National Transportation Safety Board

Boeing 787 Battery Investigation

Airworthiness Group Co-Chairmen

Robert Swaim

Michael Bauer

Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf
Or http://go.usa.gov/HJtJ

To Be Covered
Investigation in general and some findings

- NTSB and international investigation process
- Li-Ion battery basic function and potential problems
- Design of the 787 and GS-Yuasa battery
- Details known early in investigation
- Involvement of UL and others
- Test findings at the battery and cell levels
- Probable cause and safety recommendations

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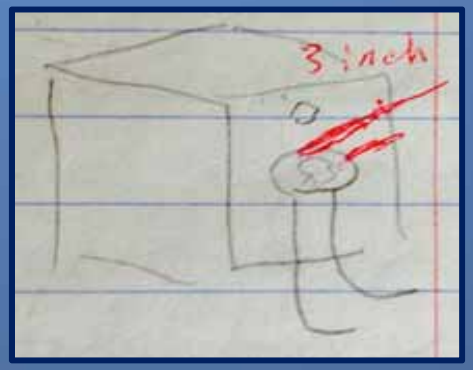
JAL 787 at Boston on January 7, 2013

APU battery removed from here

14 Months after 787 intro to airline use
3 Weeks after airplane delivery
Airplane on ground with APU power
Cleaning crew, mechanic, manager
Smoke event for about 45 minutes.
Minor burn to one firefighter.
Normal access through floor



Sketch by mechanic who saw flame

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Three Boeing 787 Airplanes

	Boston, Massachusetts	Takamatsu, Japan ("-901")	Narita, Japan (redesigned "-902")
Date	January 7, 2013	January 16, 2013	January 14, 2014
Battery version	"-901" (original)	"-901"	"-902" (redesign with containment box)
In-flight or on ground	Ground	Flight	Ground
Position	APU	Main	Main
Airplane-level result	Smoke in cabin in unpowered airplane. Thermal damage near battery. One fire fighter minor injury.	Precautionary landing. Some passengers smelled the failure.	Venting of battery in containment box was vented overboard.
Battery-level result	Venting propagated through all 8 cells.	Venting propagated through all 8 cells.	One cell vented. No propagation.

Fleet grounded January 16 until April 26, 2013
Battery enclosure added for return to flight.

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Battery Function and Potential Hazard

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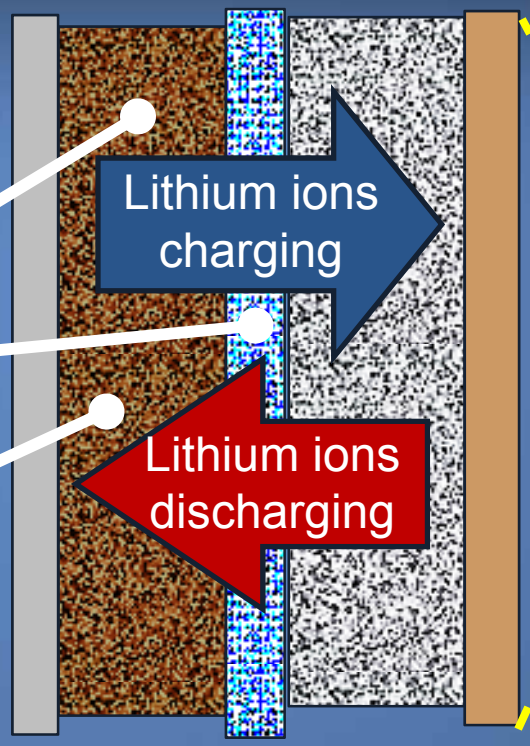
Lithium Ion Cell Basic Function

Normal: Lithium ions in electrolyte move between anode and cathode

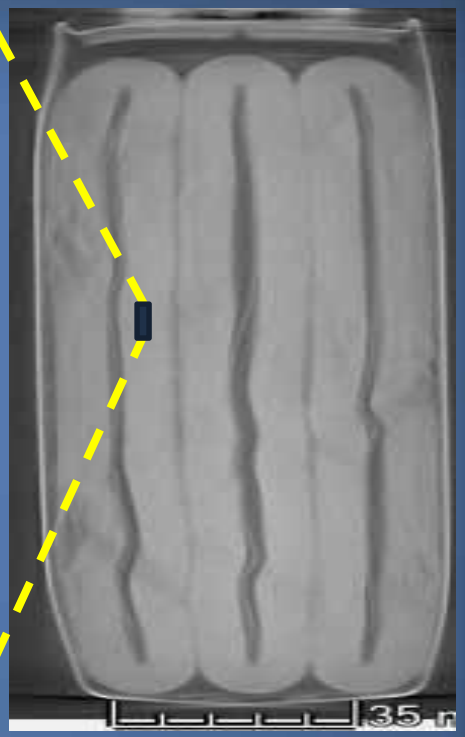
Cathodic coating on aluminum (+)

