Discussion of Issues Regarding Performance-Based Standard for Air Transportation of Lithium Batteries

A. **Background**

The carriage of Lithium-ion cells and batteries in aircraft cargo compartments present three distinct hazards

1) Lithium-ion cells and batteries can be an ignition source. A damaged, shorted, overheated or defective cell (from impurities, manufacturing defects, foreign object deposits etc.) can spontaneously go into thermal runaway. Thermal runaway can cause the cell to ignite or explode and may propagate to adjacent cells and surrounding materials;

2) Lithium-ion cells and batteries can be a source of fuel for an existing fire. Cells when heated and forced into thermal runaway release flammable electrolyte and gases.

3) Lithium-ion cells and batteries produce a pressure pulse when in thermal runaway. The gases produced, when contained, can result in an explosive mixture. This may increase the pressure within a cargo compartment, activate pressure relief features, and cause damage to the cargo liner. This results in a reduced suppressant agent concentration and rapid fire escalation and force smoke into other areas of the aircraft.

These hazards should be mitigated at several levels, considering the types of batteries being transported, the state of the battery during transport, the capabilities of the battery packaging, and the capabilities of the aircraft. Lithium cells are designed to operate safely within certain temperature and pressure limits. When a lithium cell exceeds a critical temperature (approximately 150 °C), exothermic reactions occur between the cell components that produce a chain reaction generating more heat, which increases the cell temperature and pressure. Increasing the tolerance of cells to resist high temperatures and including fail safe mechanisms may mitigate much of the hazardous effects of transporting lithium-ion cell batteries. This can be done in a number of ways including reducing the propagation of thermal runaway from the cell, reducing the number of cells in a package, including insulating material or mechanisms to cool the cells in packing material, reducing the amount of available reaction energy, and strengthening the capabilities of aircraft cargo compartments. Such measures should be considered as part of any mitigation strategy.

In considering appropriate mitigation strategies, it is necessary to conduct a system safety assessment that evaluates the capabilities of the aircraft with the type of battery being transported, the capabilities of the battery, and the type of packaging that is being used for transport.

The aircraft may provide some protection in defense of the above hazards, particularly with respect to preventing the cells from becoming fuel for an external fire. Aircraft cargo compartments equipped with smoke or fire detection systems and built-in fire suppression systems (commonly referred to as Class C compartments) will reduce but not eliminate these hazards. Halon 1301, the fire suppressant agent commonly used in these cargo compartments, can control a fire that involves burning electrolyte from Lithium-ion cells. In addition, Halon 1301 will suppress open flames from other combustible material, reducing but not eliminating the likelihood of an external fire spreading to a consignment of Lithium-ion cells or batteries.

Halon 1301, however, cannot, in the concentrations currently specified, suppress an explosion from the ignition of gases produced by thermal runaway, nor will it prevent temperature increases resulting from large quantities of cells propagating thermal runaway. Therefore, preventing the cells from propagating during transport, and/or confining the hazards (Combustible gasses, flames and smoke) within a package, is likely the best means to mitigate the risk of fire or explosion while transporting lithium ion cells.

In addition to the aircraft capabilities, there is also a direct correlation between the size of the cell and the magnitude of the hazard. Testing has shown that large format cells exhibit the same thermal runaway characteristics and hazards as small consumer size cells, but on a much larger scale.

B. **Known Hazards Associated with Transport of Lithium-ion Cell Batteries**

The following are some of the hazards that have been identified with the air transport of lithium-ion batteries:

1. Propagation of thermal runaway

   a. Cells in thermal runaway produce enough heat to cause adjacent cells to go into thermal runaway.

   b. The heat produced is sufficient to ignite normal combustibles, such as fiberboard and paper packaging.

   c. Preventing the propagation of thermal runaway from cell to cell reduces the hazard to a minimal level.

   d. Limiting the propagation of thermal runaway reduces the fire threat, but may not adequately address the combustible gases that are vented.

2. Flammable gases and explosions

   a. A cell in thermal runaway produces a mix of gases, many of which are flammable. These include various hydrocarbons and hydrogen.

   b. When these gases are contained (e.g. package, ULD, compartment, etc.), an explosive mixture can occur with catastrophic results.

   c. Tests have shown that a minimum of 10% Halon 1301 is required to suppress an explosion from these gases.

