ICAO UNITING AVIATION

Federal Aviation Administration

Hazardous Material Safety Program

Lithium Battery History and Testing

March 2015

Discussion Topics

- Challenges for mitigating lithium battery risks as technology advances

- What do we know from research related to air transportation

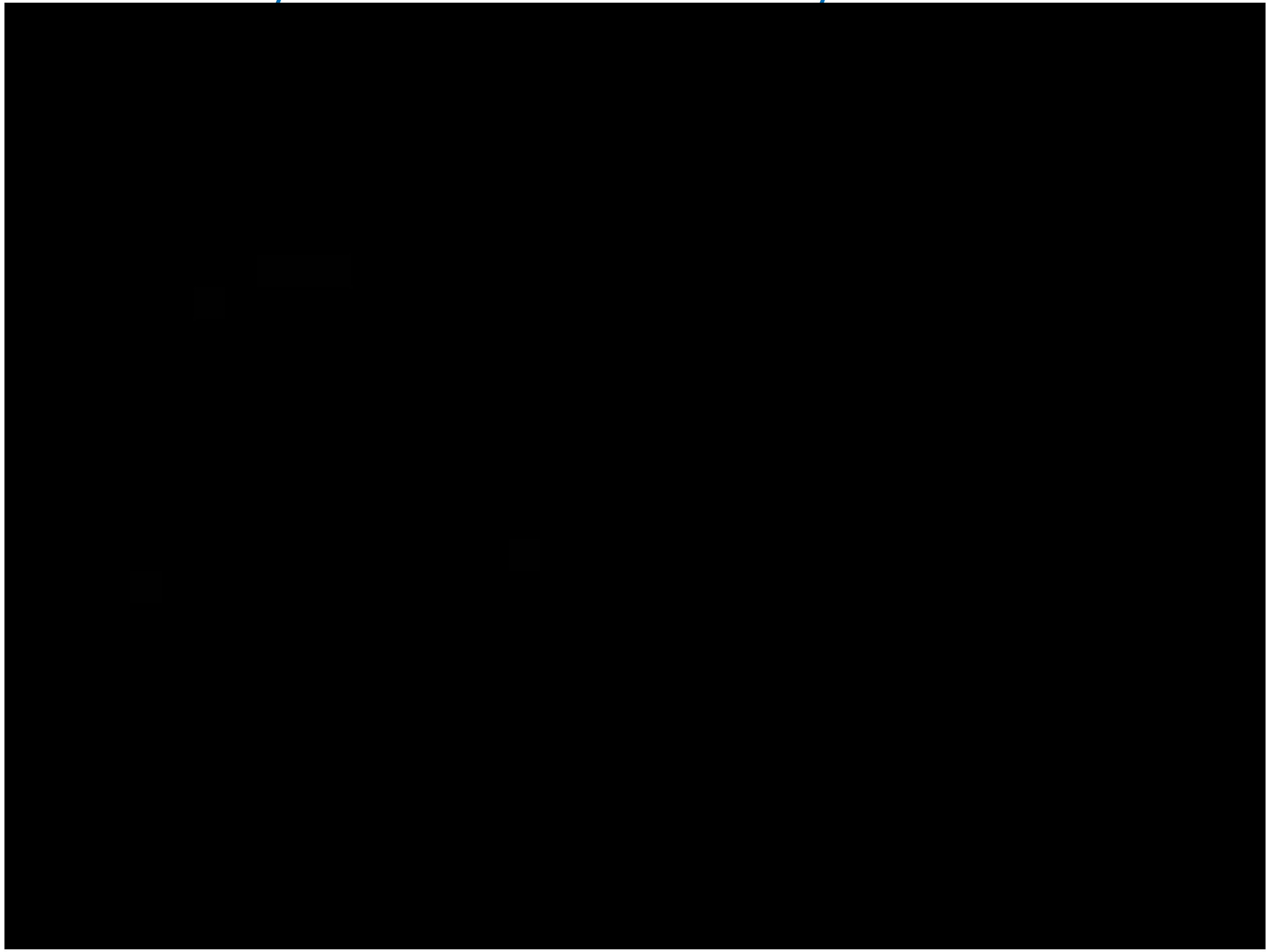
- How did we get here

LAX Incident

- 1999 LAX incident
  - Two pallets of small lithium batteries (120,000 cells) burst into fire after being unloaded from a passenger aircraft in Los Angeles. Fire reignites after initial suppression. The batteries were the small types excepted from the regulations by DOT and ICAO so there was no indication that the packages contained potentially hazardous materials.
  - The NTSB investigates, concludes that lithium batteries may present an “unacceptable risk to aircraft and occupants” and makes recommendations to remove lithium batteries from passenger aircraft pending further study and to eliminate the exceptions for lithium batteries so that they are easily identifiable and handled with the caution other hazardous materials receive.

Lithium Batteries

Relative Flammability of Various Common Battery Chemistries



FAA Technical Center

- The initial work was directed towards testing the effectiveness of Halon on a lithium battery fire.
- We are still continuing to evaluate aircraft safety systems to include fires related to lithium batteries.
- Lithium batteries are transported in significant quantities on aircraft everyday.

Methods of inducing Thermal Runaway

- Cells are forced into thermal runaway for two purposes
  1. To evaluate the cell hazards, including:
     - Case temperature
     - Vent gases
     - Flammability
     - Propagation
  2. To evaluate the effect of the thermal runaway on the local environment including:
     - Packaging
     - Adjacent cargo
     - Cargo compartment structure
     - Suppression system effectiveness

Drum Test

Develop Practical and Cost Effective Fire Resistant Packaging

FAA Tech Center Work

- http://www.fire.tc.faa.gov/systems/Lithium-Batteries
- All of the lithium battery work is now in one location.

Fatal Freighter Fire Accidents

UPS 747-400
Dubai, United Arab Emirates
September 3, 2010

Asiana 747-400
Korea
July 28, 2011

NTSB Most Wanted List

Improve Fire Safety in Transportation

What is the issue?

Fire safety combines many elements, such as design, materials, and fire detection and suppression technologies. NTSB accident investigations have revealed deficiencies in the implementation of fire safety in many modes of transportation.

In 2005, the NTSB found deficiencies in design, materials, and fire detection capabilities that led to a tragic highway accident near Wilmer, Texas. This motorcoach fire was caused by ignition of a tire and resulted in the death of 23 passengers.

In 1996, near Juneau, Alaska, a fire in the main laundry area of a passenger ship killed 5 and injured 56. In 2000, a fire in the unmanned engine room of a commuter ferry in the Hudson River caused $1.2 million in damages, but all people on board were rescued. In Boston Harbor in 2006, another fire in the unmanned engine room of a commuter ferry resulted in no serious injuries or fatalities, but damages were estimated at $800,000. These accidents were exacerbated by inadequate fire detection.

Three cargo fire accidents in the past 6 years have resulted in the deaths of two flight crews and the total loss of three aircraft. Two of those accidents involved Boeing 747-400 freighters. The NTSB involvement in these accident investigations revealed deficiencies in the fire safety strategy employed both for fire detection and fire suppression. The construction material for cargo containers was also identified as being directly related to the fire protection of cargo compartments.

