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Flammability Assessment of Bulk-Packed, Rechargeable Lithium-Ion Cells in Transport Category Aircraft

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Final Report

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16. Abstract

This report documents the findings of a series of tests conducted to determine the flammability characteristics of rechargeable lithium-ion cells and the dangers associated with shipping them in bulk form on commercial transport category aircraft.

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LIST OF ACRONYMS

NTSB	National Transportation Safety Board
FAA	Federal Aviation Administration
FedEx	Federal Express
mAh	milliampere hour

EXECUTIVE SUMMARY

A series of tests were conducted to determine the flammability characteristics of type 18650 rechargeable lithium-ion cells, both individually and as packaged for bulk shipment onboard cargo and passenger aircraft. The tests were designed to determine the conditions necessary for cell ignition, the characteristics of the cell fire, the effect of state of charge, the potential hazard to the aircraft as a result of the fire, and the effectiveness of the standard Halon 1301 fire suppression systems in extinguishing the fire.

A relatively small fire source is sufficient to heat the lithium-ion cell above the temperature required to activate the pressure release mechanism in the cell. This causes the cell to forcefully vent its electrolyte through the relief ports near the positive terminal. The electrolyte is highly flammable and easily ignites when exposed to an open flame or hot surface. Fully charged cells released small white sparks along with the electrolyte.

Halon 1301, the fire suppression agent installed in transport category aircraft, is effective in suppressing the electrolyte fire and easily extinguishes any fire at both the 5% knockdown concentration as well as the 3% suppression concentration. Halon 1301 has no cooling effect and did not prevent the release of electrolyte from heated cells.

The release of the electrolyte caused by heating a lithium-ion cell produces a pressure pulse that can raise the air pressure within a cargo compartment. Exposing only a few cells to a small alcohol fire was sufficient to increase the air pressure by more than 1 psi in an airtight, 10-meter-cubed pressure vessel. Cargo compartments are only designed to withstand approximately a 1-psi pressure differential. A fire involving a bulk-packed lithium-ion shipment may compromise the integrity of the compartment by activating the pressure relief panels. This can allow the Halon 1301 fire suppressant to leak out of the compartment, reducing its effectiveness.

Fully charged cells produced a larger pressure pulse and more forceful venting.

A cargo fire involving lithium-ion cells does not present any unusual stresses on the cargo liner material.

1. INTRODUCTION.

The tests described in this report are an effort to assess the flammability characteristics of lithium-ion rechargeable cells and the potential hazard associated with shipping them on transport aircraft.

Both primary (nonrechargeable) and lithium-ion (rechargeable) cells are popular power sources for many small electronic appliances. Most of the cells used in the United States are manufactured in Japan, China, and South Korea. The cells are packed in bulk corrugated cardboard containers and stacked on pallets and shipped in the cargo holds of passenger and cargo aircraft. There has never been a known in-flight fire associated with shipping the cells in this manner; however, two separate incidents, one involving primary cells and one involving lithium-ion cells, have drawn attention to the potential flammability hazards for each type of cell.

The first incident involved a shipment of lithium primary cells that occurred at Los Angeles International Airport in April 1999. A pallet of cells 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 common extinguishing agents. As a result, in 1999, the National Transportation Safety Board (NTSB) recommended such cells be prohibited on passenger flights as air cargo and that a safety analysis be conducted to determine if such cells are safe.

The safety analysis conducted by the Federal Aviation Administration (FAA) found that (1) lithium cells could self-ignite during an unrelated aircraft cargo compartment fire even after the fire was suppressed by the halon used in aircraft compartments, (2) burning lithium cells would not be extinguished or suppressed by halon, and (3) burning lithium cells would spew molten lithium that could penetrate aircraft cargo compartment liners [1].

The second incident involved a shipment of lithium-ion cells onboard a Federal Express (FedEx) aircraft on the ramp in Memphis, Tennessee. The individual cells were assembled into a cell pack for an electric car. The crate containing the cell 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 cell 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 cell pack.

The Pipeline and Hazardous Materials Safety Administration 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 primary cells 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 cells and will initiate additional actions as necessary." Specific activities include "investigate flammability characteristics, extinguishing system effectiveness, cell charge state, and cell failure mode."

2. TEST DESIGN.

2.1 SCOPE.

These tests were designed to determine the flammability characteristics of lithium-ion rechargeable cells and any associated potential hazard to transport aircraft when shipped on bulk pallets in Class C cargo compartments. Cargo compartment spaces have different requirements for fire protection based on crew accessibility and potential hazard to passengers. All cargo compartments in passenger-carrying transport aircraft fall under the Class C requirements. These requirements include both fire detection and fire suppression systems. Appendix A lists the fire detection and suppression requirements for Class A, B, C, and E cargo compartments. Lithium-ion cells are defined as rechargeable cells containing no metallic lithium. The flammability parameters investigated included ignition source intensity, effect of cell quantity, effect of cell charge state, fire propagation between cells, temperature rise in the test chamber, pressure rise in the test chamber, effect of Halon 1301 fire suppression systems, autoignition temperature, and effect on cargo liner integrity.

The cell type used in these tests was the same as commonly found in a laptop computer cell pack, designated: 18650 (18 is the diameter and 650 is the length in mm), as shown in figure 1.

FIGURE 1. 18650 LITHIUM-ION CELLS PREPARED FOR TEST

Five different manufacturers supplied the cells with a capacity of 2200 milliampere hour (mAh), in two states of charge. Fifty percent of the cells were delivered charged at 50%; this is the level of charge the cells are normally shipped. The remaining cells were charged to full capacity. Measuring the cell voltage level can approximate the state of charge. A cell voltage of 3.8 to 3.83 represents a 50% charge. A cell voltage of 4.15 to 4.2 represents a 100% charge.

One manufacturer supplied a second version of the 18650 cell with 2700 mAh capacity, in both the shipping and full charge states.

2.2 TEST FACILITY.

A test chamber was constructed to measure the flammability of the subject cells. The chamber was constructed of 1/8″ uninsulated steel sheeting and measured 4′ by 4′ by 4′, producing a 64-cubic-foot test facility. The entire front side opens for access and is fitted with a Plexiglas windowpane to allow observation and videotaping of the fire test. The 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 overpressure from damaging the structure. The facility was fitted with a Halon 1301 fire-extinguishing system designed to provide both a 5 percent and a 3 percent concentration of Halon 1301. The 5 percent concentration is equal to that provided in a standard cargo compartment for initial fire knockdown. The 3 percent concentration is equal to that provided in a standard cargo compartment for fire suppression after the initial knockdown. A steel angle frame was constructed to support a basket made from 0.5″ wire mesh, used to support the cells over the fire pan. Figure 2 shows a diagram of the test chamber.