Porous plastic separator film filled with electrolyte

Anodic coating on copper (-)



Function in a single layer



787 Cell has three windings of many layers

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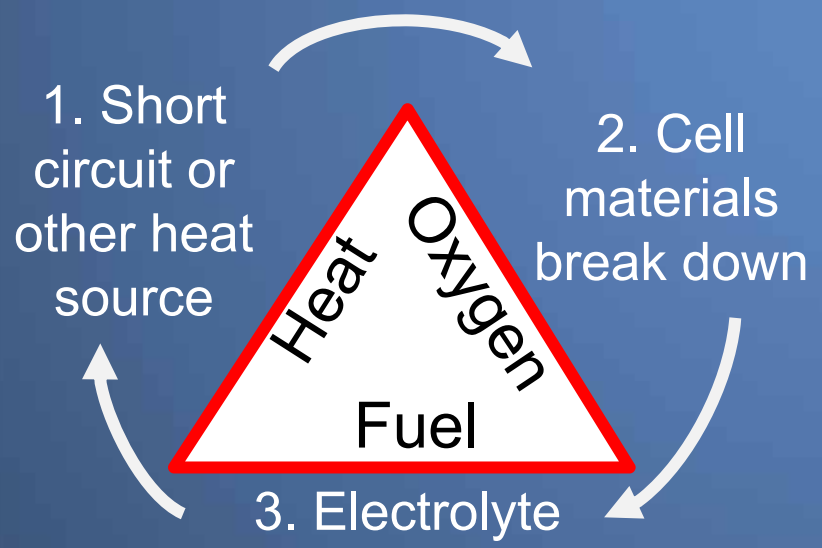
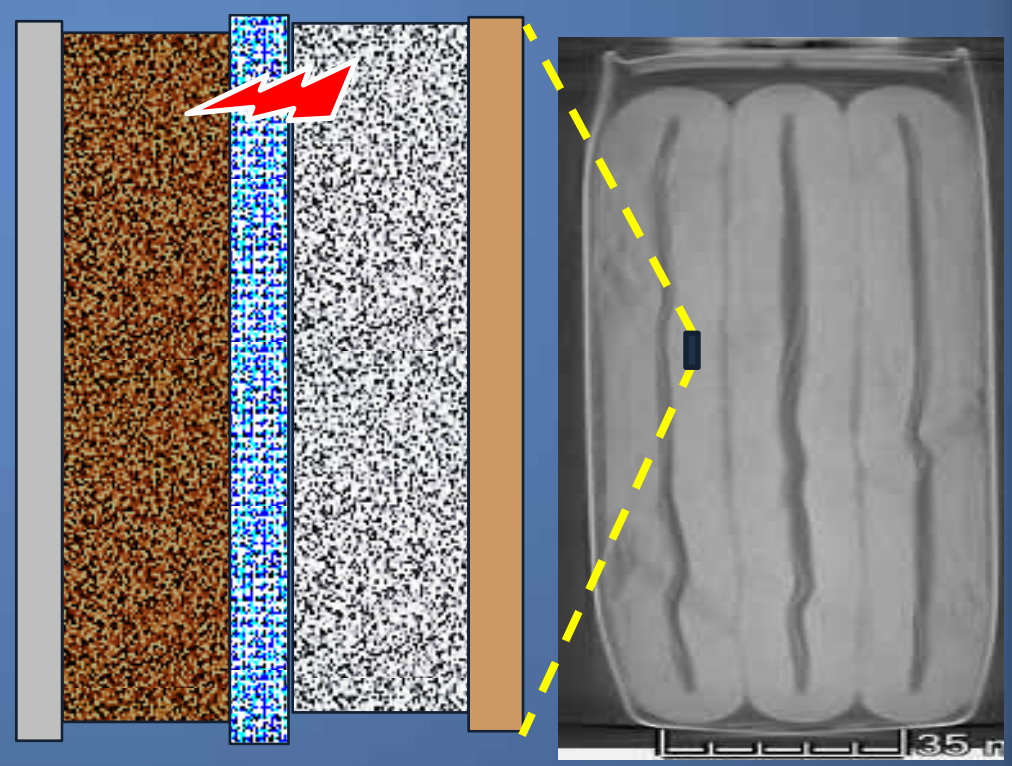
Lithium Ion Cell Internal Short Circuit (ISC)

Potential problem:
The plastic separator can melt, tear, or puncture, creating a short circuit.
An internal short circuit (ISC) is an uncontrolled discharge which may heat.
Electrolyte chemicals are flammable and the cell materials contain oxygen.
Increasing heat may result in thermal runaway.