3. Flammable electrolyte

   a. The vented electrolyte is flammable and once ignited contributes to both the overall fire and the rate of propagation of thermal runaway.

4. Explosive cells

   a. Certain cell chemistries and cell construction combinations can result in explosions when heated. These chemistries include, but are not limited to thionyl chloride, manganese dioxide and iron phosphate.

5. Pressure pulse.

   a. All cells in thermal runway produce a pressure pulse when they vent, some much more forceful than others. . The larger the cell size, the larger the pressure pulse.

6. Large Format Cells

   a. At this time, most of the cells being transported are consumer sized. The market for large format cells is increasing, however, as they are used for power storage by the automotive and power industries.

   b. The hazard from these large format cells is similar to that of the smaller consumer cells, only on a much larger scale. Failure of a single large format cell produces a significant event, without any propagation to other cells. With the propagation of thermal runaway, the hazard escalates dramatically.

7. External fires

   a. When a shipment size exceeds a certain number of cells, the effect of external fire exposure needs to be examined. Issues that need to be considered are the type and size of battery being transported, and type size and load factor of the compartment.

   b. This hazard is somewhat mitigated by shipping in a Class C compartment where available, but not eliminated. The temperature in a Class C compartment that is suppressed by Halon 1301 can still exceed that required to send a cell into thermal runaway, allowing the buildup of explosive gases.

8. Halon consumption and leakage

   a. Cells in thermal runaway produce pressure and gases that are released into the cargo compartment. This pressure and volume of gases will cause increased leakage of Halon 1301 from the compartment reducing the effectiveness of the agent and length of time that

C. **Mitigating Risk Associated with Air Transport of Lithium-ion Cell Batteries**

To address these hazards, there are a range of mitigations that may be necessary to reduce the risk of fire or explosion in transporting lithium ion batteries. The mitigations range from the capabilities of the aircraft, to the type of battery, the state of the battery during transport, and the packaging in which the battery is transported. A combination of these mitigations may be necessary to achieve a desired level of risk.

Aircraft Cargo Compartment-Based Mitigations:

1. Smoke detectors

    a. Are required in both the Class C and Class E cargo compartments

    b. Alert the flight crew that there is an event

    c. Time from a fire's ignition to detection is critical due to the rapid build-up of lithium battery fires

2. Fire Suppressant

    a. Class C compartments, found in all commercial passenger aircraft and some freighters

    b. Exclusively utilize Halon 1301 as an active suppressant agent

    c. Effective in suppressing the electrolyte portion of a lithium ion cell fire, as well as the packaging materials and adjacent combustibles

    d. NOT EFFECTIVE in preventing a gas explosion at the design concentrations (3-5%) of Halon 1301 systems. Hydrogen requires close to a 30% concentration of Halon 1301 to prevent an explosion. Tests of the mixture of gases vented from a lithium-ion cell required a 10% concentration of Halon 1301 to suppress explosion.

3. Ventilation control

    a. Class E compartments rely on decompression and oxygen starvation to control fires

    b. Tests have shown marginal success with lithium ion cells

    c. Tests have shown to not be effective with lithium metal cells

    d. Tests have shown that ventilation procedures designed to keep smoke from penetrating the flight deck may not be successful when the fire involves large numbers of lithium cells

    e. Limited ventilation is also important in class C compartments to maintain agent concentration and prevent smoke penetration into occupied areas.

4. Fire Hardened Cargo Containers

    a. Cargo operators and others are developing cargo containers that are fire resistant

    b. These containers have been shown to be effective against normal combustibles.

c. Tests with lithium ion cells have resulted in explosions due to gas build-up.

d. Tests with lithium metal cells have been largely unsuccessful.

e. These containers may prevent Halon 1301 from penetrating into the container when used in a Class C compartment.

f. These containers may extend the time from fire ignition to detection by containing the smoke within the container for a period of time.

5. Fire Containment Covers

a. These are covers designed to be installed over palletized cargo.

b. These covers have been shown to be effective against fires involving normal combustibles.

c. Tests have shown that these covers are not successful at containing a lithium metal cell fire.

d. Tests have shown that the covers have mixed success at containing lithium ion cell fires.