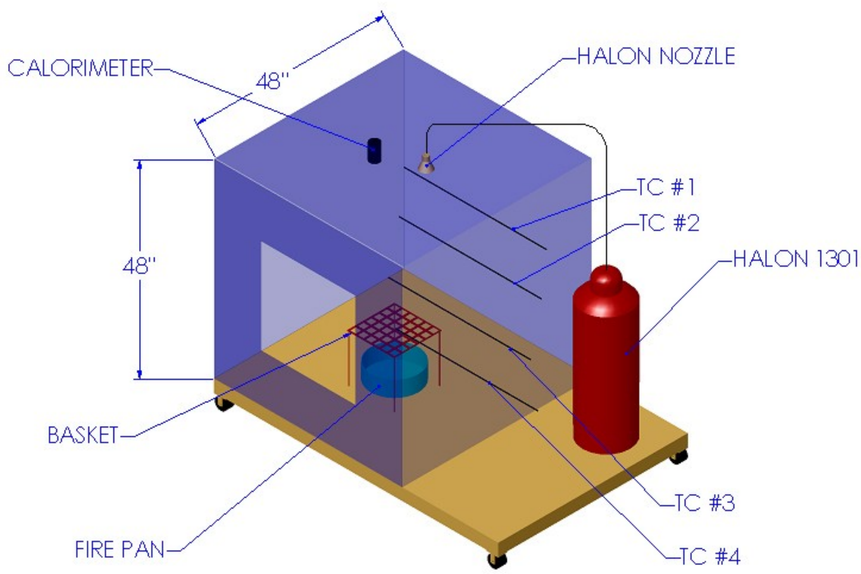

FIGURE 2. THE 64-CUBIC-FOOT TEST CHAMBER

2.2.1 Instrumentation.

The 64-cubic-foot test facility was fitted with four type C thermocouples located in the center of the chamber and spaced 12, 24, 36, and 48 inches from the floor. The thermocouples are numbered from the top, with the 48″ height assigned number 1 and the 12″ height assigned number 4. These thermocouples measure the temperature rise in the chamber. In addition, a calorimeter was installed. The calorimeter was centered in the ceiling of the chamber and assigned channel 5. The calorimeter was used to measure the heat flux produced by the ignition source fires and the cell fires.

A video camera was positioned outside the chamber and recorded the fire event through the Plexiglas door.

2.2.2 Ignition Fire Source.

The chamber was fitted with a circular 5.25″ diameter, 1-inch-deep fire pan. This was loaded with 50 ml of 1-propanol to provide a low-intensity fire with a surface area of 20.6 square inches. The fire pan was centered on the chamber floor.

3. BASELINE TESTS OF THE 5.25″ FIRE PAN CALIBRATION.

The test facility was designed to simulate temperature conditions that are typical of a cargo compartment fire that has been suppressed with Halon 1301. Under these conditions, deep-seated fires can continue to smolder, producing isolated pockets of temperatures in the 1000° to 1200° range. The air temperatures in a suppressed cargo compartment measured at the ceiling can range from 410° to 665°F [1].

The facility was calibrated with a series of baseline tests. 1-propanol (C3H7OH) was used as the fuel throughout these tests. The volume of 1-propanol determined the duration of the fire. The amount of 1-propanol was adjusted to ensure a 3-minute ignition fire. The 5.25″ pan required 50 ml of 1-propanol.

The 5.25″ fire pan reached a peak temperature of approximately 725°F, measured 12″ above the fire pan. The temperature at the ceiling of the chamber only rose to 225°F. The heat flux measured at the top of the chamber peaked at 0.18 Btu/ft^2-sec. These numbers define a fire that is lower in intensity than what might be found in a suppressed cargo compartment, as shown in figure 3.

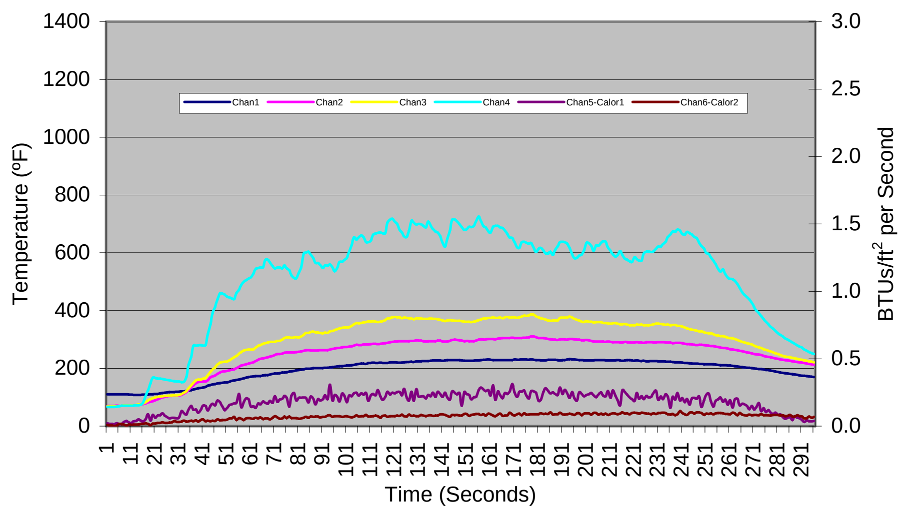

FIGURE 3. THE 5.25″ IGNITION FIRE CALIBRATION

4. THERMAL ABUSE TESTS.

4.1 SINGLE CELL FAILURE MODE WITH HIGH-SPEED VIDEO DOCUMENTATION.

A series of tests were conducted with the 5.25″ fire pan and a single cell from each manufacturer to determine flammability behavior. The cell was suspended in a wire basket 4″ above the fire pan. The pan was loaded with 50 ml of 1-propanol and ignited with a propane torch. The cells were tested in both a nominal 50% charge and a 100% charge, as delivered from the manufacturer. The cells are normally shipped at a 50% charge state.

Typically, the cells from all manufacturers exhibited similar failure characteristics when exposed to the small, 1-propanol alcohol fire. There was an initial venting of a small amount of liquid sprayed through the overpressure vents surrounding the positive terminal. The vented liquid is flammable and easily ignites when exposed to the alcohol flame. There was a small pressure pulse associated with the event. For purposes of this report, this was defined as the First Event.