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Thermal Runaway Process

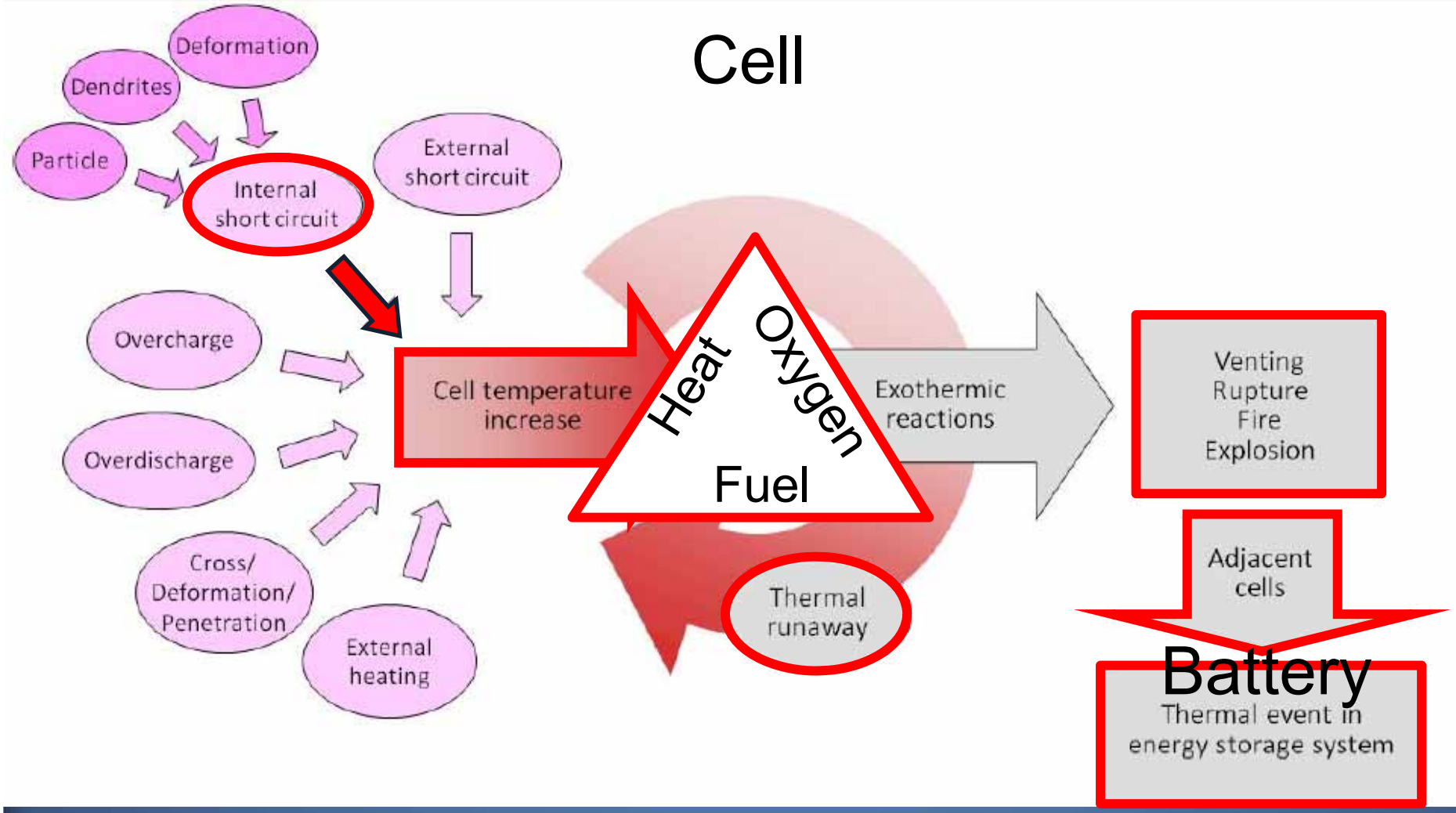

Figure 1. Potential chain of events for a thermal event on the cell level developing to system level.
Modified from "Energy storage system safety in electrified vehicles," by Larsson and Mellander

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Thermal Runaway Example

Lithium ion cells have combination of electrical and chemical energy.

Generation of electrical internal short circuit (ISC) may ignite chemicals.

