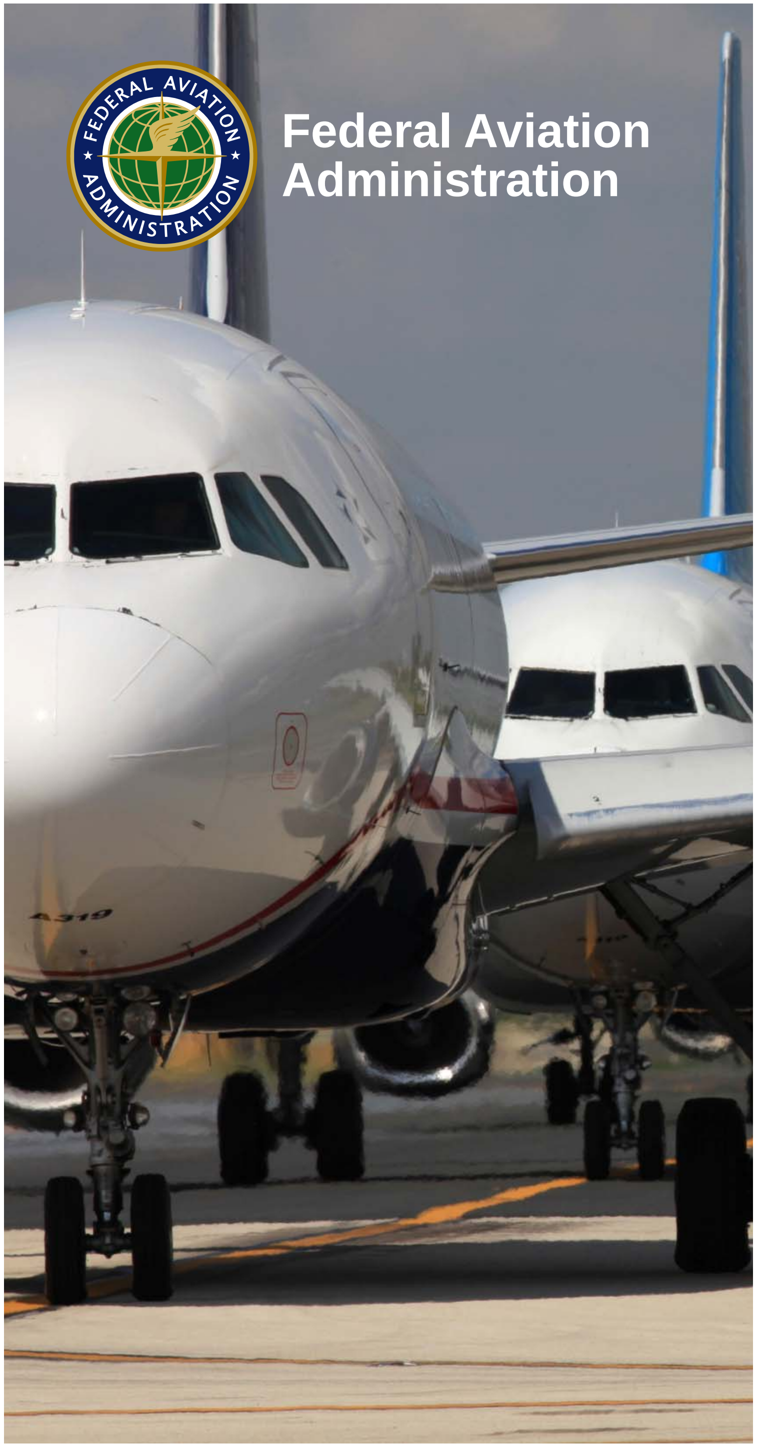
# Full Scale Battery Tests

- **Mixed Cells**
- **Lithium-ion**
- **Lithium metal**

Presented to: ICAO Dangerous Goods Panel

By: Harry Webster, FAA Fire Safety Br.

Date: October 31, 2013



# Summary of Findings From Previous Tests – Lithium-ion

- Capable of thermal runaway, through cell defect, cell damage, heat, rapid discharge, overcharging
- Thermal runaway results in high case temperatures, exceeding 1100 DegF
- Releases flammable electrolyte
- Generates sufficient heat to cause adjacent cells to go into thermal runaway
- Will propagate thermal runaway throughout shipping box, and box to box

# Summary of Findings From Previous Tests – Lithium-ion

- Can experience catastrophic disassembly
- Generally do not self ignite, but high case temperatures easily ignite current packing materials, which ignite the electrolyte.
- Halon 1301 can suppress the electrolyte fire.
- In the presence of Halon, or no ignition source, unburned hydrocarbons from released electrolyte accumulate, increasing the risk of flash fire or explosion.

# Summary of Findings From Previous Tests – Lithium Metal

- Capable of thermal runaway, through cell defect, cell damage, heat, rapid discharge
- Thermal runaway results in high case temperatures, exceeding 1400 DegF
- Releases flammable electrolyte and molten burning lithium
- Generates sufficient heat to cause adjacent cells to go into thermal runaway
- Will propagate thermal runaway throughout shipping box, and box to box, very rapid fire buildup.