There was a second venting of electrolyte liquid that occurs 20 to 30 seconds after the First Event. The second venting was much more forceful than the first one and involved a much larger volume of liquid. The electrolyte liquid easily ignited and formed small torch-like fires through the overpressure vent ports near the positive terminal. There was a stronger, sometimes substantial, pressure pulse associated with this electrolyte release. This was defined as the Second Event.

Occasionally, the pressure release ports failed to operate correctly, causing buildup of pressure inside the cell case until the casing failed. When this occurred, the cell literally exploded, expelling the contents throughout the test chamber and releasing a substantial pressure pulse. The entire electrolyte was released at once, which formed a fireball when ignited by the alcohol fire. Generally, when a cell failed in this manner, the entire positive end cap was blown off, releasing the contents. In two incidences, the end cap remained and the cell casing ruptured on the side. In one case, the bottom of the cell ruptured.

The state of charge did not affect the failure mode, but it did cause slightly different characteristics. The venting, both First and Second Events, was more forceful in the fully charged cells. The Second Event electrolyte release also included small white sparks along with the liquid.

The cells followed the same pattern (all times are nominal), as shown below.

Time (min)	Event
0:00	1-propanol fire ignited
0:45	First Event—initial venting
1:05	Second Event—release of electrolyte, producing a torch fire
1:25	Cell expended

A typical expended cell that vented normally had an intact casing and exhibited small beads of a metallic substance on the positive terminal end, as shown in figure 4. An exploded cell had an empty casing and sheets of copper-colored material were found in the chamber, as shown in figure 5.

FIGURE 4. EXPENDED CELL WITH METALLIC BEADS ON POSITIVE TERMINAL

FIGURE 5. EXPLODED CELL AND ITS CONTENTS

Figure 6 is a typical temperature and heat flux profile obtained in the 64-cubic-foot chamber by exposing a single cell, at 50% charge, to the alcohol fire. Peak temperatures measured just above the cell were approximately 300° higher than the pan fire alone. The single cell had a negligible effect on the heat flux measurements.

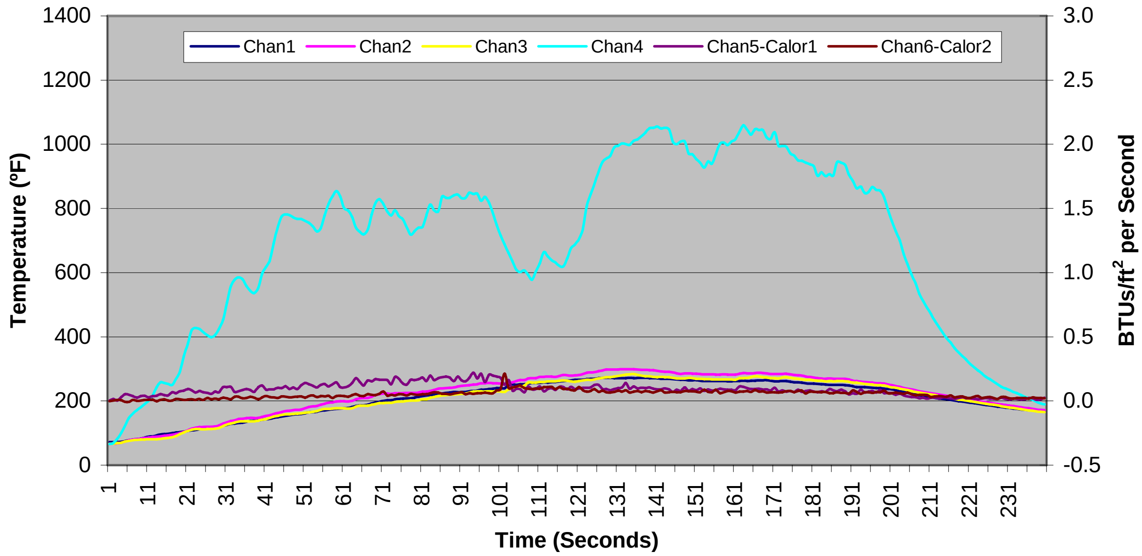

FIGURE 6. SINGLE CELL TEMPERATURE PROFILE AT 50% CHARGE

A high-speed video camera was used to document the failure mode of each manufacturer's cell. The tests were conducted in the 64-cubic-foot chamber with the door open to allow clear view for the video camera. Each cell was wired to a support arm and suspended over the 5.25″ fire pan to keep the cell in the field of view of the video camera. The fire pan was loaded with 50 ml of 1-propanol.

The high-speed video revealed that the electrolyte liquid was being ignited by the alcohol fire and was not self-igniting. Figure 7 shows a single frame from the video of a typical First Event. Figure 8 shows a typical Second Event. Figure 9 shows an exploded cell, as recorded by the high-speed video. The explosion was forceful enough to lift the heavy steel stand off the floor of the chamber.

FIGURE 7. HIGH-SPEED VIDEO CAPTURE OF FIRST EVENT

FIGURE 8. HIGH-SPEED VIDEO CAPTURE OF SECOND EVENT

FIGURE 9. HIGH-SPEED VIDEO CAPTURE OF EXPLODING CELL

4.2 MULTIPLE CELL TESTS IN THE 64-CUBIC-FOOT CHAMBER.

A series of tests were conducted to determine the flammability of multiple cells, simulating the tightly packed configuration that would be found in bulk shipment. The tests were conducted using the 5.25″ fire pan, 50 ml of 1-propanol, and a wire basket suspending the cells 3″ above the fire pan. The cells were tested in groups of 4, 8, and 16 in both 50% and 100% charged states.

4.2.1 The 50% Charge.

Each test resulted in similar peak temperatures, measured 12″ above the fire pan, of approximately 1200°-1300°F. The duration of the peak temperature increased with additional cells, but the actual peak did not significantly vary. This peak is about 500°-600°F above that of the 1-propanol fire alone. Peak heat flux was under 0.5 Btu/ft^2-sec. The heat generated by the burning electrolyte was usually enough to cause the adjacent cells to vent. Generally, the cells would eventually reach the Second Event; however, once the alcohol fire was exhausted, the electrolyte did not ignite. Cells at a 50% charge rarely exploded. Figure 10 shows a typical test with eight cells.