Venting electrolyte may heat and smoke without ignition or may ignite.

Demonstration of lithium ion battery ignition in laptop computer

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Single 787 Cell During Nail Penetration Test

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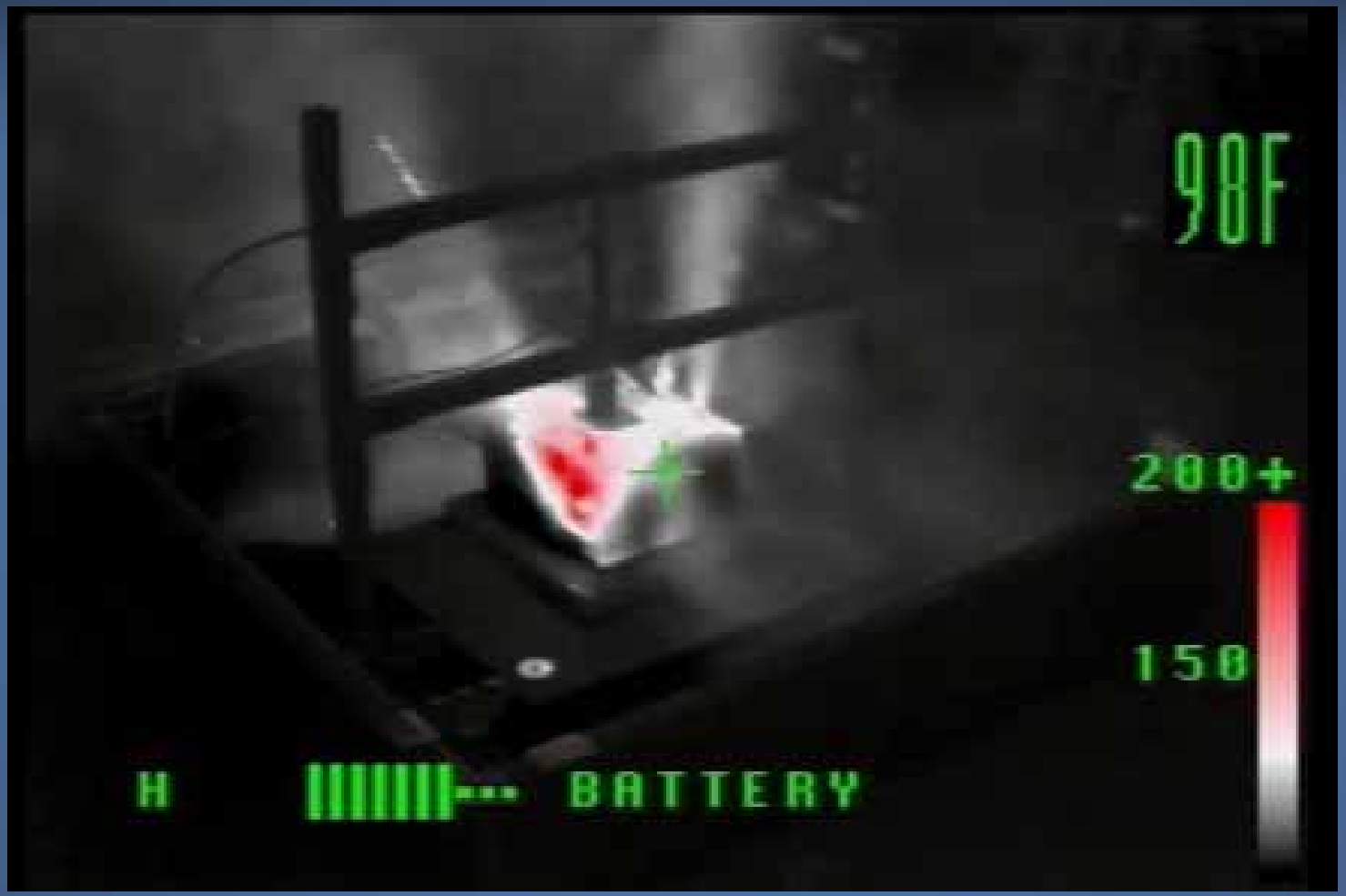
IR Image of Battery in Thermal Runaway Shows Hot Ejecta



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Extreme Variation About Airline Hazard

- Estimate of historic Li-ion battery failure rate per flight range:

one in 32 flights to 32,000 flights.