UPS DC-8, PHL, 2/8/2006

Study on Risk of Transporting Batteries in Freighter Aircraft


DOT/FAA/AR-11/18

Air Traffic Organization
NextGen & Operations Planning
Office of Research and
Technology Development
Washington, DC 20591

Freighter Airplane Cargo Fire Risk Model

September 2011

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

U.S. Department of Transportation
Federal Aviation Administration

Transport Canada　Transports Canada

Civil Aviation Authority

Developed Model to Compare Cost/Benefit of Various Mitigation Methods


DOT/FAA/AR-12/3

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Freighter Airplane Cargo Fire Risk and Benefit Cost Model

March 2012

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U.S. Department of Transportation
Federal Aviation Administration

Transport Canada Transports Canada

Future Risk of Fire Accidents

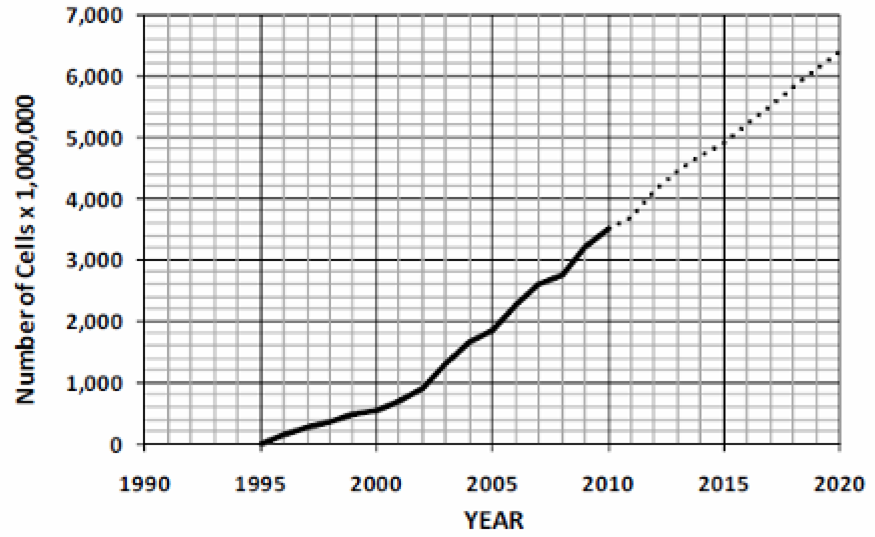


Figure 3 Estimation of the Annual Number of Lithium Ion batteries produced worldwide

6 ACCIDENTS OVER NEXT 10 YEARS

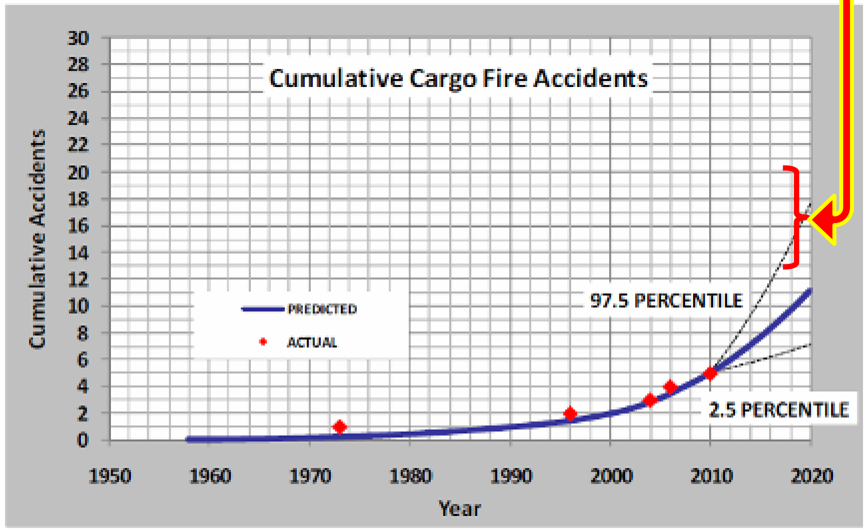


Figure 6 Predicted Number of Freighter Airplane Cargo Fire Accidents through to 2020

Administration

Full Scale Fire Tests

Class E Cargo Compartment

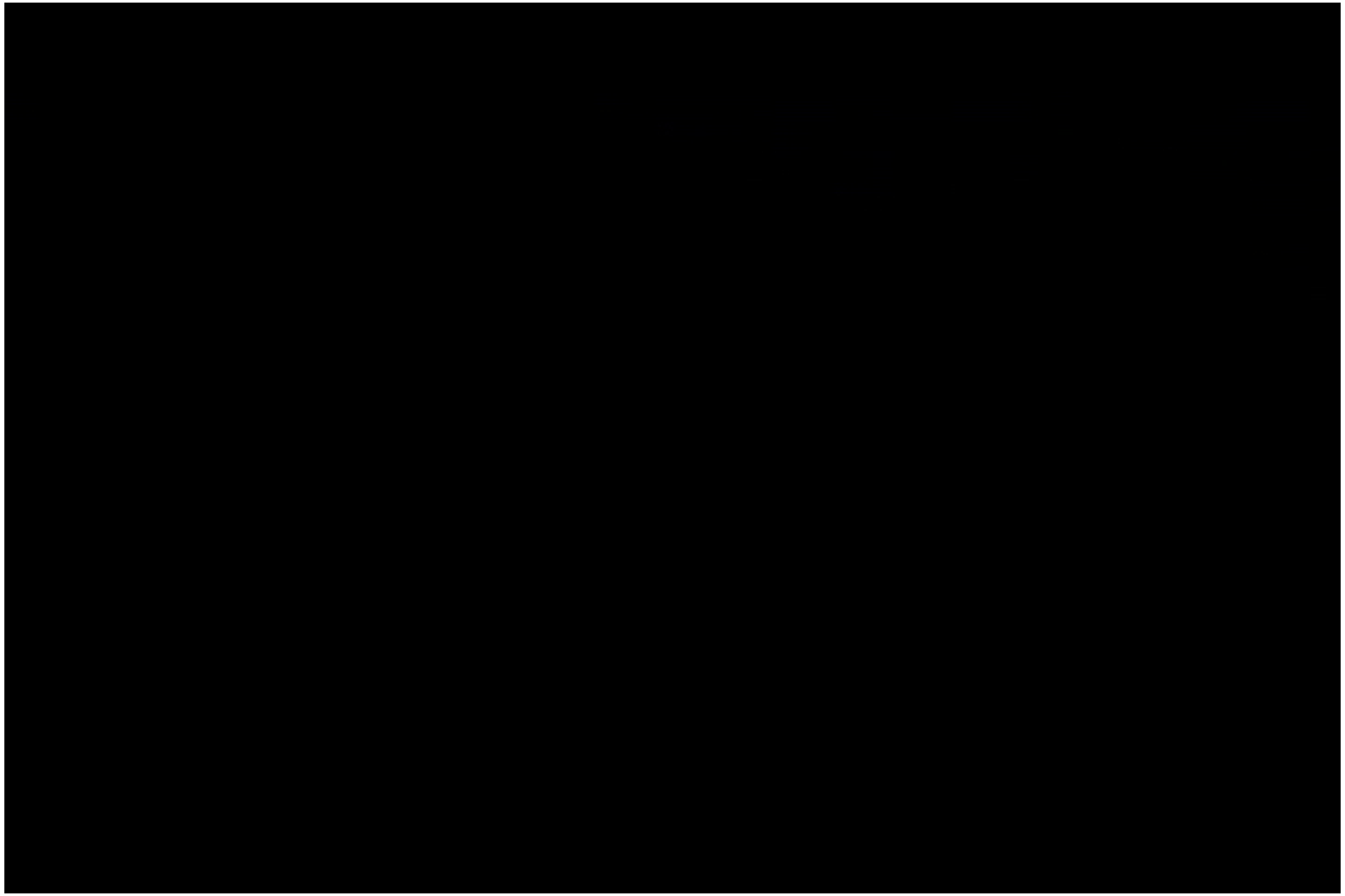
- Upper deck compartment on most freighters
  - Has Fire detection system
  - Means to shut off ventilation flow to the compartment
  - Means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment