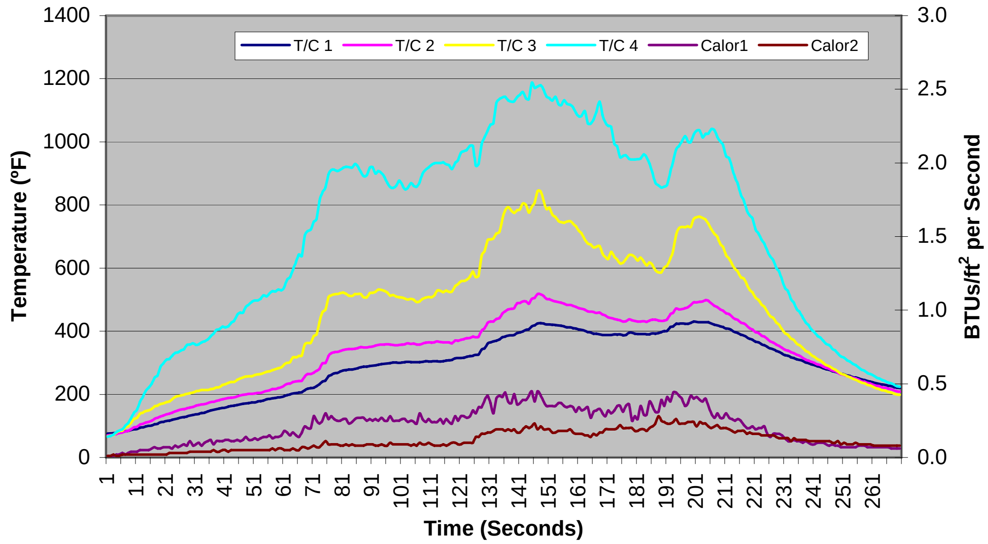

FIGURE 10. EIGHT-CELL TEST AT 50% CHARGE

4.2.2 The 100% Charge.

Results were similar to the 50% charge, but the venting and torching were more forceful. Small white sparks could be seen in the Second Event torch fires emitting from the positive terminal end. The forcefulness of the burning electrolyte was often enough to propel the cells away from the 1-propanol fire and explosions were more common. This led to lower peak temperatures; however, the heat flux was usually significantly higher—two to three times that found in the 50% charge tests. Efforts to restrain the cells without influencing the results were of limited success. Propagation between cells was more pronounced, but electrolyte ignition only occurred if there was an external ignition source, such as the 1-propanol fire or an adjacent burning cell. Figure 11 shows a typical eight-cell test at 100% charge.

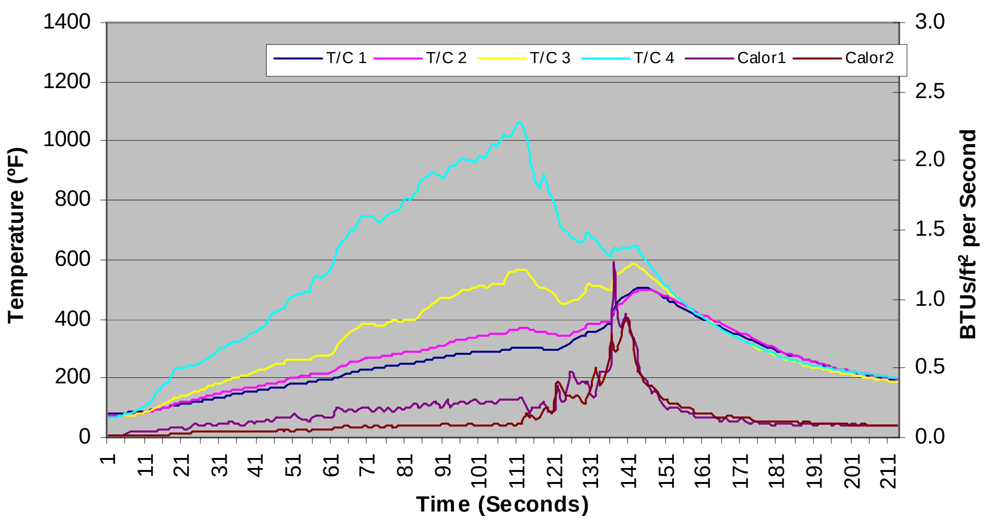

FIGURE 11. EIGHT-CELL TEST AT 100% CHARGE

4.3 HALON 1301 FIRE SUPPRESSION TESTS.

A series of tests were conducted to evaluate the effectiveness of the standard cargo compartment fire suppression system in controlling a fire that was fueled by lithium-ion 18650 cells. The 64-cubic-foot test chamber was fitted with a Halon 1301 fire suppression system designed to flood the chamber and achieve either a 5% or 3% concentration of Halon 1301. Cargo compartment fire suppression systems are designed to initially flood the compartment to a minimum of 5% Halon 1301 concentration to knockdown the fire, and then maintain 3% concentration to keep the fire suppressed.

A charge of 1.3 pounds of Halon 1301 was required to achieve a nominal 5.5% concentration in the 64-cubic-foot chamber. A charge of 0.74 pound of Halon 1301 was required to achieve a 3% concentration. This was verified and monitored using an infrared gas analyzer.

The tests were conducted using eight cells per test. Two fire suppression discharge protocols were used. The first protocol required the Halon 1301 agent to be discharged at First Event. The second protocol required the Halon 1301 agent to be discharged at Second Event. The tests were repeated for each manufacturer, at 50% and 100% charges and at 3% and 5% Halon 1301 concentrations.

The halon agent at both concentrations was effective in controlling the 1-propanol fire and the burning electrolyte from the lithium-ion cells. The test conditions and results were as follows:

- 50% Charge, 5% Halon 1301, First Protocol. Discharging the halon agent at the initial First Event extinguished the 1-propanol fire and always prevented any of the cells from reaching Second Event. Up to four cells still reached First Event after discharge, but no fire resulted.

- 50% Charge, 5% Halon 1301, Second Protocol. Discharging the halon agent at the initial Second Event extinguished the 1-propanol fire and the electrolyte fire of the burning cell. All eight cells generally reached First Event, and an average of six cells reached Second Event; however, no fire resulted (i.e., the vented electrolyte did not ignite).

- 50% Charge, 3% Halon 1301, First Protocol. There was no difference in fire suppression effectiveness between the 5% concentration and the 3% concentration discharges. The 1-propanol fire was extinguished and no cells reached Second Event.

- 50% Charge, 3% Halon1301, Second Protocol. There was no difference in the fire suppression effectiveness between the 5% concentration and the 3% concentration discharges under these conditions. The halon agent extinguished the 1-propanol fire, the burning cell, and prevented any additional fire. Again, all eight cells reached First Event, and an average of six cells reached Second Event.