Shipment-based Mitigations:

1. Prohibitions

a. Theoretically 100% successful at preventing fires involving known shipments of lithium cells.

b. ICAO has prohibited shipping lithium metal cells and batteries on passenger aircraft.

c. ICCAIA proposes a prohibition on the transport of lithium ion cells and batteries on passenger aircraft, unless a performance-based standard is developed that adequately addresses the risks associated with lithium batteries.

2. Lithium Battery Transport Density

a. Reduce the number of cells shipped per compartment.

b. Tests have shown that only a few hundred cells can produce an explosive mixture of gases in a large shipping container, and the gas from as few as eight- 18650 cells can dislodge pressure relief panels in class C cargo compartments.

3. State of charge

a. Reduce the state of charge of shipped cells to a level that is unlikely to propagate.

b. Reduced state of charge can be very effective, although difficult to monitor in service. For some chemistries, a low state of charge reduces the severity and risk of thermal runaway within the shipment.

Packaging-Based Mitigations

1. Prevent propagation of thermal runaway

   a. Prior to the gas data recently developed, it was thought acceptable to simply contain the fire to within a package.

   b. This, however, can result in the buildup of explosive gases, which may be difficult if not impossible to contain.

   c. Preventing propagation solves the explosive gas problem as well as mitigating the other fire hazards presented by a cell in thermal runaway.

   d. This becomes critical as the number of cells shipped in the package increases.

2. Contain the cell fire to within the package

   a. For shipments of small numbers and sizes of cells this may be sufficient.

3. Prevent, contain, or limit the release of gases from the package.

4. Protect from external fire.

   a. For shipments exceeding a certain number of cells or large format cells, protecting the shipment from external fires and heat becomes important. The number of cells is dependent on the size of shipping container or compartment.

   b. May need two criteria dependent on the availability of a Class C compartment.

   c. Class C compartment suppressed with Halon 1301 will not have open flames. However, the temperatures can exceed that required to drive a cell into thermal runaway, resulting in release of electrolyte and flammable gases.

   d. Class E compartments, with no active fire suppression system, rely on decompression to suppress the fire. Temperatures of fires in Class E compartments can be much higher than Class C compartments, and the fire can intensify as the aircraft reduces altitude.

Battery Cell Level Based

1. Battery chemistry. Certain battery chemistries are have less violent failure modes than others.

2. Cell design. Cells can be designed to fail more benignly, and contain a greater amount of the byproducts of failure within the cell itself.

3. Cells can be equipped with safety features that limit propagation to adjacent cells.

4. Preventing propagation at the cell level may limit the explosive gas problem as well as reducing the other fire hazards presented by a cell in thermal runaway.

5. State of charge. For some chemistries, a low state of charge reduces the severity of thermal runaway.

D. DISCUSSION OF RECENT RESEARCH

Shipping Lithium-ion Cells and Batteries in a Passenger Aircraft Class C Cargo Compartment

Class C compartments are all fitted with smoke detection and fire suppression systems. The Halon 1301 fire suppression systems are designed to flood the compartment to a concentration of 5% and then maintain a minimum of 3% for the duration of the flight. Halon will generally extinguish open flames, though deep seated fires will continue to smolder. The temperature in a cargo compartment with a fully suppressed fire can exceed the temperature needed to drive lithium-ion cells into thermal runaway.

Halon 1301 will prevent the ignition of the electrolyte and gases released by a lithium-ion cell in thermal runaway. This can allow the buildup of flammable gases within the cargo compartment or container as thermal runaway propagates from cell to cell. The hazard from the buildup of gases is twofold. The added volume of gas increases the leakage rate of the Halon 1301, reducing its effectiveness and protection time. In addition, the containment of these gases can result in an explosion which cannot be suppressed by the 3-5% Halon 1301 concentration.

The volume of gas release is dependent on both the number and size of the cells in thermal runaway.

Fires involving lithium-ion cells in bulk transport fall into two scenarios. The first is a fire started by the failure of a single cell. The second is the shipment of cells is exposed to a fire from another source within the compartment.

Scenario 1: Single cell failure resulting in thermal runaway.
Fire is initiated by a single cell going into thermal runaway. The cell gets very hot, releases flammable gases and electrolyte. Current packaging allows the failed cell to heat adjacent cells,

driving them into thermal runaway. This process cascades throughout the shipment. The hot cells easily ignite current packaging materials, which in turn ignite the electrolyte and gases.