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

Instrumented 727 Test Article

Conducted Air Exchange Tests



Conducted Baseline Test

Results Lithium Metal Class E

- 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

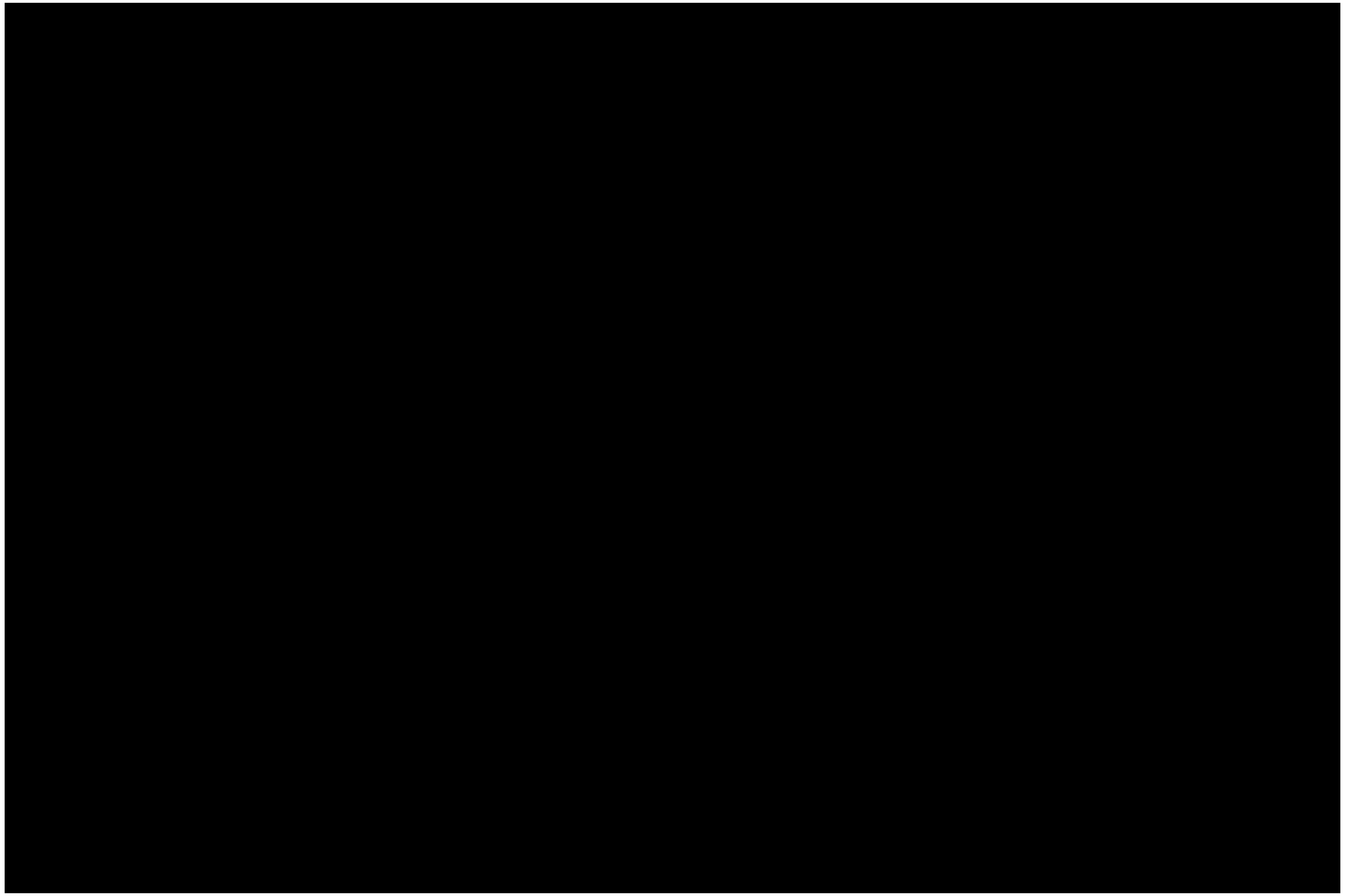
from first observable fire, obscured in less than 6 minutes.

- Significant cargo liner damage

Results Lithium-ion Class E

- 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

Class E Lithium Metal Video



Class C Tests

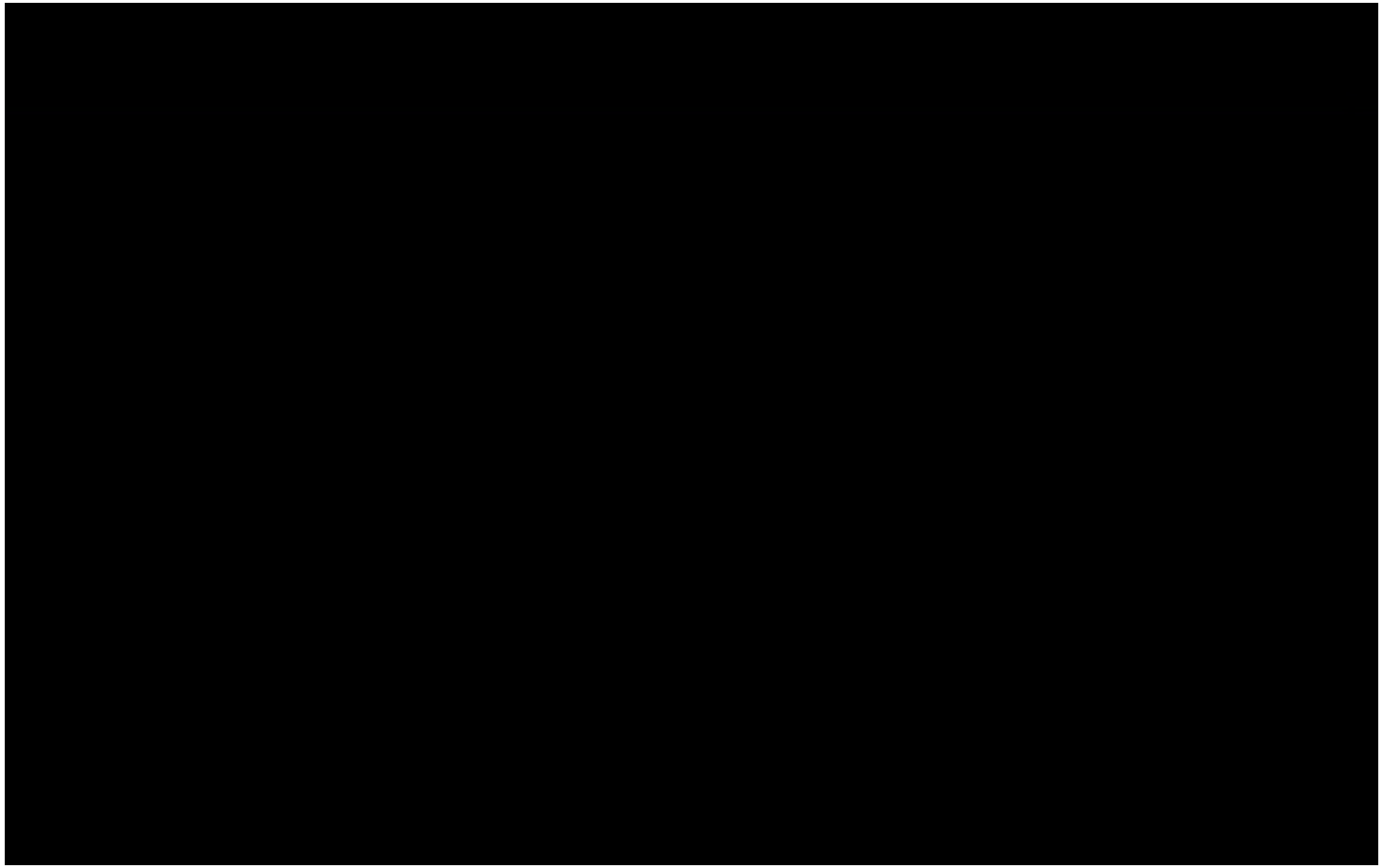
- Ventilation configured for fire in lower cargo compartment
- Halon discharged one minute after initial smoke observation