- 100% Charge, 5% Halon 1301, First Protocol. The results were similar to the 50% charge tests. The 1-propanol fire was extinguished and the halon agent prevented any of the cells from burning. An average of four cells reached First Event and none of them reached Second Event.

- <u>100% Charge, 5% Halon 1301, Second Protocol</u>. The Halon 1301 agent extinguished the 1-propanol fire, the burning cell, and prevented any further fire. All the cells reached First Event, and an average of seven cells reached Second Event. On two occasions, cells exploded after the halon agent was discharged, but no fire resulted.

- <u>100% Charge, 3% Halon 1301, First Protocol</u>. There was no difference in the fire suppression effectiveness between the 5% and 3% Halon 1301 agent concentrations under these conditions. The 1-propanol fire was extinguished and no additional fire resulted. An average of four cells reached First Event and none of the cells reached Second Event.

- <u>100% Charge, 3% Halon 1301, Second Protocol</u>. The results were identical to the 5% tests. The Halon 1301 extinguished the 1-propanol fire, the cell fire, and prevented any additional fire. The cells continued to vent, with an average of seven cells reaching Second Event. On one occasion, a cell exploded after the halon agent was discharged, but no fire resulted.

Halon 1301 has proven to be effective against lithium-ion cell fires at both 5% and 3% concentrations.

Figure 12 shows a typical 5% Halon 1301 test, 50% charge, discharged under first protocol conditions. The 1-propanol fire was immediately extinguished, resulting in lower temperatures.

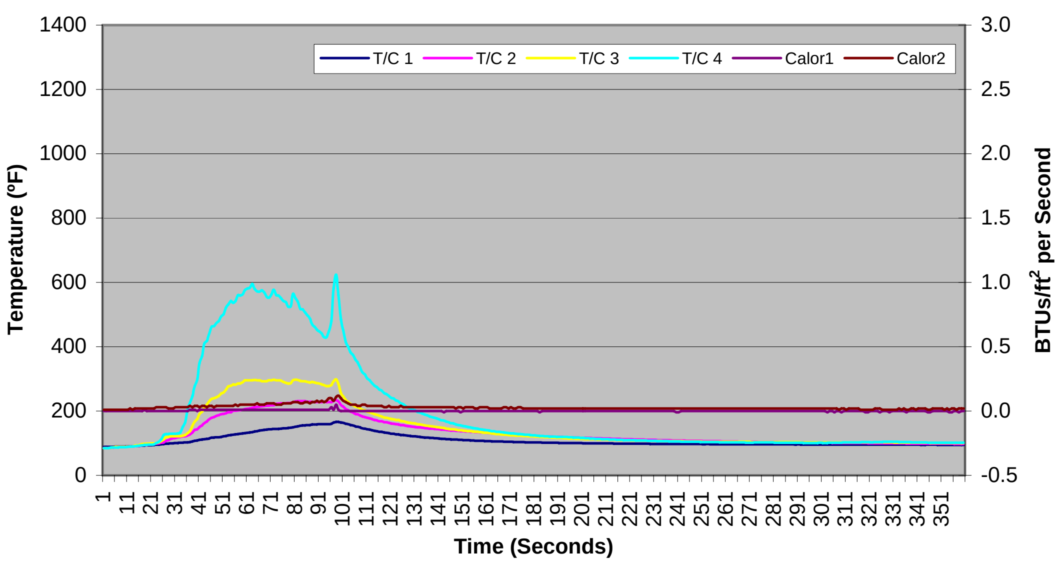

FIGURE 12. EIGHT 50% CHARGED CELLS, HALON 1301 AT 5% CONCENTRATION, FIRST PROTOCOL

Figure 13 shows a typical 5% Halon 1301 test discharged under second protocol conditions. The fires were extinguished, resulting in lower temperatures. Six cells reached Second Event, but little increase in temperature was noted.

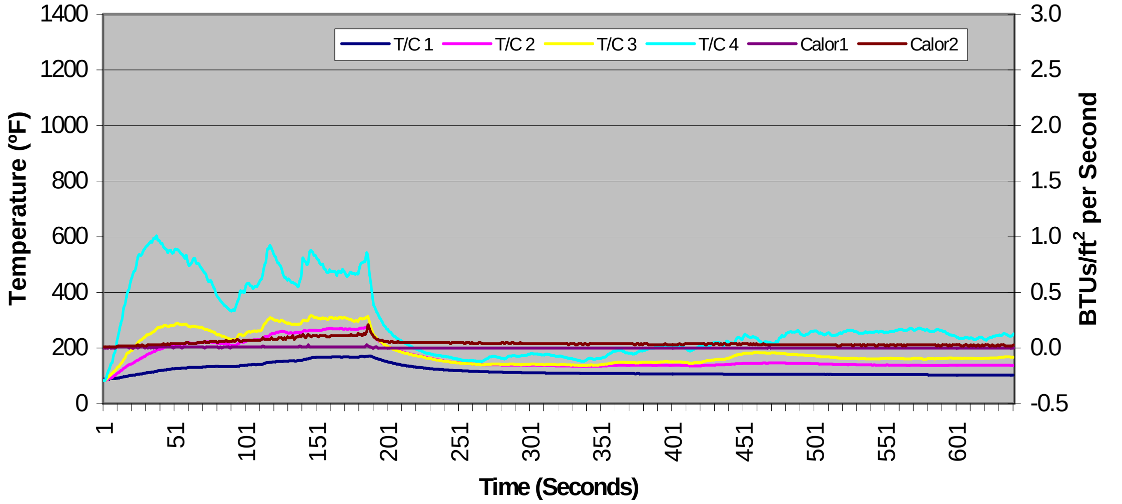

FIGURE 13. EIGHT 50% CHARGED CELLS, HALON 1301 AT 5% CONCENTRATION, SECOND PROTOCOL

4.4 CARGO LINER INTEGRITY TESTS.

A series of tests were conducted to determine the effect of burning lithium-ion cells on standard cargo liner material. The tests were conducted in the 64-cubic-foot test chamber using the 5.25″ fire pan and 50 ml of 1-propanol. The tests were designed to maximize the exposure of the cargo liner to the torching electrolyte emitted from the burning cells.

The tests were configured by standing a 24″ high by 24″ wide piece of cargo liner vertically in a semicircle around the fire pan. Four cells were wired together and fastened to the support basket suspended over the fire pan. The cells were arranged so that the positive ends were pointed at the cargo liner with about 3″ separating the cells from the cargo liner. The tests were conducted using a thin-wall cargo liner, which has a single layer of fiberglass cloth.

