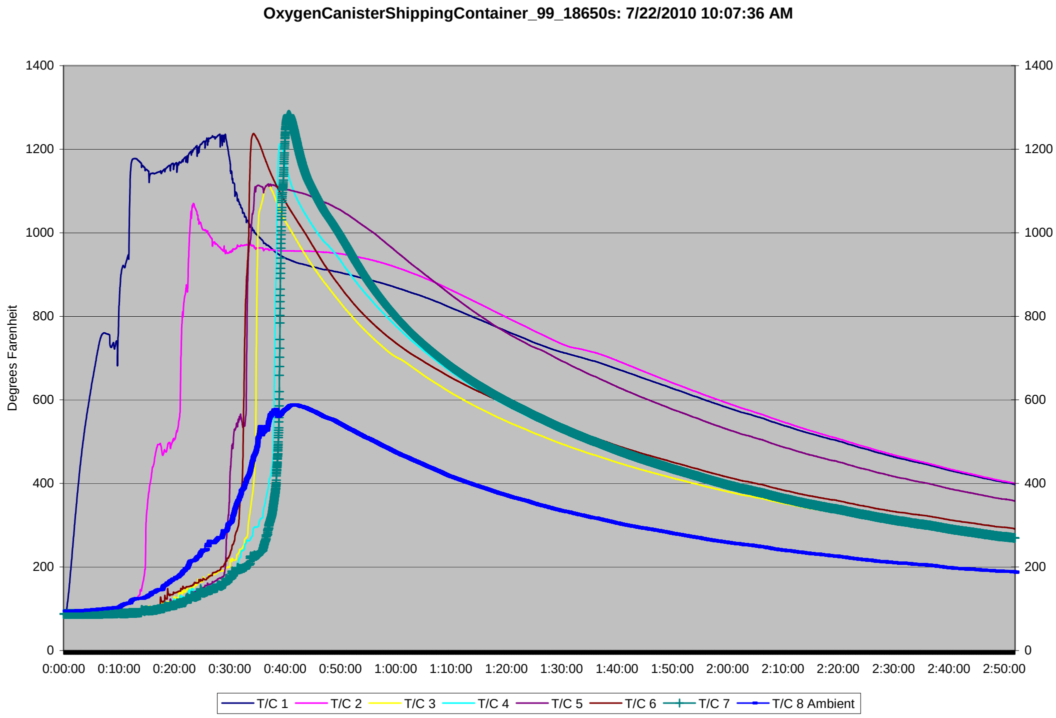

Figure 17. Oxygen Generator Overpack Lithium-Ion Test Cell Temperature Data

The overpack was opened after 3 hours. The inside of the overpack was soot covered but undamaged (figure 18). The exterior of the overpack was not discolored except for a coating of soot on the top, and the top flaps were slightly brittle but intact. The cardboard box containing the cells was charred but intact. All the cells were consumed. The overpack successfully contained the lithium-ion cell fire. The oxygen generator overpack performance standards can be used as a basis for a performance standard for lithium-ion cells.

Figure 18. Oxygen Generator Overpack Lithium-Ion Posttest

5.3 LITHIUM-ION POLYMER CELL TEST.

Lithium-ion polymer cells have different characteristics than standard cylindrical lithium-ion cells. The cells are highly flammable and capable of thermal runaway when heated. Unlike the cylindrical cells, there is no pressure pulse or sprayed electrolyte. When configured for use in a laptop computer, several cells are assembled in a metal casing. Two tests were conducted using cartridge heaters to induce thermal runaway (figure 19). The first test involved only the battery; the second test included the shipping box. The first test did not result in open flame. The battery smoked heavily, the plastic end fittings melted, and the outer metal case reached 1000°F. The second test resulted in the shipping box catching fire. These flames ignited the polymer cells, and a very vigorous fire ensued (figure 20). The results of these tests and previous work to characterize the cells indicate that the shipping requirements for polymer cells and batteries should be the same as the lithium-ion cell shipping requirements.