Results Lithium-ion Class C

- 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

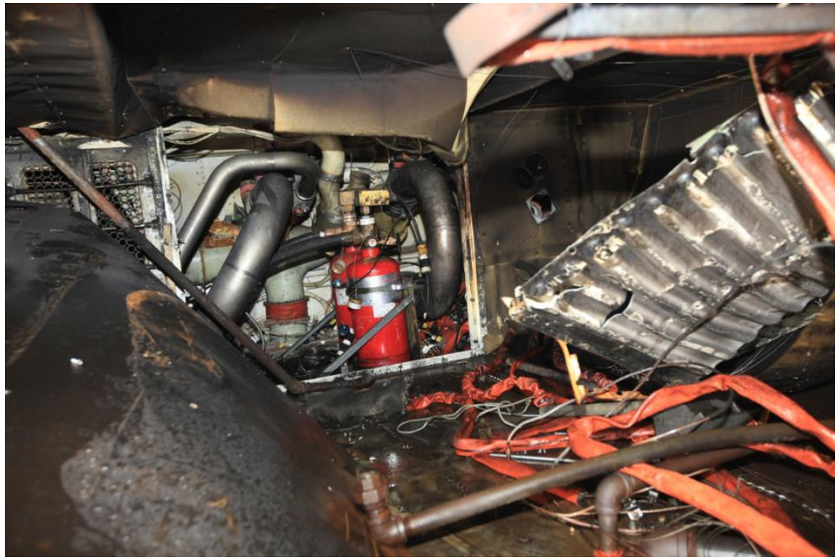
Results Lithium Metal Class C

- 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



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



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

Administration

ULDs

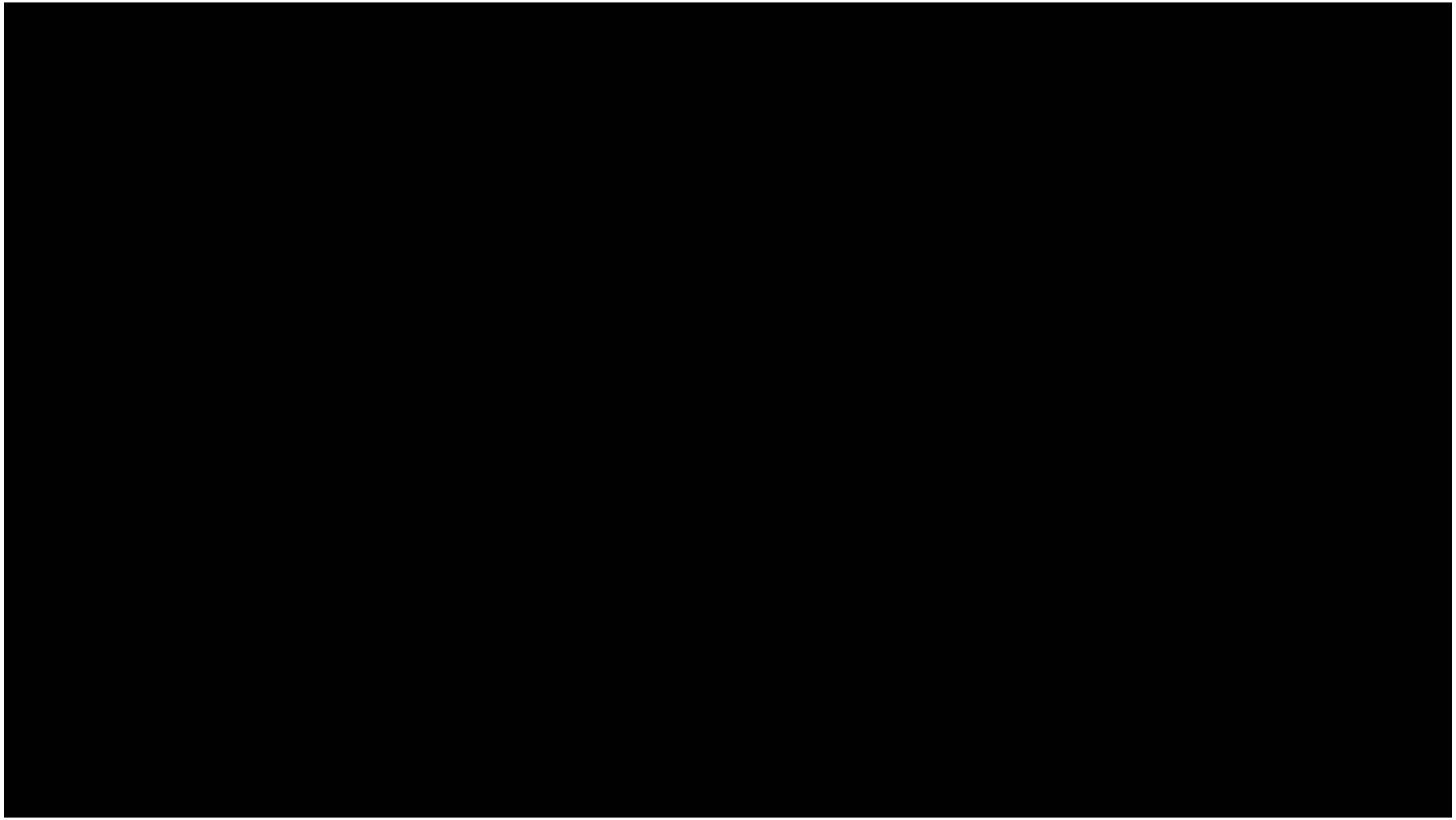
- Currently used ULDs can not contain deep seated fires even with the discharge of an aerosol based fire suppression agent.
- The agent escapes from the door which allows for fresh air to enter the container.

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.



Cell types

- Cells come in various sizes and chemistries
- Cell hazard varies by chemistry, size and cell construction and manufacturer