- 2013 world airline traffic: 100,000 flights/day,

3.3 billion pass, 32.2 million flts, average 102 pass/flt.(Data: IATA)

- Estimates of Li-Ion battery actual failure rates vary from one in a million to one per billion.
- Million is minimum limit for CPSC recall. Billion estimate by battery industry
- Assumes one battery per passenger

(Ref: Lithium-Ion Batteries Hazard and Use Assessment, July 2011 by Exponent for Fire Protection Research Foundation (FPRA), Mikolajczak, Kahn, White, Long)

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In-Flight Battery Failure Data

- FAA 2011 data: Smoke/fumes accidents, incidents, and service difficulties:

	ACC/INC	SDR
2010	16	1,250
2009	9	1,035

- FAA recorded 132 batteries leading to smoke, fire, extreme heat, or explosion from 1991-2012.
  - Majority were lithium-ion toward end of period.
  - Example: 4/18/2012 Pinnacle Airlines CRJ at 28,000 feet had in-flight fire when passenger device in cargo ignited.

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Notable accidents with lithium-ion batteries

2/7/2006, UPS DC-8-71F, Philadelphia. Area of fire had Li-Ion batteries and flammable fluids.
9/3/2010, UPS 747F, Dubai. Cargo included 81,000 Li-Ion batteries.

Dubai showed hazard of control loss to area beneath flight path

7/28/2011, Asiana 747F, Korea. Area of fire had Li-Ion batteries next to flammable fluids.

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UPS DC-8-71F Landed at Philadelphia

Typical airport with approach path over populated areas

A key difference:
The JAL 787 battery which failed in Boston was permanently installed as aircraft equipment.

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787 Investigation General

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NTSB Involvement

National Transportation Safety Board

- Independent US agency for transportation accidents, incidents, other criteria
- Legal thresholds for what to investigate
  Injuries, damage hazard level, new technology
- "Party process"
  NTSB selects participants who support investigations
- Results publicly available (except proprietary redactions)
- "Products" are reports and safety recommendations

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Multi-National Investigations

International investigations per U.N. ICAO Annex 13

- Country of occurrence responsible for investigation.
- Invites countries of manufacture, crew/passengers, etc.
- French BEA and Japanese JTSB support NTSB Boston 787

  Thales power sub-system and GS-Yuasa battery
- NTSB and BEA support JTSB and JCAB 787 investigations

  Boeing supports Japanese investigations through NTSB

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Challenges in 787 Investigation

- Classify as non-reportable failure? or incident to investigate?
- Grounding of the entire 787 fleet
  - Pressure to find problem
  - Redesign required time and people involved in investigation
- Simple transportation of batteries as evidence
- Extreme public interest
  - 787 was a newly certificated high-profile model
  - Perceptions about “hazards of new technology”
  - Numerous leaderships involved in multiple countries
- Government shutdown
- Time diverted to Public Hearing early in investigation

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Large 787 Effort Led to Work Division

- **NTSB Airworthiness Group**, assisted by

  UL and US Naval Research Laboratory
- NTSB Battery Forensic Group (Materials Lab), assisted by

  TIAX and US Naval Surface Warfare Center
- NTSB Aircraft Certification Group
- NTSB Airport and Response Group
- NTSB Manufacturing Group

NTSB was assisted by numerous experts

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Airworthiness Group Functions

Following on-scene documentation:

- On scene documentation
- Learn design and history
  - Included batteries destroyed in prior testing and accidents
- Examine charger and other non-battery system components
- Examine other batteries and cells

- Conduct functional and component tests
- Tests with Boeing of cell, battery, system, and in-flight
- Tests with Japanese JTSB and JAXA (resulted in JTSB report)
- Tests with UL - both contracted and contributed