The cargo compartment smoke detectors alert the crew on the flight deck to the presence of smoke. The crew can elect to discharge the Halon 1301 fire suppression agent. The agent suppresses the open flames, though some smoldering continues between tightly packed boxes. The propagation of thermal runaway continues at a slightly slower pace. Cells continue to release flammable gases and electrolyte.

The concentration of Halon may be reduced as the gases produced by the cells increase the pressure as well as the normal leakage rate. The gases may pocket, or be trapped in a container resulting in an explosive mixture.

The volume of gases from a relatively small number of cells is sufficient to cause an explosion large enough to activate the pressure equalization features, including blow out panels and cargo liner fastenings. A pressure rise of only one psi or less is sufficient to activate these features. Once this occurs, the Halon suppressant agent will leak out, allowing the fire to grow out of control.

Scenario 2: Shipment of cells exposed to an external fire.
A fire occurs within a class C cargo compartment that also includes a bulk shipment of lithium-ion cells. The smoke detectors alert the flight deck crew, who in turn activate the Halon 1301 fire suppression system. The surface flames are suppressed. Generally, the fire will be suppressed into a smoldering condition.

Temperatures within the compartment, even when suppressed with Halon1301, can rise to a point where lithium-ion cells may be driven into thermal runaway (approximately 400 DegF). At this point the scenario is similar to the one above with one exception: Due to the compartment heating, many cells may go into thermal runaway in a short amount of time. The rest of the scenario plays out similar to scenario one above.

Vent gas considerations.
The amount and constituents of flammable vent gases released during thermal runaway are dependent on several factors: the size of the cells, the number of cells, cell chemistry, and state of charge. Recent testing has shown that the hazard from the vent gases can be very severe, causing the rupture of pressure relief panels in class C cargo compartments. The number of cells needed to produce an explosive mixture is very small. Limiting the volume of vent gas is extremely important.

E. PERFORMANCE-BASED STANDARD FOR AIR TRANSPORT OF LITHIUM BATTERIES

(1) GENERAL

The purpose of this standard is to ensure that during air transport, the shipment of lithium ion batteries will (1) withstand a thermal runaway event experienced by one or more cells or batteries, and (2) contain the effects of thermal runaway induced from the external effects of a suppressed cargo compartment fire. To demonstrate compliance with performance standards designed to address these concerns, testing methods would need to be developed to test propagation of thermal runaway, containment of hazards at the cell or battery level or within the package, and the level of flammable gases that may escape from the cell, battery or packaging. Options for compliance and testing could be met through a variety of means and could range from testing batteries, whether by themselves, in minimum packaging requirements, or in the condition as transported. Substantial changes to the design of a cell, battery, or packaging could warrant retesting under any method of compliance that is developed.

The following section presents methods for assessing performance at the battery/cell design level, the packaging level, and the ability at the cell, battery, or packaging level to withstand an external fire.

A. CELL/BATTERY LEVEL

(1) GENERAL. The purpose of this standard is to ensure that a lithium-ion cell or battery will withstand a thermal runaway event without propagation to adjacent cells or batteries irrespective of how the cells or batteries are packaged for transport. Cells and batteries must be tested for each cell or battery manufacturer, size, and model number. Substantial changes to the design of a cell or battery that would affect the hazard characteristics, even if the model number does not change, will require retesting.

(2) DEFINITIONS

a. Thermal runaway. An internal reaction within a cell or battery that generates enough heat to cause the cell or battery to fail in one or more of the following modes: vent smoke, jet incandescent particles, jet fire, or ignite/catch fire.

b. Thermal runaway propagation. The spread of thermal runaway within a package caused by the heat from the initial cell or battery in thermal runaway inducing thermal runaway in adjacent cells or batteries.

(3) REQUIREMENTS

a. The cell or battery must demonstrate that it can preclude thermal runaway from leading to thermal runaway propagation to adjacent cells or batteries.

b. The cell or battery must prevent any release of gases, heat or other products in quantities that would be hazardous to the airplane.