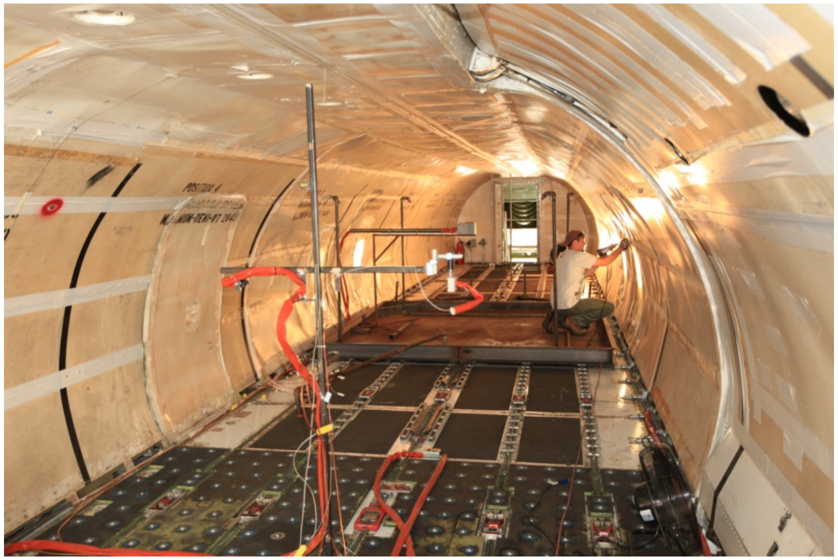
# Summary of Findings From Previous Tests – Lithium Metal

– Can experience catastrophic disassembly
– Self igniting, will rapidly ignite packaging
– Generates pressure.
– Halon 1301 can suppress the electrolyte fire, but not the lithium fire. Has no effect on propagation of thermal runaway.
– In the presence of Halon, unburned hydrocarbons from released electrolyte accumulate, increasing the risk of flash fire or explosion.

# Full Scale Fire Tests

# Objective

- **To document the characteristics of large battery fires in a realistic aircraft environment.**
- **No Suppression- Class E**
- **With Suppression- Class C**



# Class E Cargo Compartment

- **Upper deck compartment on most freighters**
  - Has Fire detection system
  - Means to shut off ventilation flow to the compartment
  - Means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment

# Class C Cargo Compartment

- **Passenger aircraft under floor cargo compartments**
  - smoke detector or fire detector system
  - built-in fire extinguishing or suppression system controllable from the cockpit
  - means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers
  - means to control ventilation and drafts within the compartment

# Full Scale Fire Test Plan

- **Baseline**
- **Class E Cargo**
  - Lithium-ion 5000 18650 cells
  - Lithium metal 4800 SF123A Cells
  - 5000 mixed alkaline, NiCad, NiMH

# Full Scale Fire Test Plan

- **Class C Cargo w/ Halon 1301 Suppression**
  - Lithium-ion 5000 18650 cells
  - Lithium-metal 4800 SF123A cells
  - 5000 mixed alkaline, NiCad, NiMH

# Instrumented 727 Test Article

# Aircraft Ventilation

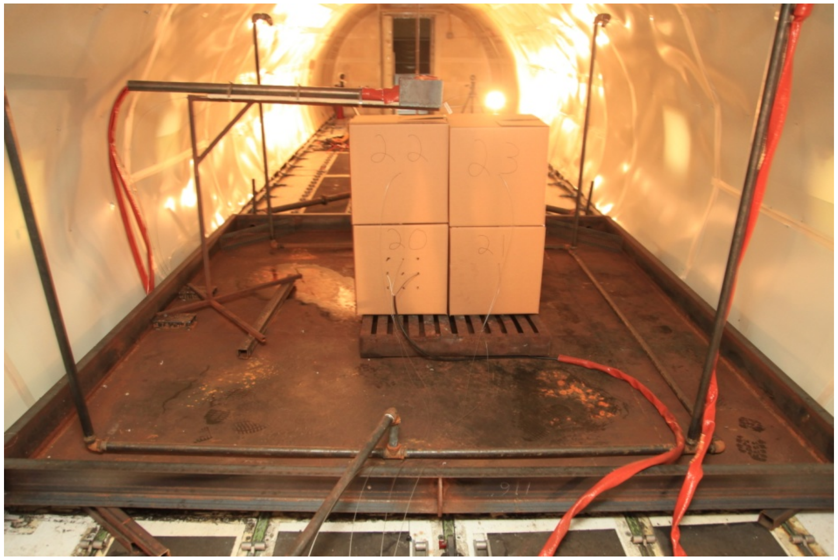
- **Airflow patterns within the aircraft can have significant impact on the behavior of the battery fire and smoke penetration.**
- **The aircraft air packs are configured differently depending on the location of the fire.**
- **Two configurations were developed with input from the Boeing Company, one for the maid deck class E fire and one for the forward class C compartment**

# Conducted Air Exchange Tests

# Air Exchange Rate Results

- **Pressurized configuration**
  - Main deck cabin: 5.75 minutes per air change
  - Flight deck: 1.68 minutes per air change
- **Unpressurized configuration**
  - Main deck cabin:  47.72 minutes per air change
  - Flight deck: 1.71 minutes per air change

# Conducted Baseline Test



# Preliminary Fire Assessment

# Class E Tests

- Aircraft in emergency mode
- High ventilation to flight deck
- No ventilation to main deck
- Fire control is by oxygen starvation