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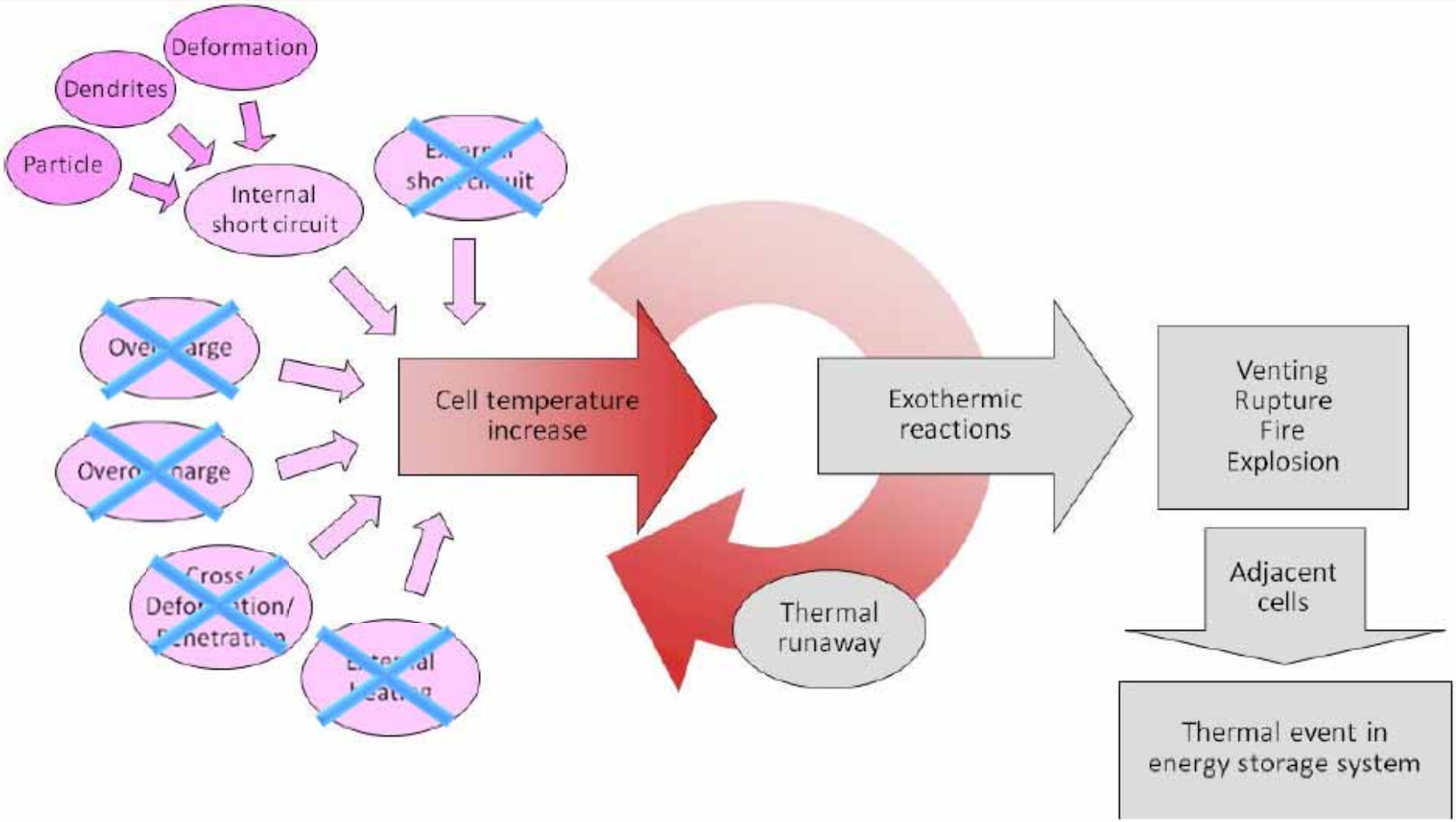
Process of Investigation:
Eliminate Potential Issues To Isolate a Path



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Testing Required Five UL Labs In Three Facilities

UL won NTSB competitive contract for testing services

Test Planning with NTSB

Cell Level Exams
Functional Tests

Instrumentation

Disassembly

Battery Level Exams

System Function Tests

Battery Destructive Tests

Analysis and 5 reports

Taipei, Taiwan
Battery Lab
Materials Labs

Melville NY
Electric Power Lab

Northbrook IL
Fire Lab
Radio Frequency Lab

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Airworthiness Activity Locations

Testing, interviews, records exams, and other research were at

- Boston Logan Airport and Takamatsu Airport
- FAA offices in Washington, DC, and Seattle
- Boeing, multiple Seattle area facilities
- Securaplane, Tucson, AZ

- Thales, Paris, France
- GS-Yuasa, Kyoto, Japan, and sub-contractor facilities
- JTSB / JAXA, Japan
- Underwriters Laboratories, Taiwan, Melville NY, Northbrook IL
- Other industry, academia, and Government sources

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Battery Installation and Component Configurations

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Boeing 787 Battery Locations