4.4.1 The 50% Charge Cells.

The 1-propanol fire heated the cells until they reached Second Event. The torch fire from the burning electrolyte caused some minor scorching of the cargo liner face. The cargo liner did not catch fire, and there was no penetration.

4.4.2 The 100% Charge Cells.

The torch fire and small white sparks had no impact on the cargo liner other than some minor scorching. The cargo liner did not catch fire, there was no penetration, and the integrity of the cargo liner was not compromised.

4.5 PRESSURE PULSE TESTS.

A series of tests were conducted to measure the pressure pulse effects of the 18650 lithium-ion cell. The cells tested were charged at either 50% or 100% capacity. The tests were conducted at the FAA Pressure Modeling Facility. This facility consists of a 10-cubic-meter airtight chamber that is fitted with pressure- and temperature-monitoring instrumentation. The pressure transducer port and the thermocouples were located near the center of the chamber.

The chamber was fitted at one end with a 5.25″ fire pan and a steel support arm to suspend the cells 3″ above the fire pan. A video camera was installed inside the chamber, as well as a remote ignition device for the fire pan. The pan was loaded with 50 ml of 1-propanol. The cells were tested individually and in groups of four in both 50% and 100% charges. Figure 14 shows the inside of the chamber with the fire pan and cell holder.

FIGURE 14. PRESSURE MODELING FACILITY AND CELL TEST APPARATUS

4.5.1 The 50% Charge, Single Cell.

A single cell at Second Event raised the pressure in the airtight chamber between 0.2 and 0.25 psi. Figure15 shows a typical pressure rise profile for a single cell at a 50% charge. The gradual pressure rise up to the 110-second mark is due to the increased air temperature. At the 110-second mark, the cell achieved Second Event and released a pressure pulse; in this case, approximately 0.23 psi.

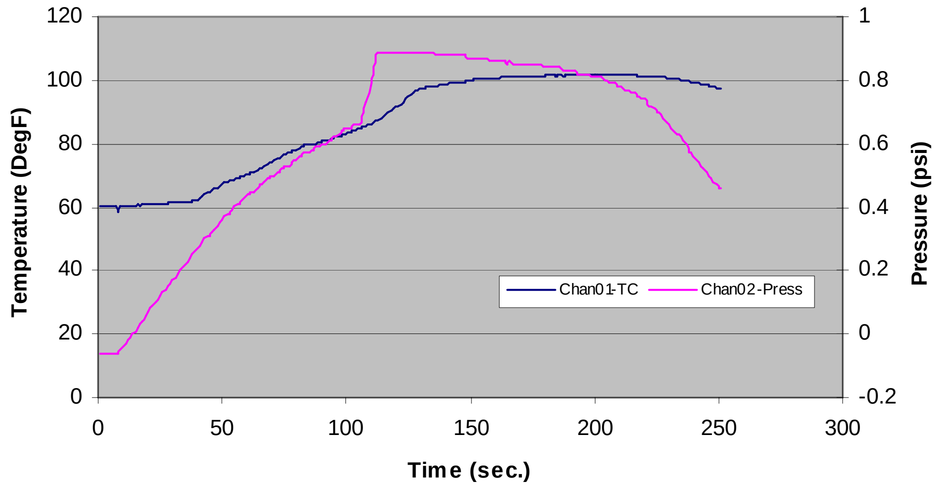

FIGURE 15. PRESSURE RISE DUE TO SINGLE 50% CHARGED CELL IGNITION

4.5.2 The 100% Charge, Single Cell.

A single cell at Second Event raises the pressure inside the chamber by 0.21 to 0.25 psi. On one occasion, the cell exploded, raising the pressure by 0.60 psi. Figure 16 shows the pressure rise for the exploding cell.

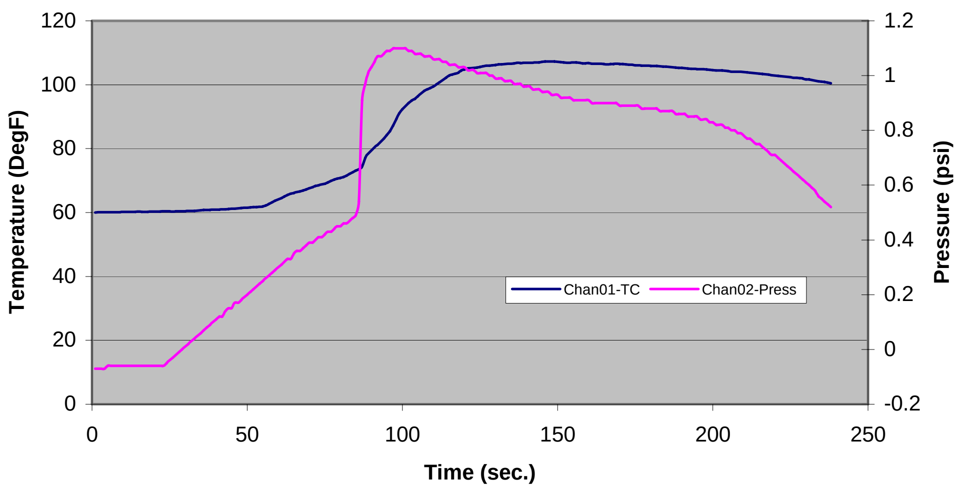

FIGURE 16. PRESSURE RISE DUE TO EXPLODING CELL

4.5.3 The 50% Charge, Four Cells.

The four-cell tests usually did not have all four cells achieve Second Event. This may have been due to interior thermal air currents in the chamber causing the 1-propanol flame to move away from the cells. The number of cells that reached Second Event can be easily determined by counting the pressure peaks on the graph. The pressure rise in these tests ranged from 0.74 to 0.84 psi. Figure 17 shows a typical test with three peaks, indicating three cells achieved Second Event. The small bumps prior to the large increases are from First Event venting.