# Results Mixed Cell Test

- Test terminated at 102 minutes with water
- Approximately 700 cells were damaged
- Low ceiling temp: 119 DegF@ 40 min
- Moderate battery fire temp: 975 DegF@ 44 min.
- Gradual smoke obscuration in the compartment
- No smoke on the flight deck

# Results Lithium-ion

- **Test terminated at 57 minutes with water**
- **More than half of the cells consumed**
- **High ceiling temp: 1490 DegF@ 49 min**
- **High battery fire temp: 1300 DegF@ 55 min.**
- **Oxygen depletion slowed fire progress**
- **Some light smoke on the flight deck**
- **Significant damage to cargo liner**

# Results Lithium Metal

- Test terminated at 16 minutes with water
- Approximately half of the cells were consumed
- Very high ceiling temp: 1700 DegF@ 16 min
- Very high battery fire temp: 2250 DegF@ 12 min.
- Oxygen starvation had little or no effect on fire intensity
- Smoke on flight deck in less than 4 minutes from first observable fire, obscured in less than 6 minutes.
- Significant cargo liner damage

# Class E Lithium Metal Video

# Class C Tests


- Ventilation configured for fire in lower cargo compartment
- Halon discharged one minute after initial smoke observation

# Results Mixed Cells

- Halon suppressed the surface fire
- Minimal cell damage
- Low ceiling temperature
- Fire continued to smolder between boxes.
- Smoke contained in the compartment
- No damage to cargo liner

# Results Lithium-ion

- **Halon suppressed surface fire and the electrolyte fire**
- **Thermal runaway propagated between boxes**
- **Approximately 1200 cells were consumed**
- **Low to moderate ceiling temperatures**
- **Smoke contained within the compartment**
- **Little damage to cargo liner**

# Results Lithium Metal

- Halon suppressed the cardboard and electrolyte fire
- Thermal runaway propagated rapidly between boxes, despite Halon and extremely low oxygen levels
- 3450 cells consumed
- Smoke penetrated the mix bay and main deck
- Rapid reduction in Halon concentration
- Test was terminated due to high ceiling temperatures
- Post test event

# Lithium Metal Class C Video

# Cargo Compartment Fire Containment Summary

| Fire Load | Class E | Class C |
| --- | --- | --- |
| Mixed Cells | Contained | Contained |
| Lithium-ion | Marginal | Contained |
| Lithium metal | Did not Contain | Did not Contain |

# Post Test Explosion

- The lithium metal battery fire generated a large amount of unburned hydrocarbons in the cargo compartment
- The pressure generated by the burning cells forced the hydrocarbons into the mix bay and main deck compartments

# Post Test Explosion

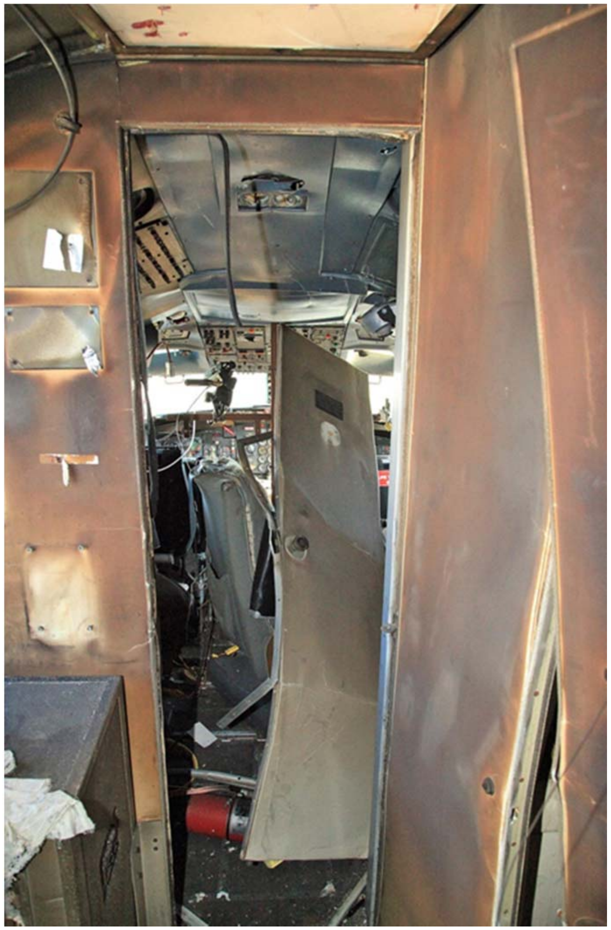
- Post test, the oxygen levels in the cargo compartment increased, while the Halon neared zero.
- A single cell in thermal runaway caused a flash fire in the cargo compartment.
- The flash fire forced open the blow out panel into the mix bay.
- This ignited the fumes in the mix bay causing an explosion