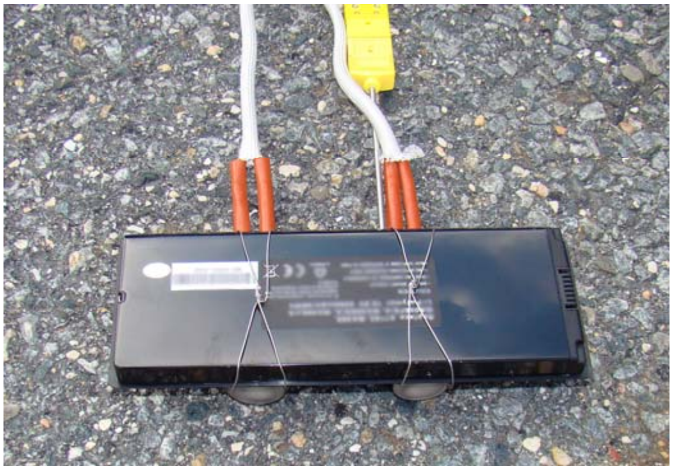

Figure 19. Lithium-Ion Polymer Laptop Battery Pretest

Figure 20. Lithium-Ion Polymer Laptop Battery With Shipping Box Posttest

6. DISCUSSION.

6.1 SHIPPING SCENARIOS.

Shipping lithium batteries by air transport can be divided into four main scenarios.

1. Lithium-ion batteries carried in the cargo compartments of passenger-carrying aircraft—All the cargo compartments in passenger-carrying aircraft are Class C and are protected with a Halon 1301 suppression system. Tests have shown that Halon 1301 can effectively control a fire involving these batteries. Halon 1301 suppresses the open fire but does not stop or hinder the propagation of thermal runaway.

2. Lithium metal batteries carried in the cargo compartment of passenger-carrying aircraft is currently prohibited. Halon 1301 has been shown to not be effective on controlling a fire involving these batteries. There is an extreme hazard from pressure pulse, flammable electrolyte, and molten lithium.

3. Lithium-ion batteries carried in Class E cargo compartments (main deck compartments of freighter aircraft)—The hazards are from either an existing external fire penetrating the battery package or from ignition occurring inside the battery package and spreading to other batteries and cargo.

4. Lithium metal batteries carried in Class E cargo compartments—The hazard is an existing external fire penetrating the battery package and ignition occurring inside the battery package and spreading to other batteries and cargo.

6.2 SHIPPING LITHIUM-ION CELLS.

The lithium-ion cell undergoes a chemical reaction once it is heated to the point of thermal runaway. This chemical reaction generates very high temperatures and pressures within the cell. The high pressure causes the cell to expel flammable electrolyte. The high temperature is sufficient to cause adjacent cells to go into thermal runaway, resulting in a cascade effect. A cell in thermal runaway can reach 1100+°F. This exceeds the ignition temperature of most ordinary combustibles, including paper and cardboard. The 1100°F temperature is also very close to the melting point of aircraft aluminum, 935° to 1180°F. A large shipment of lithium-ion cells could generate enough heat to potentially damage the structure of the aircraft.

Restricting shipment of lithium-ion cells to Class C cargo compartments would largely mitigate but may not eliminate the hazard. The Halon 1301 fire suppression system in Class C cargo compartments has been shown to effectively suppress the open fire associated with the burning electrolyte. This greatly reduces the potential ignition of adjacent flammable materials. Halon 1301 is not effective, however, in cooling any cells in thermal runaway. The cells will continue to propagate until all the cells in the shipment have gone into thermal runaway. Previous tests have shown that heating lithium-ion cells rapidly can cause some cells to explode, potentially raising the pressure within the cargo compartment. An increase of only 1 psi is sufficient to activate the cargo compartment overpressure devices, leading to the loss of Halon 1301.

One way to reduce this risk is to place the shipment in an approved overpack that has been demonstrated to be capable of containing a lithium-ion cell fire. A properly designed overpack will greatly reduce the risk of the fire and heat generated by burning lithium-ion cells. Steel drums and pails have been shown to be effective in containing a lithium-ion cell fire. Aluminum drums are not suitable due to the high temperatures generated when lithium-ion cells go into thermal runaway. Cardboard overpacks, which contain thermally resistant materials, designed to ship chemical oxygen generators have also been effective with a minimal weight penalty.

A draft performance standard for a lithium-ion cell overpack has been developed (section 7). The performance standard is similar to that developed for the oxygen generator, with the addition of a performance test requiring a fire demonstration using the types of cells to be transported.