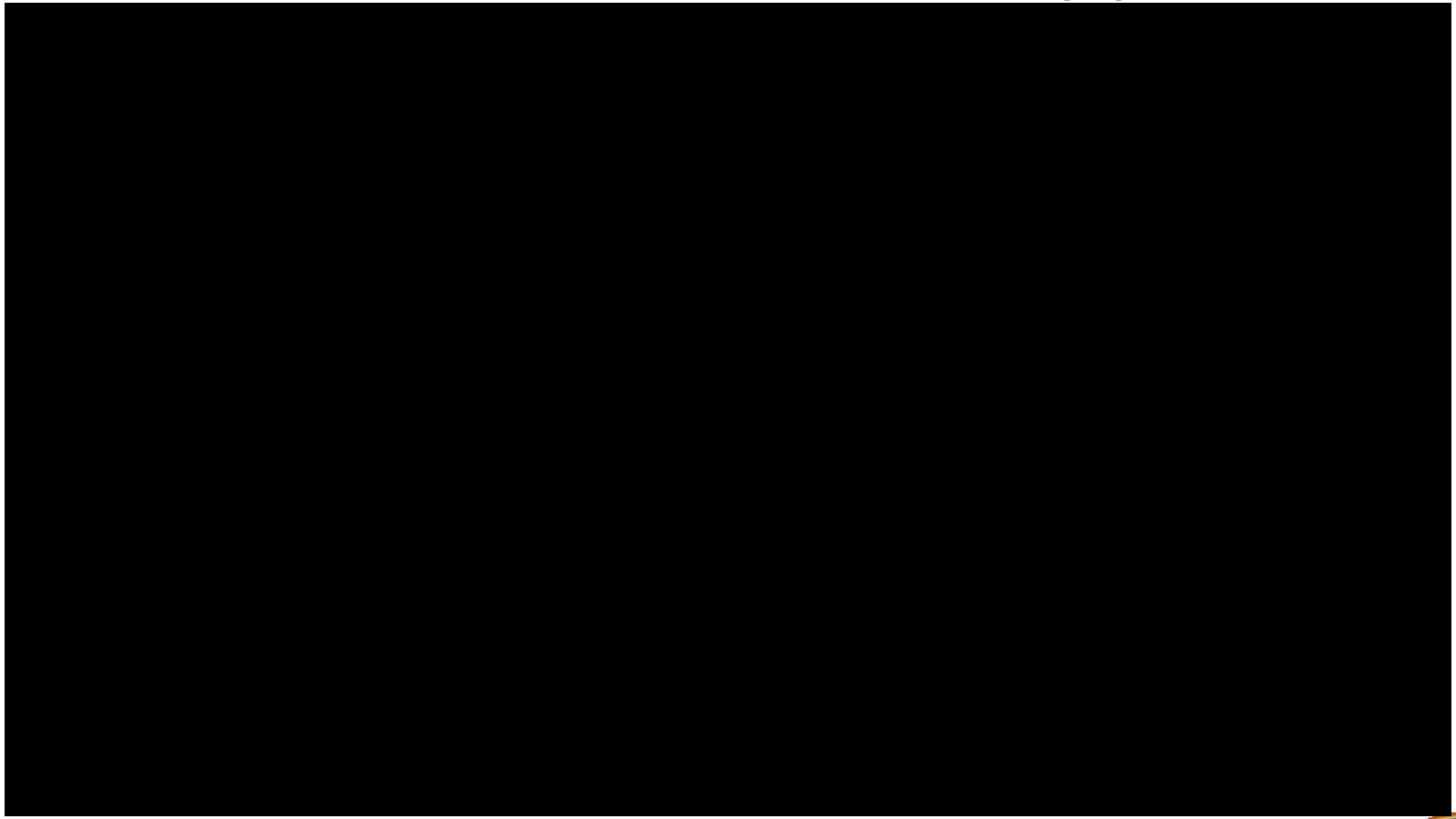
Fire Containment Tests

5000 Lithium-ion Batteries in a FCC

- Test conducted on March 2014
  - Setup involved a metal frame that supported the FCC and backup water suppression systems.
  - Batteries were placed in a steel pan. Balance of cargo cardboard boxes filled with shredded paper.
  - Thermal runaway initiated with a cartridge heater.
  - FCC contained the battery fire for the period of 4 hours.
- Repeated test without metal frames

5000 Lithium-ion Batteries in a FCC

5000 Lithium-ion Batteries in a FCC Without Support Frame



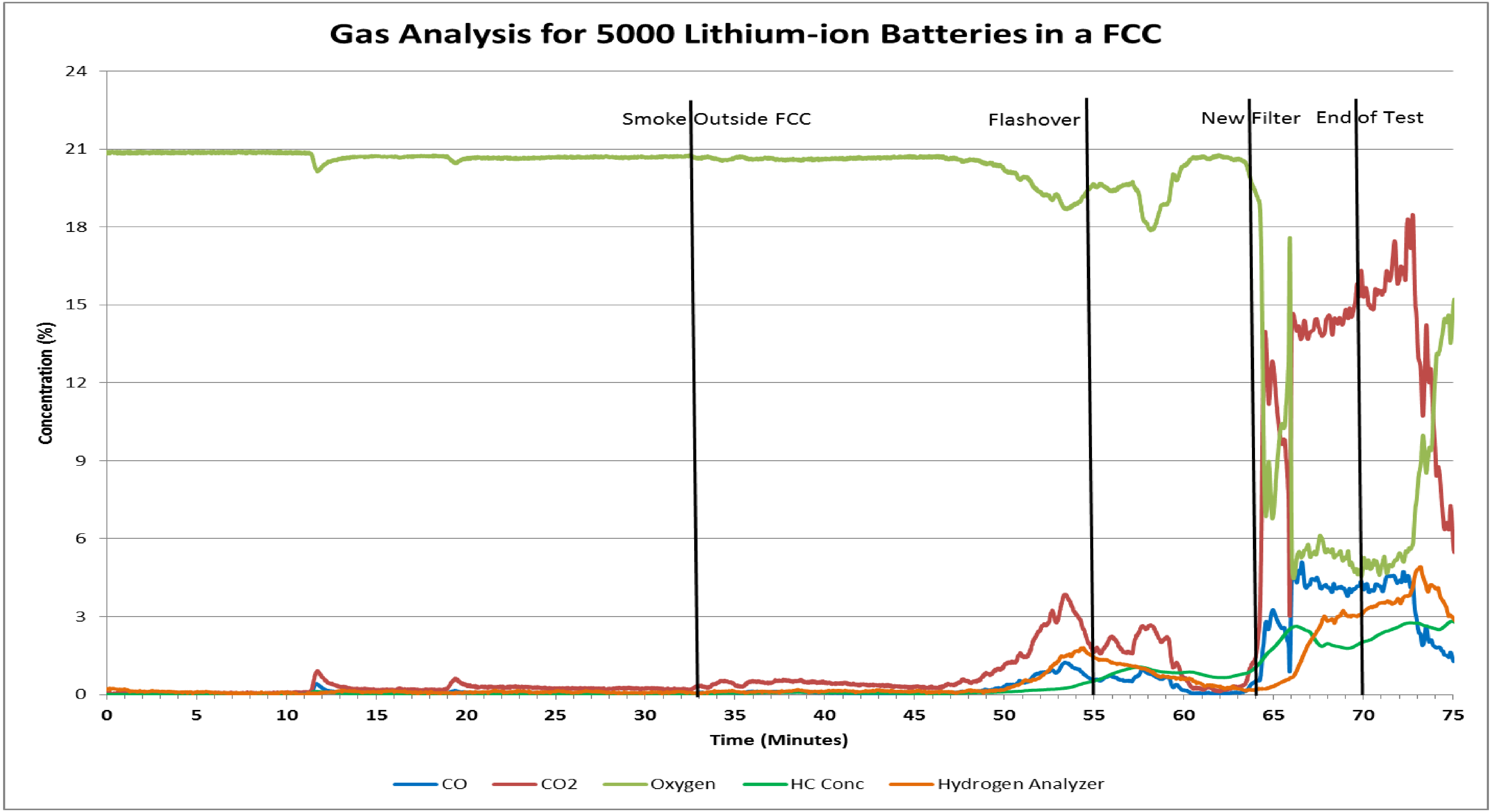
Summary of Events:

-First Signs of Smoke outside @ ~33 Minutes

-Cartridge Heater Unplugged @ ~53 Minutes

-Flashover @ ~55 Minutes

-Test Terminated @ ~70 Minutes



Gas Analysis for 5000 Lithium-ion Batteries in a FCC
Concentration (%)
24
21
18
15
12
9
6
3
0
Smoke Outside FCC
Flashover
New Filter
End of Test
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
Time (Minutes)
CO
CO2
Oxygen
HC Conc
Hydrogen Analyzer

Lithium Battery Thermal Runaway Vent Gas Analysis

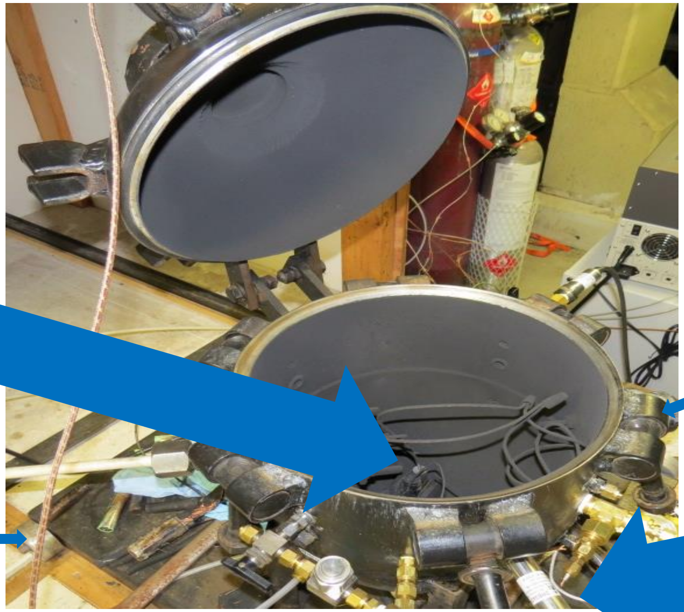
Administration

Introduction

- Three test Setups.
  1. **Small Scale** tests with multiple cell chemistries and SOC to analyze hazard.
  2. **Small Scale** tests with LiCoO2 chemistry to determine pressure rise vs. concentration of vent gas.
  3. **Large scale** tests with lithium-ion cells to verify the hazard on a full scale and evaluate the effectiveness of Halon 1301 at suppressing combustion.

Small Scale Tests (Vent Gas Analysis)

- Tests were carried out in a smaller 21.7L combustion sphere to characterize the type and quantity of gasses emitted.