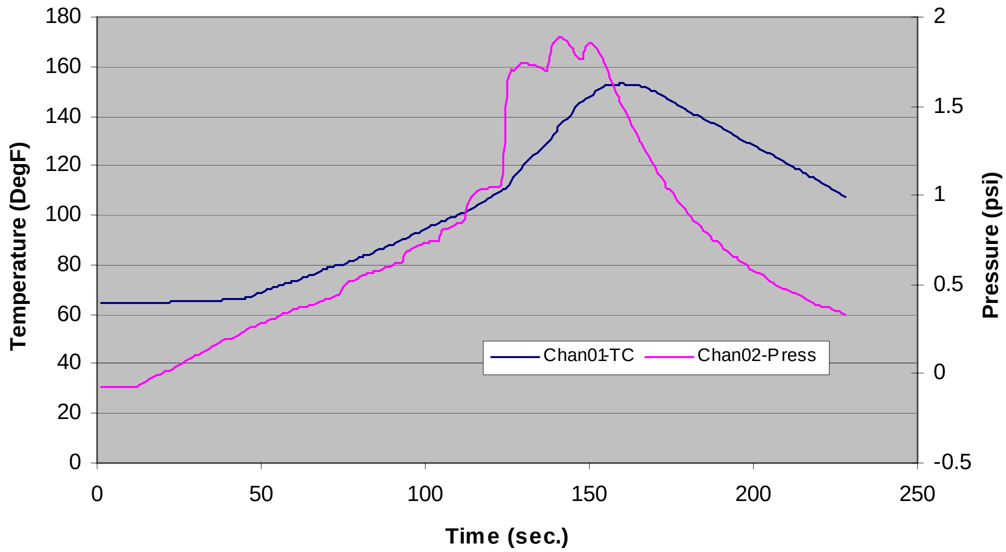

FIGURE 17. PRESSURE RISE DUE TO FOUR CELLS AT 50% CHARGE

4.5.4 The 100% Charge, Four Cells.

The 100% charged cells were more energetic than the 50% charged cells in these tests. The pressure rise in these tests ranged from 0.9 to 1.94 psi. Figure 18 shows a typical test from this series.

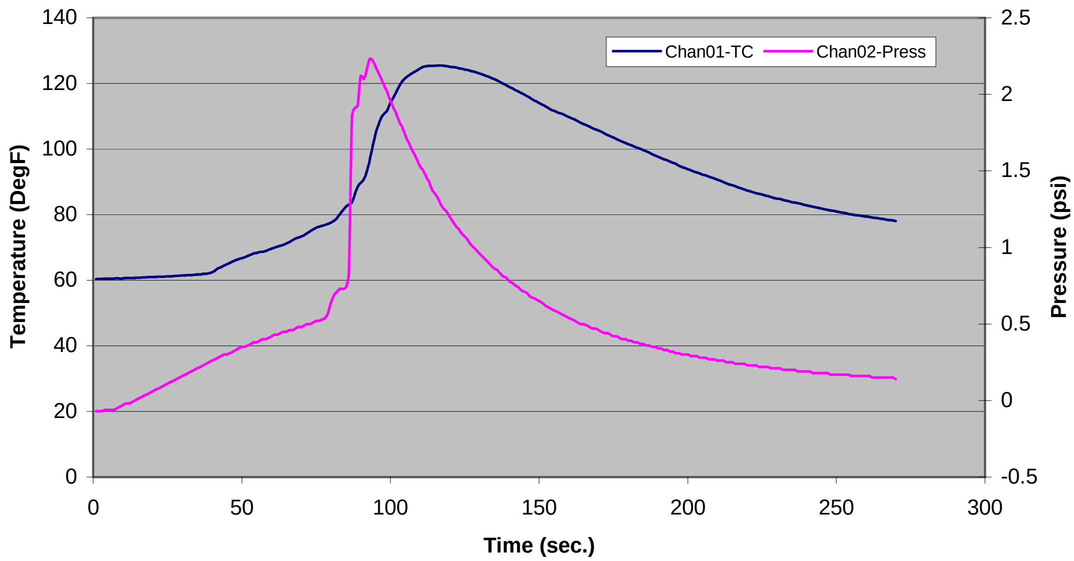

FIGURE 18. PRESSURE RISE DUE TO FOUR 100% CHARGED CELLS

4.6 AUTOIGNITION TESTS.

The purpose of these tests was to determine the risk of a cell reaching thermal run away due to a smoldering suppressed fire in a cargo compartment. The temperature in a fully suppressed cargo compartment fire can locally exceed 1000°F in a smoldering fire, and the air temperature at the ceiling can range from 410° to 665°F [2].

A 1-cubic-foot steel test chamber was constructed. The chamber was insulated and provided with an external acetylene torch heat source fitted with a rosebud nozzle. The cells were suspended in the center of the chamber. Two thermocouples were installed; one near the top of the chamber and one near the cell. Figure 19 shows the test chamber and torch setup.

FIGURE 19. AUTOIGNITION TEST CHAMBER

The cell was installed in the test chamber, and then the acetylene torch was lit. The temperature rise in the chamber was monitored, with a sudden rise in the chamber temperature signaling Second Event venting. This was accompanied by smoke leaking from the edge of the lid. Approximately 10 minutes were required to raise the temperature in the chamber high enough to cause the cells to vent.

When the cells vented and reached Second Event, releasing electrolyte fluid, the chamber temperature ranged from 444° to 489°F. This was noted by a sudden temperature spike in the box. The electrolyte occasionally ignited, due to the hot surface at the bottom of the chamber where the torch impinged. This ignition was often powerful enough to dislodge the heavy lid from the chamber.

There was no difference in the Second Event venting temperatures between the 50% and 100% charged cells. The temperature rise after venting was also similar. Figure 20 shows the temperature profile in the chamber and the temperature rise due to Second Event venting for a typical 50% charged cell. The temperature rise at venting measured 117°F. Figure 21 shows the temperature profile for a 100% charged cell. The temperature rise at venting measured 108°F.