# Explosion Video- Exterior Full

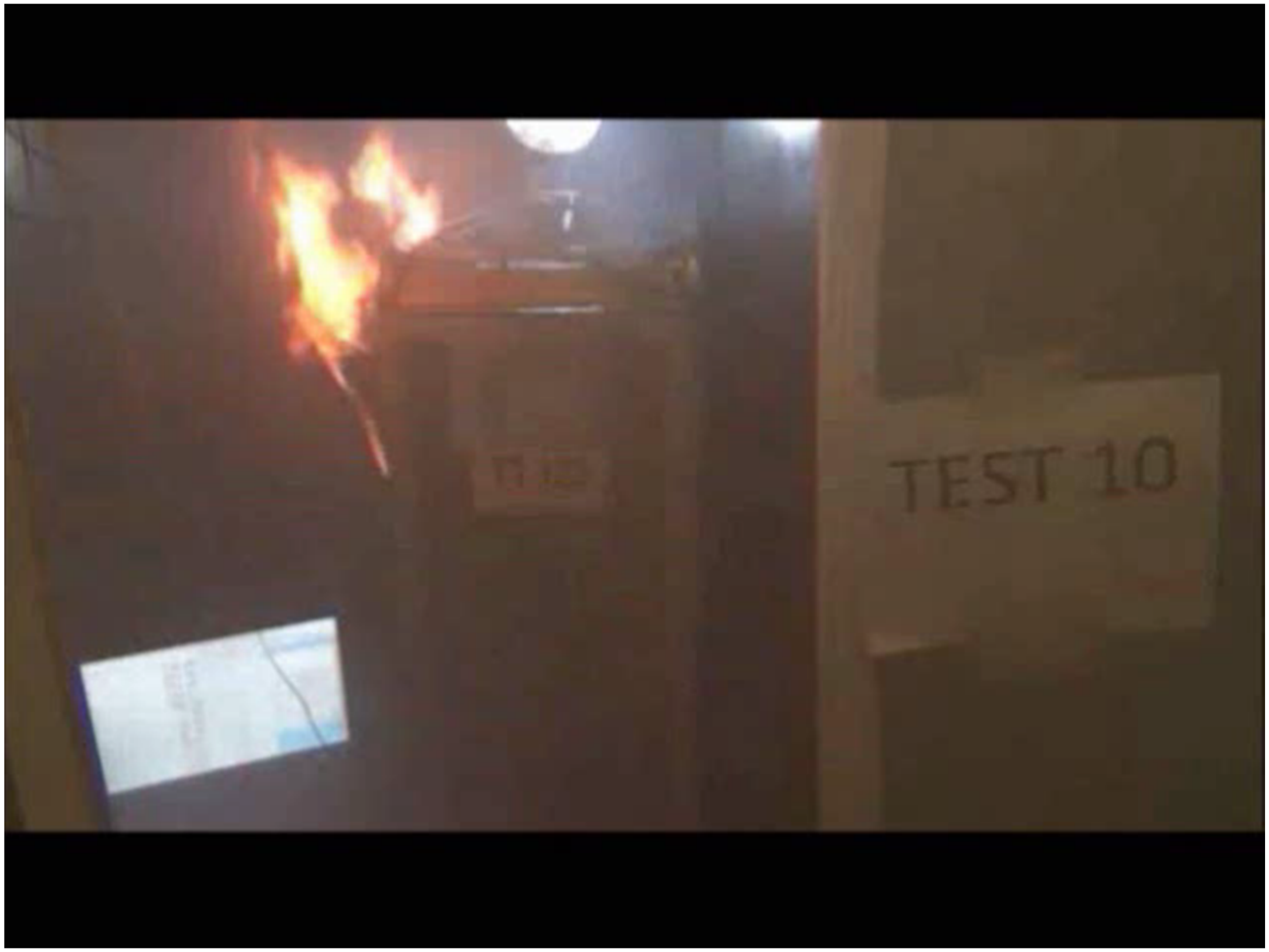
# Post Test Explosion

- The explosion blew the aft cargo access panel into the cargo compartment, as well as the forward cargo bulkhead into the EE bay.
- The floor boards in the main cabin above the mix bay were blown upward.
- The door to the flight deck was blown off the hinges and into the flight deck