The use of an overpack would allow the shipment to be placed in either a Class C or Class E cargo compartment. It should be noted that using a cargo compartment that has fire suppression capability will add another layer of protection.

6.3 SHIPPING LITHIUM METAL CELLS.

The result of thermal runaway in a lithium metal cell is a more severe event compared to a lithium-ion cell in thermal runaway. The lithium metal cell violently releases a flammable electrolyte mixed with molten lithium metal. The process is accompanied by a large pressure pulse. The combination of flammable electrolyte and the molten lithium metal can result in an explosive mixture. Halon 1301, the suppression agent found in Class C cargo compartments is totally ineffective in controlling a lithium metal cell fire. The explosive potential of lithium metal cells can easily damage cargo compartment liners or activate the pressure relief panels in a cargo compartment. The molten lithium has also been demonstrated to perforate cargo liner compartments. Either of these circumstances could lead to a loss of Halon 1301, which would allow rapid fire spreading to other flammable materials within a cargo compartment. For this reason, lithium metal cells were banned on passenger-carrying aircraft.

ICAO still allows small quantities of lithium metal cells to be shipped on passenger aircraft if they are encased in metal containers. FAA tests have shown that this not a viable option. Two types of robust readily available containers were tested: 5-gallon steel pails with crimp-on gasketed lids and 30-gallon steel drums with bolt-closed ring seals and gasketed metal lids. For both types of containers, as few as six CR2 lithium metal cells, which were induced into thermal runaway by a cartridge heater, were sufficient to cause failure. The confined electrolyte and the molten lithium ignition source formed an explosive condition. When ignited, the explosion blew the lid off of the container, causing it to fly 75 feet into the air. The explosive force is high enough to cause physical damage to the aircraft, particularly in the confined space of a Class C cargo compartment. The remaining cells then continued to burn vigorously, potentially spreading the fire.

Lithium metal cells shipped in a Class E cargo compartment (freighter) pose an extreme hazard. Tests have shown that depressurizing, which is the primary means of firefighting in a Class E cargo compartment, has no effect on a lithium metal cell fire. Locating the shipment of lithium metal cells in a more accessible location is not effective. Onboard hand-held fire extinguishers, primarily Halon 1211, are not effective in extinguishing a lithium metal cell fire.

There is no safe location on aircraft for bulk shipment of lithium metal cells. The hand-held fire extinguishers (Halon 1211) and suppression systems in Class C compartments (Halon 1301) are totally ineffective in fighting a lithium metal cell fire.

A container specially designed to ship lithium metal batteries would need to demonstrate that it can withstand this explosive condition. Common metal shipping containers, pails, and drums are not designed to withstand a lithium metal cell fire.

FedEx has developed a suppression system for their main deck (Class E) cargo compartments. This system has been shown to be effective in controlling metal fires, but has not been tested against a lithium metal cell fire. Tests are pending.

A fire involving a small number of cells, such as installed in electronic equipment contained in carry-on luggage, can be fought with Halon 1211 by preventing the spread of fire to adjacent flammable materials. The halon will have no effect on the lithium metal cells. Water, if available, can be used to cool the device and stop the propagation of thermal runaway from cell to cell. If water is unavailable, Halon 1211 should be used to prevent the fire from spreading until all cells have been consumed.

7. DRAFT OVERPACK PERFORMANCE STANDARD FOR LITHIUM-ION CELLS.

Tests have shown that cardboard containers designed to meet the requirements of PHMSA Rule HM224B have been successful in containing a lithium-ion cell fire. The requirements for a lithium-ion cell shipment overpack are somewhat different than for oxygen generators. The following performance standard states that an overpack constructed from any type of material (steel, cardboard, or other) must

- meet the same flame penetration resistance standards as required for cargo compartment sidewalls and ceiling panels in transport category aircraft.

- provide certain thermal protection capabilities to retain its contents during an otherwise controllable cargo compartment fire.

The outer packaging standard that is being proposed addresses two safety concerns:

- Protecting a shipment of cells from direct exposure to a fire
- Protect a shipment of cells from indirect heating from a suppressed fire

These performance requirements must remain in effect for the entire service life of the outer packaging.