Spark Igniter

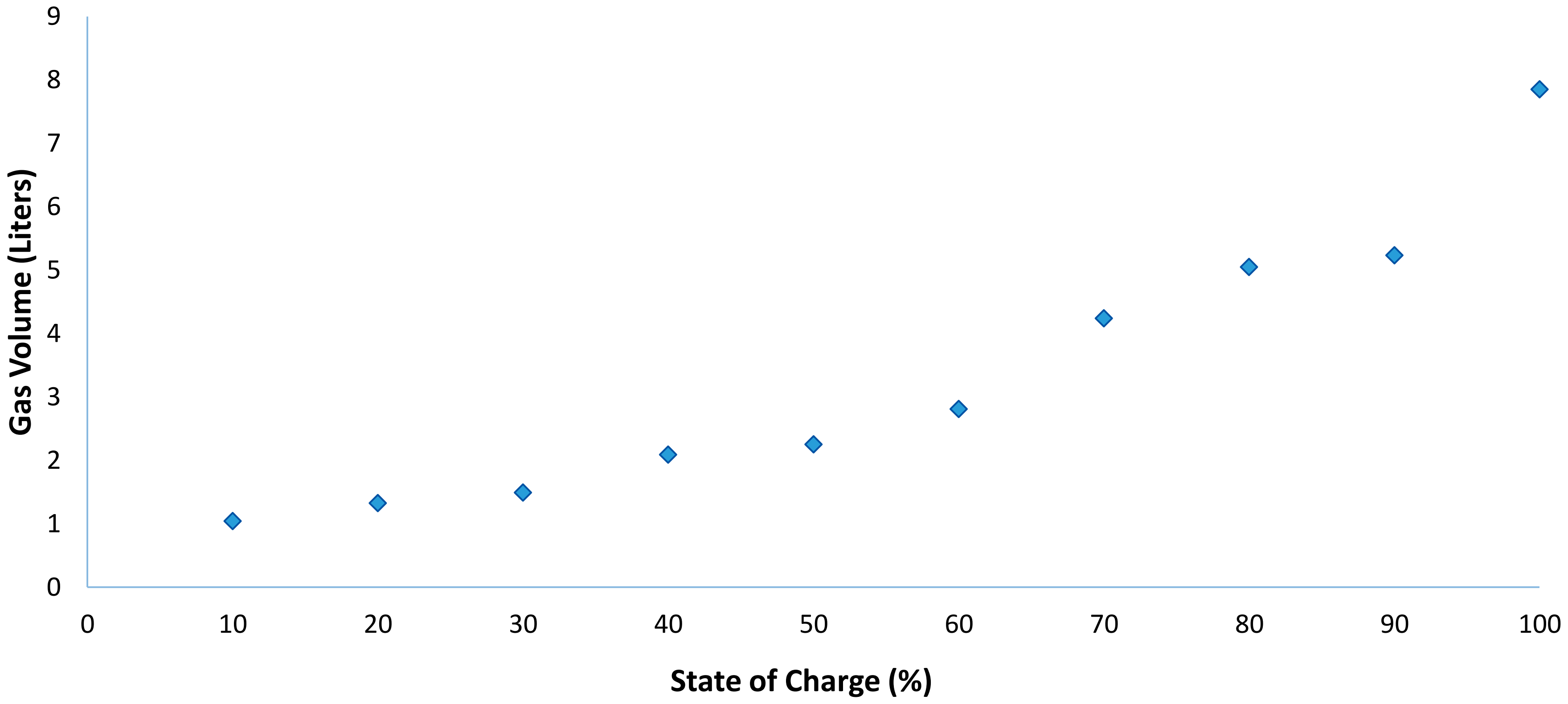
Gas collection port for sample bag.

Pressure Transducer (1Hz, 0-15psia)

Clamp-style cell holder (for cell and cartridge heater)

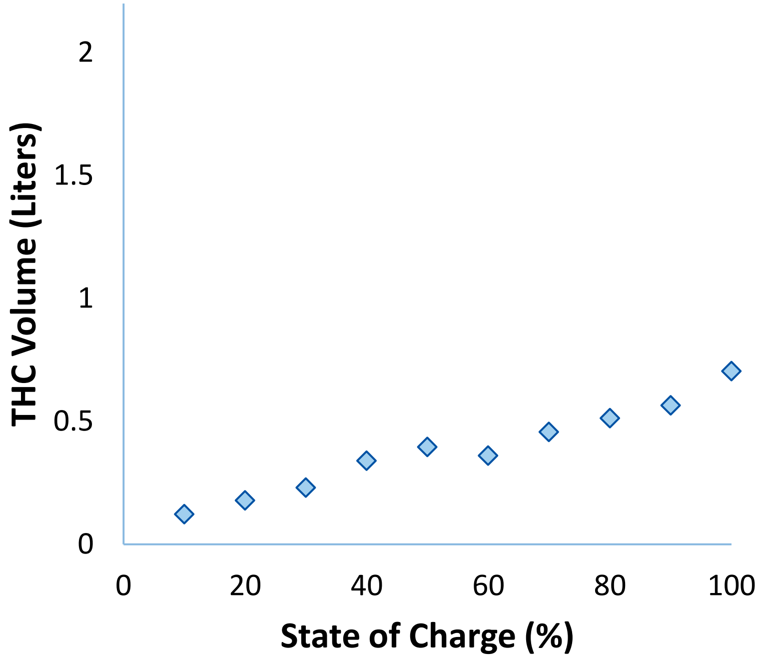
Pressure Transducer (500Hz, 0-100psia)

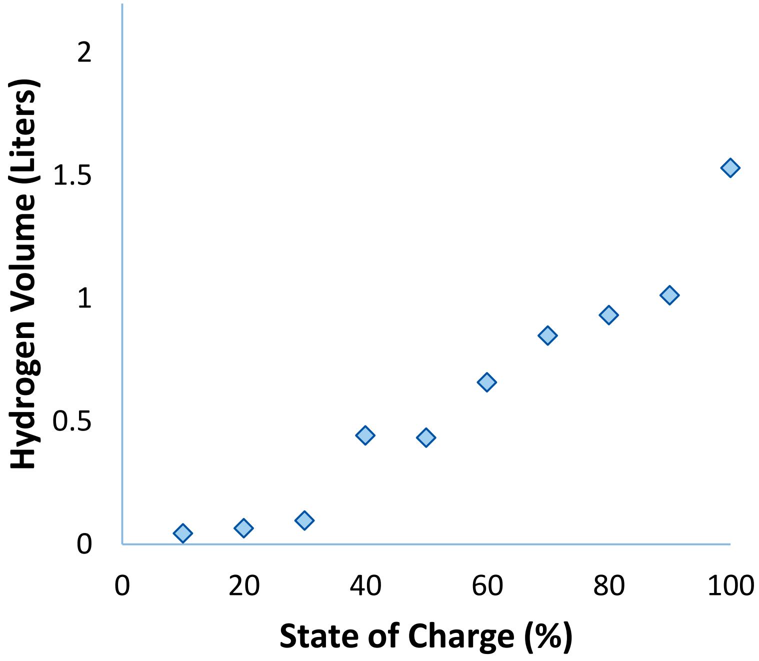
Results: State of Charge ($LiCoO_2$)

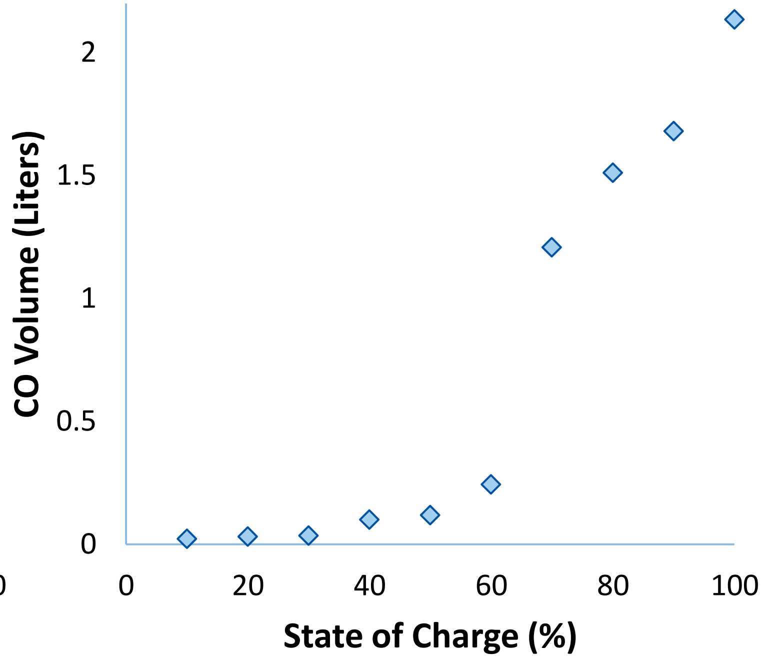


Gas volume emitted increases as SOC increases.