Auxiliary Power Unit (APU) Battery located beneath main cabin

Main Battery located beneath forward galley

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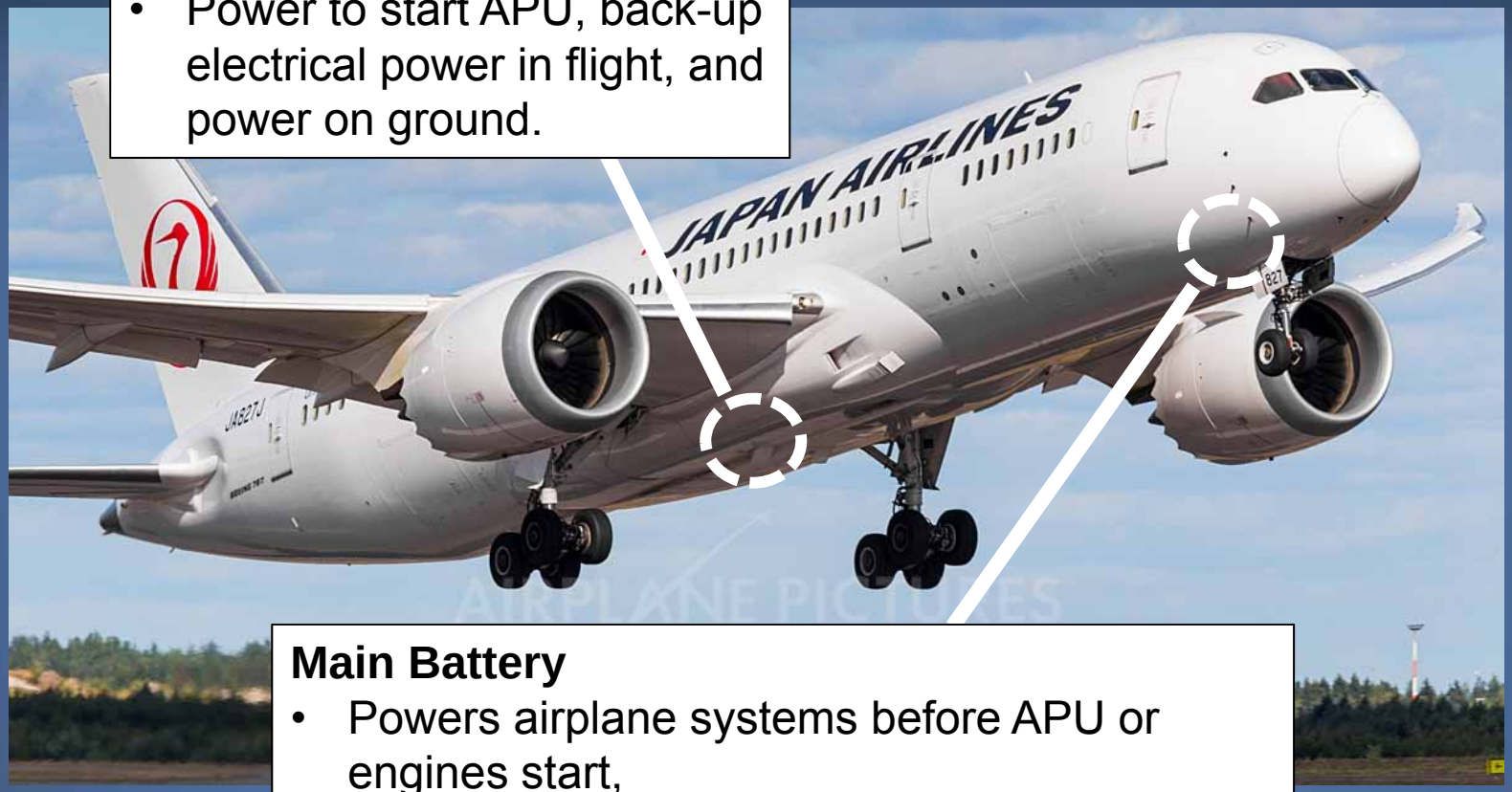
Boeing 787 Battery Functions

Auxiliary Power Unit (APU) Battery

- Power to start APU, back-up electrical power in flight, and power on ground.



Main Battery

- Powers airplane systems before APU or engines start,
- Supports refueling and other ground requirements,
- **Emergency power source for instruments and electric braking systems**.