(4) NOTES

a. Experiments involving intentionally driving lithium ion cells into thermal runaway have shown that the state of charge directly impacts hazardous effects associated with thermal runaway. Specifically, the heat released and the volume of flammable gas released decreases with a reduced state of charge. A higher state of charge is also associated with a lower thermal runaway onset temperature.

b. Propagation may be limited by cell or battery design, chemistry, or state of charge.

c. In some cases, testing only for propagation will not address all known hazards. In some cases, batteries may not propagate but could still generate enough gas, that if not reduced or vented, could lead to an explosion. To address this issue, additional research is needed to develop a performance standard.

B. **PACKAGING**

(1) **GENERAL.** The purpose of this standard is to ensure that a lithium-ion cell or battery, in the condition as transported, will withstand a thermal runaway event without creating a condition that would be hazardous to the airplane. Packages would be tested as presented for shipment. Packages could be tested for each cell or battery manufacturer, size, and model number. Substantial design changes to the

battery or the package, including construction, material, or dimensional changes may require retesting. Packages tested in accordance with this standard could be used to ship up to the number of cells tested and may be used to ship fewer number of cells or batteries of the same type.

(2) DEFINITIONS

a. Package Integrity. The package, upon completion of the test, maintains structural rigidity, has not been breached and still retains all the contents and effects of a thermal runaway within

b. Thermal runaway. An internal reaction within a cell or battery that generates enough heat to cause the cell or battery to fail in one or more of the following modes: vent smoke, jet incandescent particles, jet fire, or ignite/catch fire.

c. Thermal runaway propagation. The spread of thermal runaway within a package caused by the heat from the initial cell or battery in thermal runaway inducing thermal runaway in adjacent cells or batteries.

(3) INTERNAL EVENT THERMAL RUNAWAY TEST.

a. A test would need to be developed to simulate the effect of a single cell experiencing a thermal runaway event.

(4) REQUIREMENTS

a. The package must demonstrate that it can contain the effects of a cell or cells in thermal runaway. Package integrity must be maintained.

b. No visible flames outside of the package. This includes ignition of the package materials as well as ignition of vented gases.

c. The outside surface of the package will not exceed 300 DegF (150 DegC)

d. Vent gas release is allowed, but with a hazardous limitation on quantity determined by potential pressure rise when ignited in a given compartment volume.

e. The pressure rise from ignited vent gases, when normalized for the cargo compartment free volume, cannot equal or exceed .5 psi above ambient.

C. EXTERNAL FIRE EVENT

(1) **GENERAL.** This test measures the ability of the cell, battery, or package of cells or batteries to withstand the effects of a fire from an outside source that may exceed the fire suppression capability of the aircraft and could lead to a catastrophic failure of the airframe. There are two environmental states in a class C compartment fire. The first state includes ignition, fire buildup, and detection. The second state is after the Halon fire suppressant is discharged. After discharge, open flames are suppressed, and temperatures are reduced. There is a package standard and test already in existence developed for the shipment of oxygen generators that is applicable, with some minor changes, to the shipment of lithium batteries. The standard includes a flame test simulating the first condition and an oven test for the second suppressed condition.

(2) **REQUIREMENTS**

a. Unless the aircraft systems and cargo loading procedures, or cell design provide for equivalent means of addressing an external fire, the cell, battery or package must be able to withstand the fire conditions in a cargo compartment prior to the release of the suppression agent. The cell, battery, or package must maintain integrity and prevent flame penetration by a 1700 DegF flame for five minutes. The existing standard for cargo liners is applicable and can be found in Part III of Appendix F, 14 CFR Part 25, paragraphs (a)3 and (f)5, "Test method to Determine Flame Penetration Resistance of Cargo Compartment Liners."

b. The cell, battery, or package must maintain integrity and prevent or contain the effects of thermal runaway when exposed to a temperature of 400 DegF (mean temperature in a suppressed cargo compartment fire) for a period of 360 minutes (max ETOPS/LROPS time).

c. Vent gas release is allowed, but with a hazardous limitation on quantity determined by potential pressure rise when ignited in a given compartment volume.

(3) **NOTES**

a. Package design can range from full containment of all cells in thermal runaway, to designs that limit propagation.

b. Propagation may be additionally limited by cell design, chemistry, or state of charge.

c. Protection from external fire may be considered by methods other than packaging, including, but not limited to, fire resistant containers and fire containment covers.

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