The overpack for lithium-ion and lithium-ion polymer cells must meet the standards in Part III of Appendix F of 14 Code of Federal Regulations (CFR) Part 25. An outer packaging's materials must prevent penetration by a flame of 1700°F for 5 minutes, in accordance with Part III of Appendix F, paragraphs (a)(3) and (f)(5) of 14 CFR Part 25.

In addition, the lithium-ion cell shipment overpack must remain below the temperature at which the lithium-ion cells self-ignite (thermal runaway). Lithium-ion cells typically go into thermal runaway at 450°F and lithium polymer cells reach thermal runaway at 330°F. The interior of the overpack must remain below 300°F when exposed to an external temperature of at least 400°F for 3 hours. The 400°F temperature is the estimated mean temperature of a cargo compartment during a halon-suppressed fire. Three hours and twenty-seven minutes is the maximum estimated diversion time worldwide; based on an aircraft flying a southern route over the Pacific Ocean.

In addition, a performance test is required to demonstrate the ability of the overpack to contain a lithium-ion or lithium polymer fire in the event of a thermal runaway. The test must be performed for each type of cell or battery that is to be shipped in the overpack. The performance test is proposed as follows:

- Remove one cell from the shipping box and replace with a cartridge heater capable of reaching 1100°F; or insert an electric flat plate heater between larger battery assemblies that can reach 1100°F. Protect the heater leads with high-temperature sheathing.

- Load the overpack with boxes of lithium-ion or polymer cells or batteries to capacity, with the modified box containing the cartridge heater near the center of the overpack.

- Close the overpack as per the manufacturer's instructions, modifying the seal as needed to pass the wires for the cartridge heater to the outside of the overpack.

- Energize the cartridge heater for 30 minutes.

- The cells adjacent to the cartridge heater will go into thermal runaway. This will in turn induce adjacent cells to go into thermal runaway. This propagation will continue until all cells in the overpack are consumed.

- Pass/fail criteria:

    - Smoke leaking through seals is acceptable.

    - Fire and flames escaping through the seals or sidewalls or top and bottom is not acceptable.

    - The overpack must maintain its integrity until the internal temperature returns to ambient.

8. CONCLUSIONS.

The following conclusions can be drawn from the results of this test series and the previous work done in this area as it relates to bulk shipping of lithium-ion, metal, and polymer batteries.

- Halon 1301 in a Class C cargo compartment and hand-held fire extinguishers containing Halon 1211 will extinguish the open flames from a lithium-ion or lithium-ion polymer cell fire and prevent the spread of fire to other ordinary combustibles.

- A lithium-ion cell in thermal runaway will generate enough heat to induce adjacent cells into thermal runaway. This results in the propagation of thermal runaway throughout the entire shipment.

- The propagation of thermal runaway of lithium-ion cells will occur even in the presence of Halon 1301 suppression in a Class C cargo compartment. Halon 1301 has an insufficient cooling effect to stop the propagation.

- Halon 1211 in hand-held fire extinguishers will not prevent flare-up as addition cells go into thermal runaway due to the dispersion of the agent.

- Water is effective in stopping the propagation of thermal runaway and is recommended in controlling lithium-ion cell fires in installed equipment in carry-on luggage.

- Shipping lithium-ion cells in a Class C cargo compartment as opposed to Class E will reduce the hazard significantly.

- Shipping lithium-ion cells in an approved overpack minimizes the hazard significantly.

- Combining an overpack and a compartment with suppression will add another layer of protection when shipping lithium-ion cells and batteries.

- Common metal shipping containers, such as steel drums or pails, are not effective for shipping lithium metal cells. These containers are not designed to withstand the high pressures generated by burning lithium metal cells.

- Halon 1301, in a Class C cargo compartment and hand-held Halon 1211 extinguishers are not effective in extinguishing a lithium metal cell fire. These agents may be used to prevent the spread of fire to other ordinary combustibles. The pressures generated by metal cells in thermal runaway may dislodge the cargo liners or activate the pressure relief mechanisms, allowing the Halon 1301 to leak out.

- There is no advantage in shipping lithium metal cells in accessible locations due to the ineffectiveness of hand-held fire extinguishers in controlling a lithium metal cell fire.

9. REFERENCES.

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