Results: State of Charge ($LiCoO_2$)

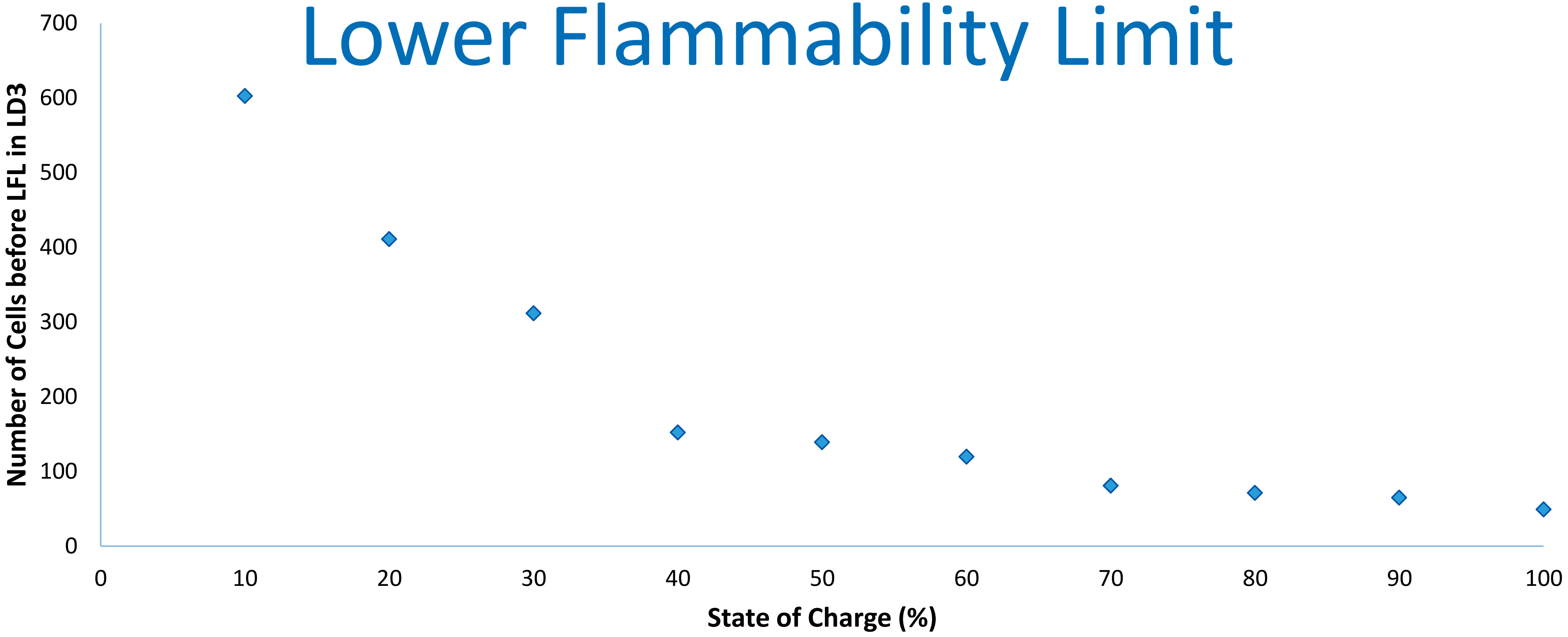






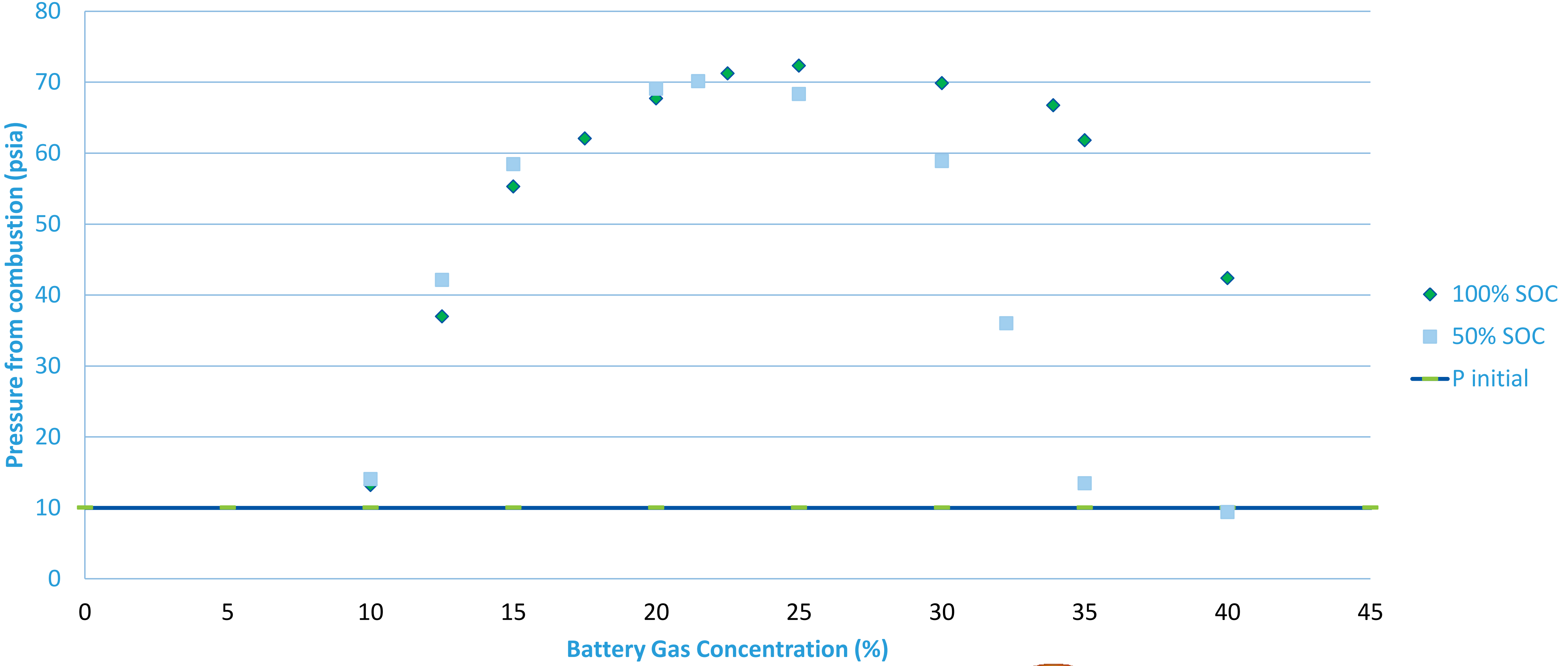
- THC, H_2, and CO increased as Charge increased.

Lower Flammability Limit



The calculated number of cells required for an explosive mixture in an LD3 ($150ft^3$) decreases as SOC increased.