# Post Test Explosion



# Explosion from Tablet Battery



# Questions?

## Contact Information

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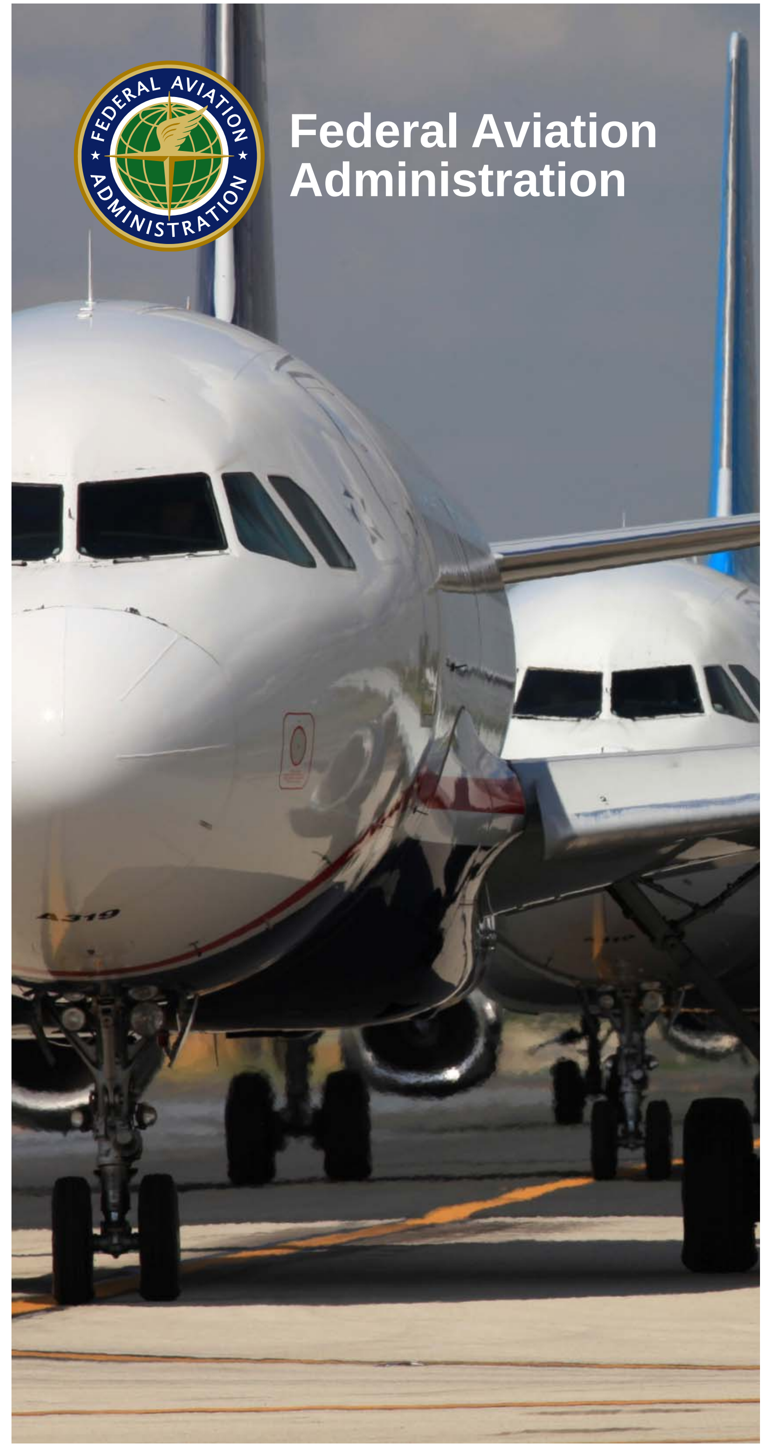
# Aircraft Installed Lithium Battery Hazard Analysis

- D Cell Tests

Presented to: ICAO Dangerous Goods Panel

By: Harry Webster, FAA Fire Safety Br.

Date: October 31, 2013



# Aircraft Installed Lithium Battery Hazard Analysis

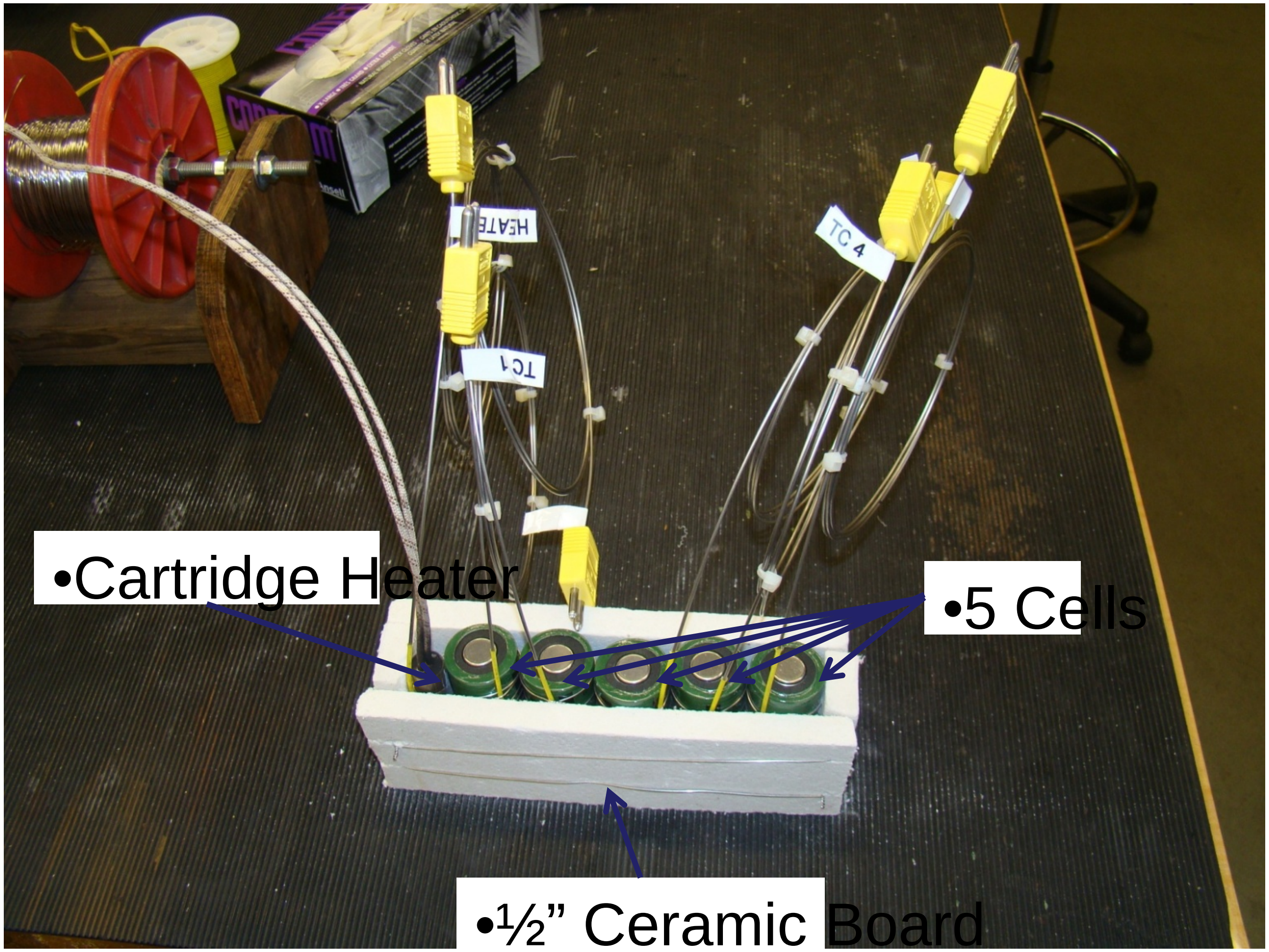
- **An effort is underway to characterize the hazard of all lithium metal and lithium-ion cells currently or proposed to be installed as part of the aircraft system.**
- **A large number of cell sizes and chemistries have been procured.**
- **A test protocol has been developed to measure:**
  - Electrolyte flammability, pressure, cell case temperature, ease of extinguishment