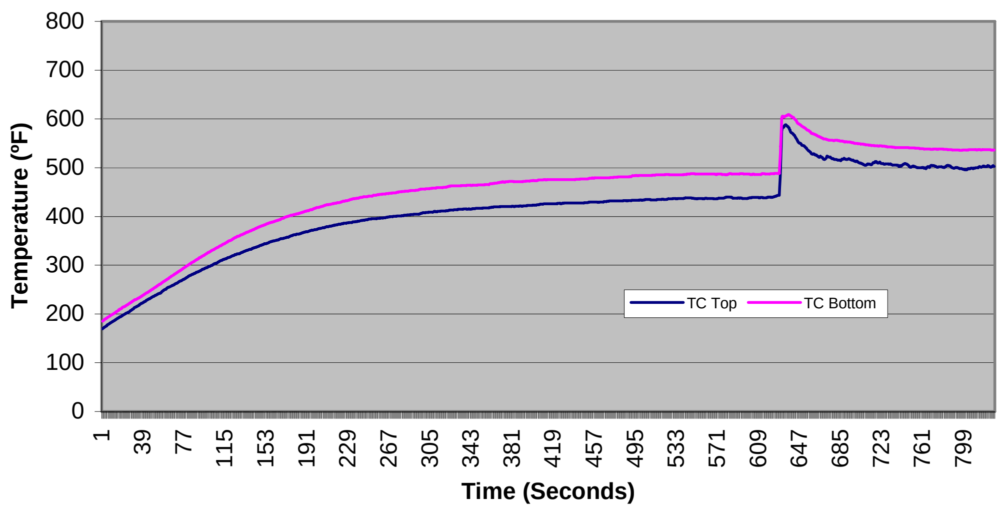

FIGURE 20. AUTOIGNITION TEST OF A 50% CHARGED CELL

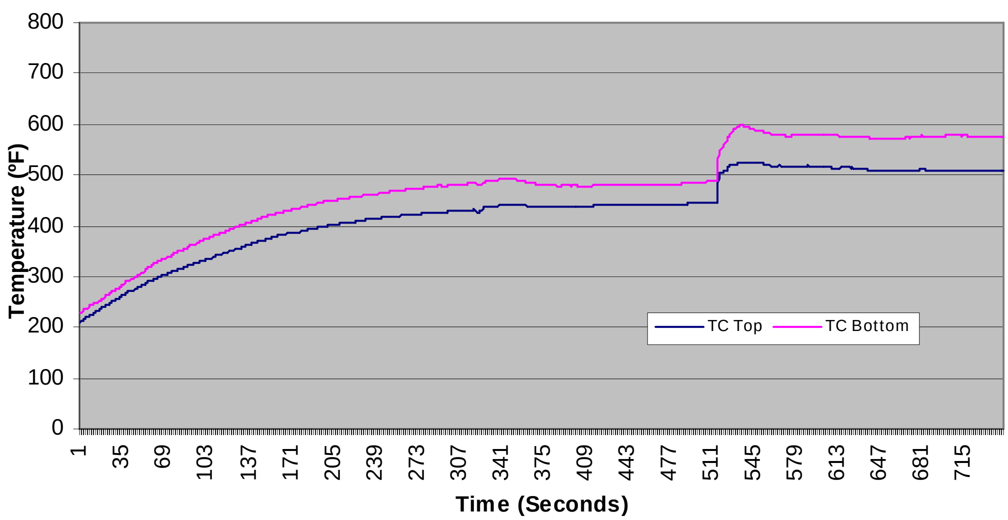

FIGURE 21. AUTOIGNITION TESTS OF A 100% CHARGED CELL

These tests show that the conditions in a Halon 1301-suppressed cargo compartment are sufficient to cause lithium-ion 18650 cells to vent electrolyte due to ambient air temperature.

4.7 HIGH-CAPACITY CELLS.

High-capacity cells were made available for testing. All previous tests were conducted with 2200 mAh cells. The higher-capacity cells are rated at 2700 mAh. The 50% charged cell test results were very similar in all respects to the 2200 mAh cells.

The 2700 mAh 100% charged cells were more forceful at Second Event, with the white sparks more prevalent in the electrolyte discharge. The incidence of explosion was also greater. Approximately 20% of the cells exploded during the 64-cubic-foot test chamber tests.

Halon 1301 was effective in controlling the electrolyte fires from the high-capacity cells.

The pressure pulse measured for a single 100% charge cell was 0.31 psi. This is somewhat higher than that measured for the 2200 mAh cells, which showed a maximum of 0.25 psi.

5. CONCLUSIONS.

A relatively small fire source was sufficient to cause a lithium-ion 18650 cell to vent flammable electrolyte liquid. This liquid easily caught fire when exposed to an external ignition source, producing a torch-like flame emitting from near the positive terminal. This flame is hot enough to cause adjacent cells to vent and ignite, propagating through the packaged cells.

The temperature conditions in a fully suppressed cargo compartment fire are sufficiently high enough to cause lithium-ion 18650 cells to vent electrolyte.

Halon 1301 is effective in suppressing the electrolyte fire, extinguishing the fire, and preventing any additional fire from subsequent venting. Cells will continue to vent due to the air temperature, but will not ignite in the presence of Halon 1301.

Cargo compartment liners are capable of withstanding a fire fueled by lithium-ion 18650 cells.

Venting lithium-ion 18650 cells released a pressure pulse that can raise the air pressure in a cargo compartment. As few as four cells venting increased the air pressure by 1 psi in an airtight 10-meter-cubed pressure vessel. Cargo compartments are only designed to withstand approximately a 1-psi pressure differential. Heating a shipment of bulk-packed lithium-ion 18650 cells to the point of venting may raise the pressure above the 1 psi limit and compromise the integrity of the compartment by activating the pressure relief panels. This would allow the Halon 1301 fire suppression Halon 1301 to leak out, reducing its effectiveness.

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. Reinhardt, J.W., Blake D., and Marker, T., “Development of a Minimum Performance Standard for Aircraft Cargo Compartment Gaseous Fire Suppression Systems,” FAA report DOT/FAA/AR-00/28, September 2000.

APPENDIX A—14 CFR 25.857, CARGO COMPARTMENT CLASSIFICATION

Title 14 Code of Federal Regulations (CFR) Part 25 details the legal requirements for operating a transport category aircraft in the United States. 14 CFR 25.857 lists the definitions of the four types of aircraft cargo compartments and labels them Class A, B, C, and E. All Class D cargo compartments have been upgraded to Class C. Each class of cargo compartment is differentiated by the ease of crew access and the potential hazard to passengers. The fire detection and means of fire suppression requirements are different for each class of compartment. The below-deck cargo compartments in all transport category passenger aircraft are Class C compartments. 14 CFR 25.857 is provided below.

(a) *Class A;* A Class A cargo or baggage compartment is one in which –

(1) The presence of a fire would be easily discovered by a crewmember while at his station; and
(2) Each part of the compartment is easily accessible in flight.

(b) *Class B.* A Class B cargo or baggage compartment is one in which –

(1) There is sufficient access in flight to enable a crewmember to effectively reach any part of the compartment with the contents of a hand fire extinguisher;

(2) When the access provisions are being used, no hazardous quantity of smoke, flames, or extinguishing agent, will enter any compartment occupied by the crew or passengers;

(3) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

(c) *Class C.* A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which –

(1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;

(2) There is an approved built-in fire extinguishing or suppression system controllable from the cockpit.

(3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

(4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

(d) [Reserved]

(e) *Class E.* A Class E cargo compartment is one on airplanes used only for the carriage of cargo and in which --
(1) [Reserved]

(2) There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station;

(3) There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment;

(4) There are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and

(5) The required crew emergency exits are accessible under any cargo loading condition.