Pressure Rise (small scale)



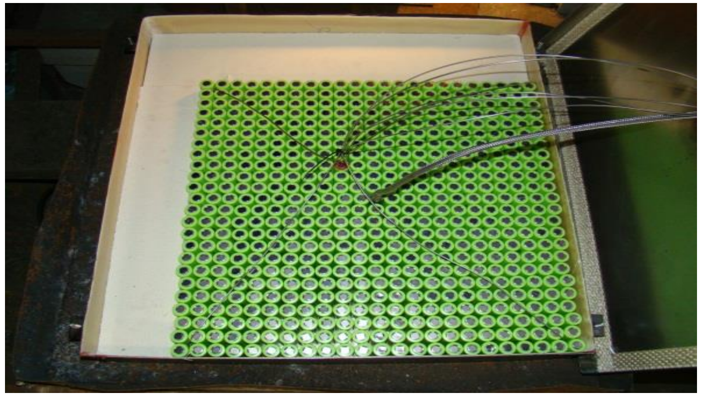
Pressure Chamber (Large Scale Tests)

Number of Cells Required (large scale test)

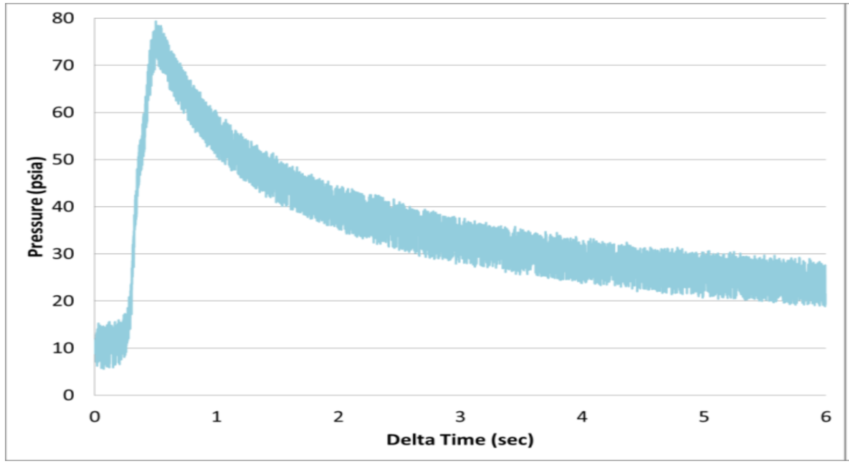
- Stoichiometric equation was used to determine the required vent gas concentration for cells at 50% SOC to be 12.4%. Calculation assumes:
    - Conc. THC ≈ Conc. C_3H_8 = 17.55%
    - Conc. H_2 = 19.22%
    - Conc. CO = 5.2%
- 550 cells produce 1237.39 liters or 12.34% concentration in the 10m^3 chamber.

Setup of Large Scale Tests

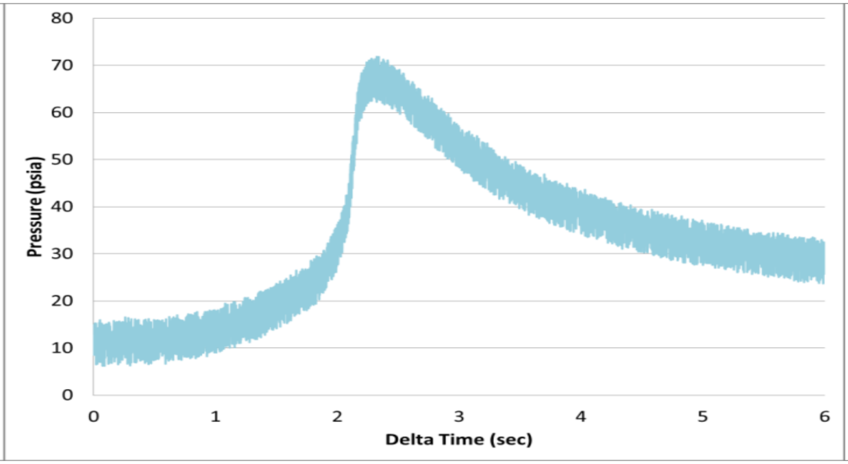
- A cartridge heater was placed in the center of a 550 cell array.
- Type-k thermocouples were attached to cells at each of the 4 corners and one was attached adjacent to the cartridge heater.
- The array of cells was enclosed in a steel container with a chimney to create a rich fuel mixture and prevent premature ignition.
- A spark igniter was installed in the center of the chamber.
- Additional instrumentation:
  - 2 THC analyzers at different heights to check for stratification.
  - An H2 analyzer.
  - A CO, CO2, O2, Halon 1301 analyzer
  - An LFL analyzer.



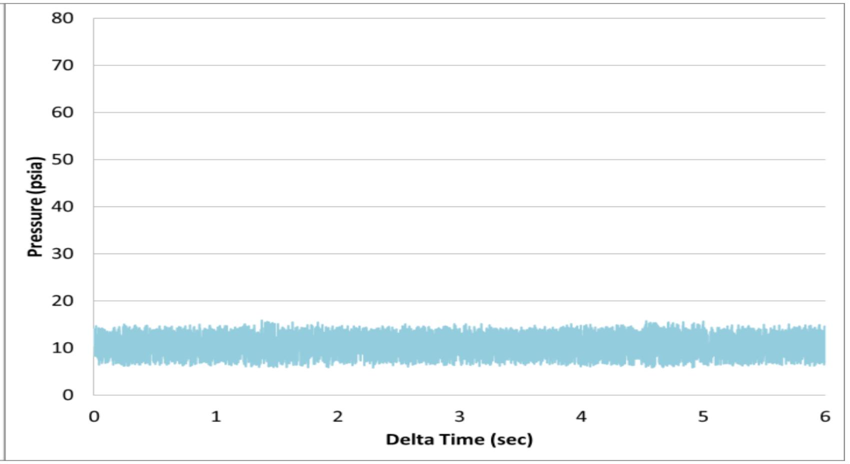
Results (Large Scale Tests)



Test without suppression



Test with 5.28% Halon



Test with 10.43% Halon

Elapsed time from spark ignition

Results (Large Scale Tests)

	Predicted Concentration (from small scale tests) 8.8m^3 chamber	Actual Concentration (No Halon)	Actual Concentration (5.28% Halon)	Actual Concentration (10.43% Halon)
THC	2.47%	2.5%	2.77%	3.2%
H_2	2.7%	2.74%	3.5%	3.54%
CO	.705%	1.4%	1.5%	2.04%
CO_2	3.58%	3.97%	3.42%	4.73%

Takes into account items in the chamber that would reduce the chambers effective volume.

Summary

- Volume of gas emitted from cells increased as SOC increased.
- THC, H_2 and CO increased as SOC increased.
- The number of cells required to reach an explosive concentration in an LD3 decreased as SOC increased.
- Vented gas composition can vary with differing cell chemistries.
- Combustion of vented gasses from the Li-Ion cells tested produced a pressure pulse of 75psia.
- Halon 1301 was less effective than previously thought at preventing combustion of battery gasses.
- Small scale tests reasonably predicted gas concentrations for large scale tests.

Cargo Safety Systems

- Aviation systems that are critical to flight safety must include continuous evaluation of operations, equipment, technology and personnel. Recognizing this approach to assess contributing factors such as incidents and accidents, history and operational data is vital to:
  - Developing and deploying systems that contribute to the defense against hazmat fires both on the ground and in flight;
  - This could include:
    - Fire-resistant containers (unit load devices (ULD))
    - Fire containment covers
    - Other suppression agents developed from research and development

Cargo Safety Systems

- Critical safety systems are based on redundancy. Therefore, if the Hazmat system fails, for any reason, the cargo safety mechanism would be the backup to prevent a catastrophic failure.

- As with all safety systems, cargo safety systems would be expected to have subcomponents that would be designed to be independent of each other so a failure would not in itself cause a catastrophic event. Hazmat packaging standards, suppression systems for ULD's, cargo fire suppression are all components of the design for the safe transportation of cargo.

Future Work

- Everyone expects continuous evolution of energy devices.
- Continue testing container systems.
- Continue to research packaging solutions.
- Encourage industry participation in developing packaging solutions for mitigation.
- We know the hazard, the probability continues to grow everyday, so how we mitigate the risk while facilitating transportation will determine the level of safety for the future.

Contact Information

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http://www.fire.tc.faa.gov/systems/Lithium-Batteries

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