# Aircraft Installed Lithium Battery Hazard Analysis

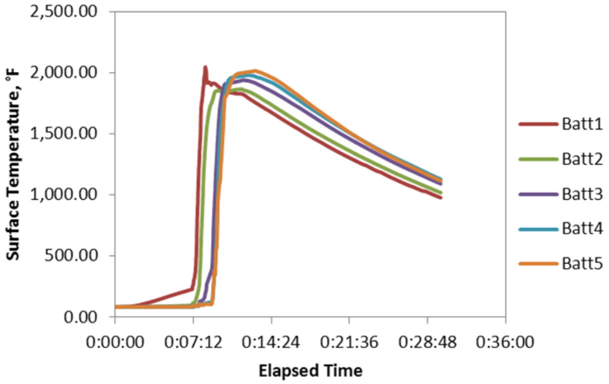
| | Li-Ion | | | | Lithium Primary | | | | Lithium Polymer | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Battery size | $LiCoO_2$ | $LiFePO_4$ | LiMnNi | LiNiMnCO | $LiMnO_2$ | $LiFeSO_2$ | $LiSO_2$ | $LiSOCl_2$ | $LiFePO_4$ | LiMnNi | LiNiMnCo | $LiCoO_2$ (std rate discharge) | $LiCoO_2$ (high Rate discharge) |
| 10440 (AAA) | | | | | | | | | | | | | |
| 14500 (AA) | | | | | | | | | | | | | |
| 15270 (CR2) | | | | | | | | | | | | | |
| 16340 (CR123A) | | | | | | | | | | | | | |
| 18650 | | | | | | | | | | | | | |
| 25500 (C) | | | | | | | | | | | | | |
| 32600 (D) | | | | | | | | | | | | | |
| 9V | | | | | | | | | | | | | |
| 2450 (button) | | | | | | | | | | | | | |
| 2025 (button) | | | | | | | | | | | | | |
| 10 Ah | | | | | | | | | | | | | |
| 4.5 Ah | | | | | | | | | | | | | |
| 0.8 Ah | | | | | | | | | | | | | |

# Lithium Manganese Dioxide Cell

# Propagation Test, Li/MnO2



# Propagation Test, Li/MnO2



# 5 D-Cell Li/MnO2 in Aluminum Enclosure

# Lithium Thionyl Chloride

- **Available in many sizes**
- **Extremely long shelf life**
- **Non-flammable electrolyte**

# Lithium Thionyl Chloride D Cell

# Lithium Thionyl Chloride LD3 Test

# Questions?

**Contact Information**

**Harry Webster**

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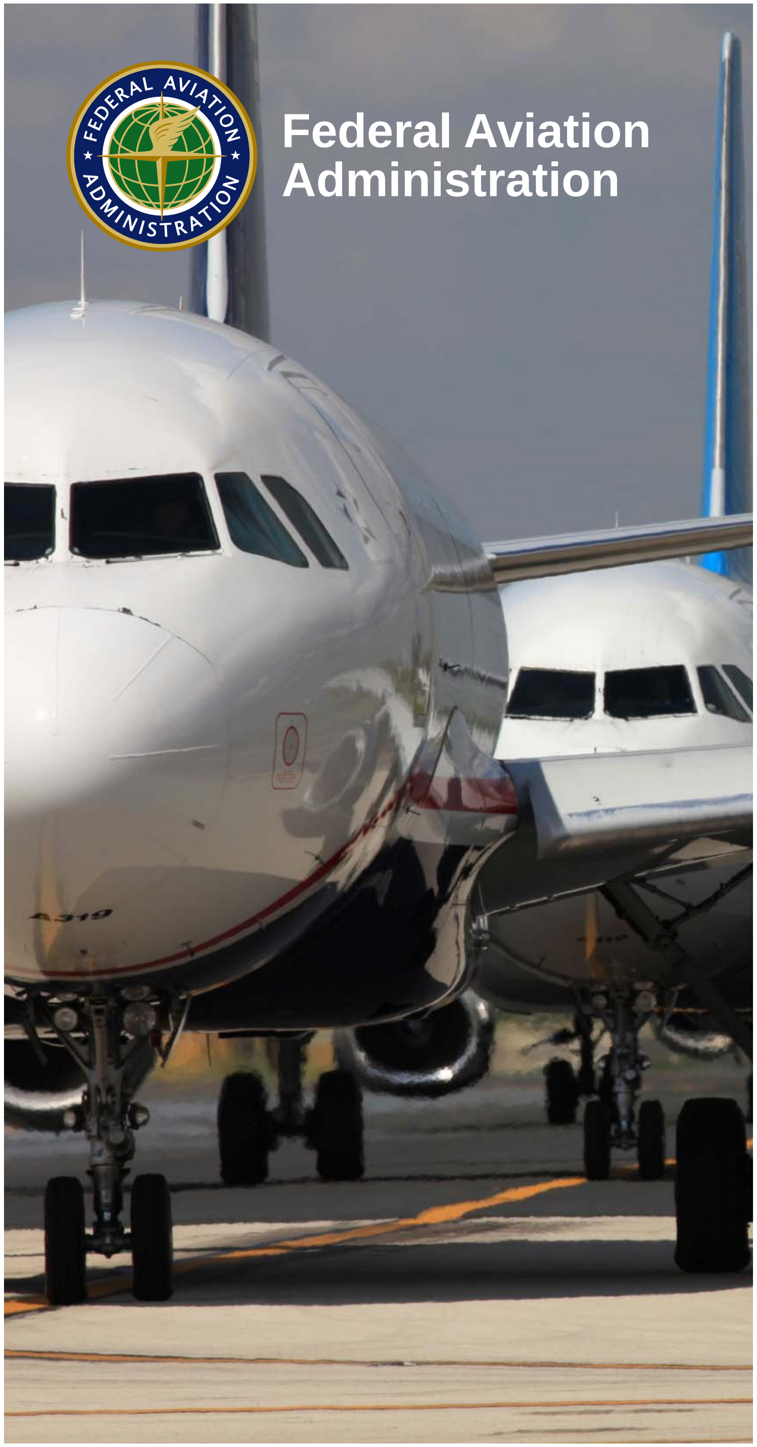
# Large Format Cells

## Flammability

## Effect of state of charge



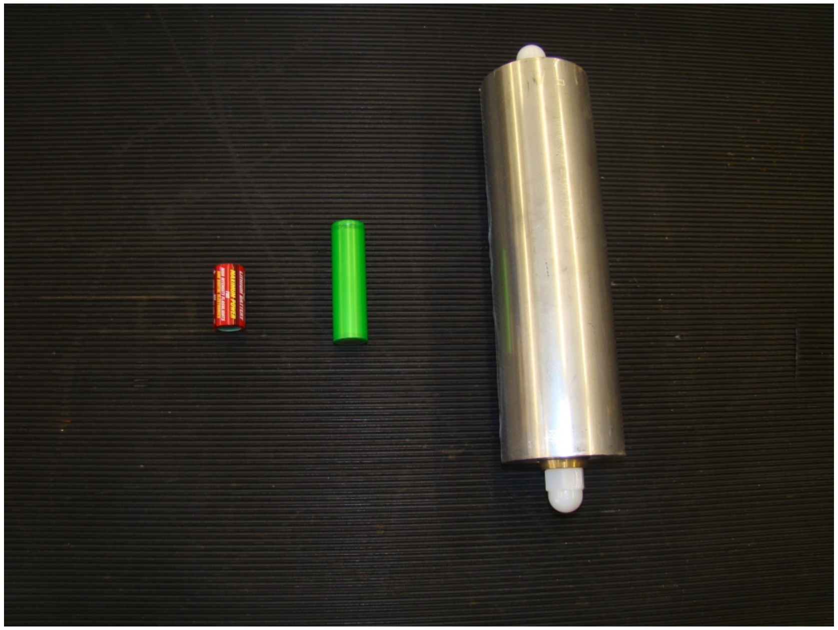

Presented to: ICAO Dangerous Goods

By: Harry Webster, FAA Fire Safety Br.

Date: October 31, 2013

# Flammability

- Cells tested: 55Ah Lithium Cobalt Oxide
- Similar behavior to 18650 cells, only more
- Thermal runaway results in release of large volume of flammable electrolyte
- Generally requires external ignition source.
- Catastrophic Disassembly



# 55 Ah, 100% SOC, Alcohol Fire

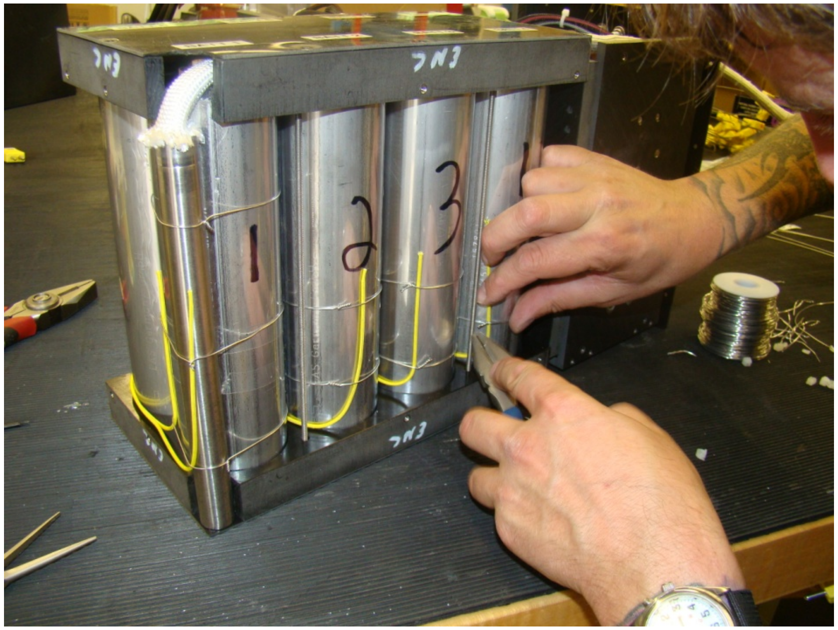
# 55 Ah, 20% SOC, Alcohol Fire

# 55 Ah, 100% SOC, Heater

# 55 Ah, 20% SOC, Heater

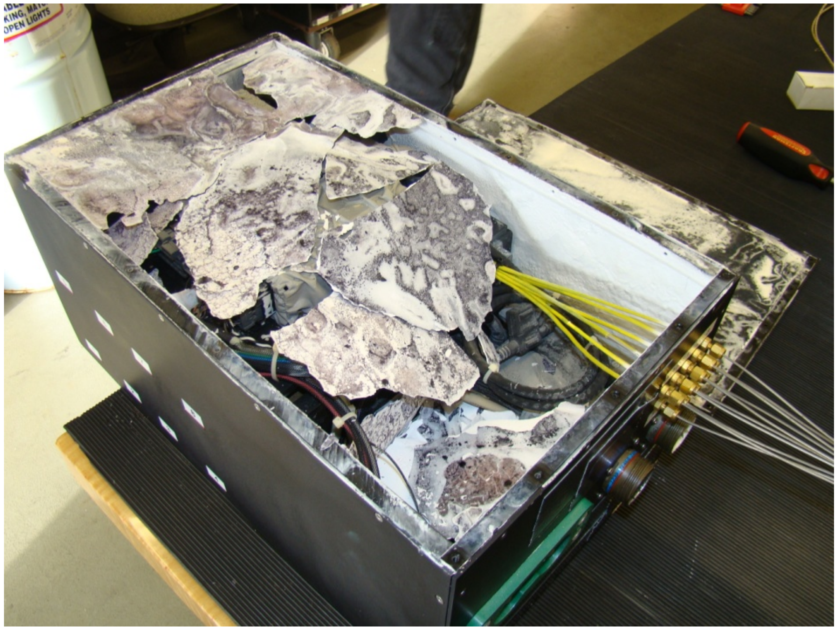
# 1.3 Kw Battery Test 25% SOC

- **Installed 600 watt cartridge heater to lower rear cell.**
- **Instrumented with thermocouples**
- **Set State of Charge to 25%**



# 1.3 Kw Battery Test 25% SOC

- **Heater was energized**
- **Lower rear cell with heater attached went into thermal runaway, did not ignite**
- **Smoke poured from front panel connections**
- **Heater was left on eventually driving top rear cell into thermal runaway, no ignition**
- **Heater shut off, no further propagation**



# 1.3 Kw Battery Test Results

- **Post test examination revealed the entire inside of the box coated with a rigid thick white material**
- **All cells showed signs of thermal exposure.**
- **Some liquid leakage from rear cells**

# 1.3 Kw Battery Test Results

- **Plastic cell retainers all charred**
- **Future tests at higher states of charge are planned**
- **Packaging**

# Questions?

**Contact Information**

**Harry Webster**

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# Fire Suppression in a Class E Cargo Compartment

Federal Aviation Administration

Presented to: ICAO Meeting

By: Dhaval Dadia, FAA Technical Center Atlantic City, NJ

Date: October 30-31, 2013

# Accident History


# Accident History


UPS Boeing 747

Sept. 3, 2010

Dubai, UAE

# Accident History


Asiana Airlines Boeing 747

July 28, 2011

South Korea

# Class E Fire Protection Testing

- Identifying ways to suppress fires in class-E cargo compartments
  - Oxygen Starvation
  - Secondary Fire Suppression Agent within the Container
  - Fire Containment Covers
  - Water Mist System

- Currently used ULDs can not contain deep seated fires even with the discharge of an aerosol based fire suppression agent.
- The agent escapes from the door which allows for fresh air to enter the container.

# Oxygen Starvation

- Develop materials that can withstand fires within the container.
- Reduce the air exchange rate to
  - Reduce oxygen
  - Retain fire suppression agent
- Reduce weight

# Secondary Fire Suppression Agent

- Detects and activates from fires within the container.
- Extinguishes or suppresses the fire within the container.
- Maintains a low oxygen concentration environment.

# Fire Containment Covers

- Testing will include the testing of both metal and ion lithium batteries

# Zone Based Water Mist System