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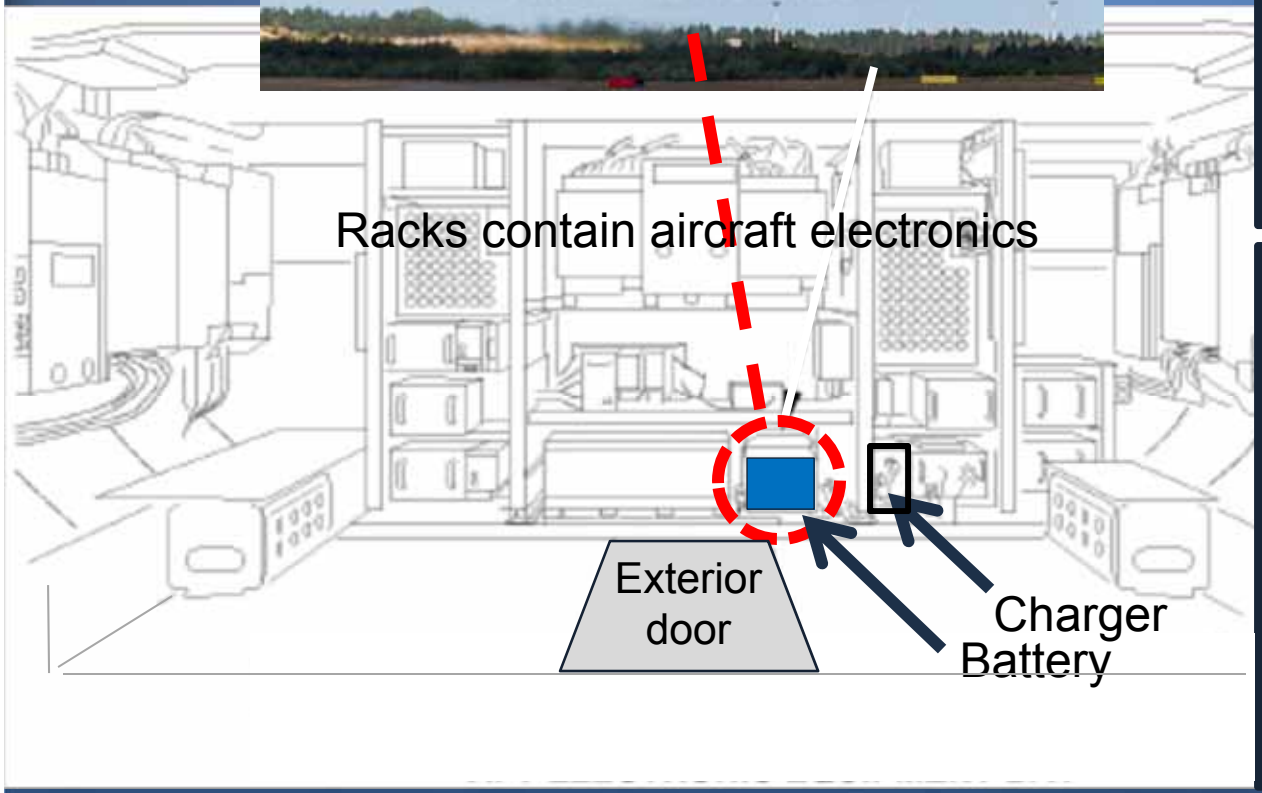
APU Battery In Small Aft Electronics Bay



Original APU battery

Forward battery installation is similar

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Smoke Output of 787 Battery

Video shows amount of smoke output from eight cells of battery at UL Fire Laboratory (edited)

This smoke is hazardous to breath, potentially flammable, and corrosive.

Original location and size of compartment

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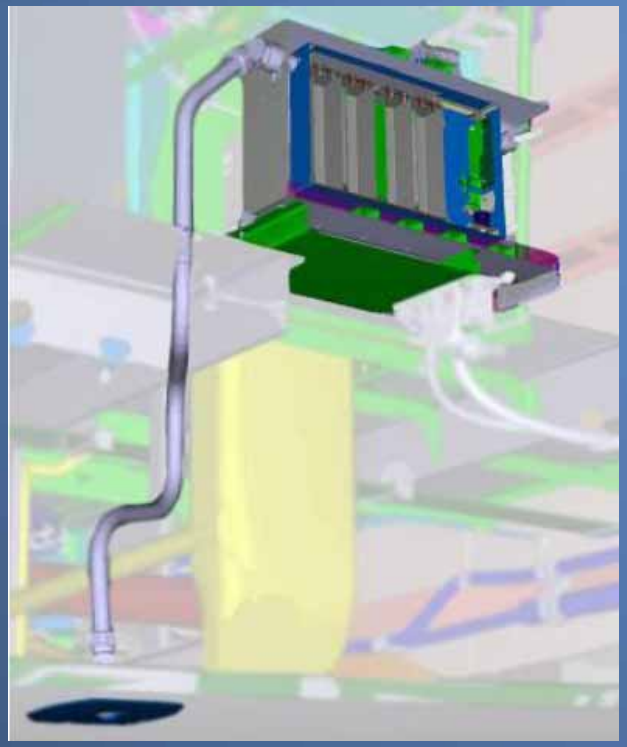
APU Battery Installation - Redesign

- Containment chamber added for battery, as shown in photo on right
- Cells vent out of battery case and overboard

- Battery design also changed
- Maintenance changes adopted



Boeing graphic of overboard vent.

Boeing photo of chamber being installed.

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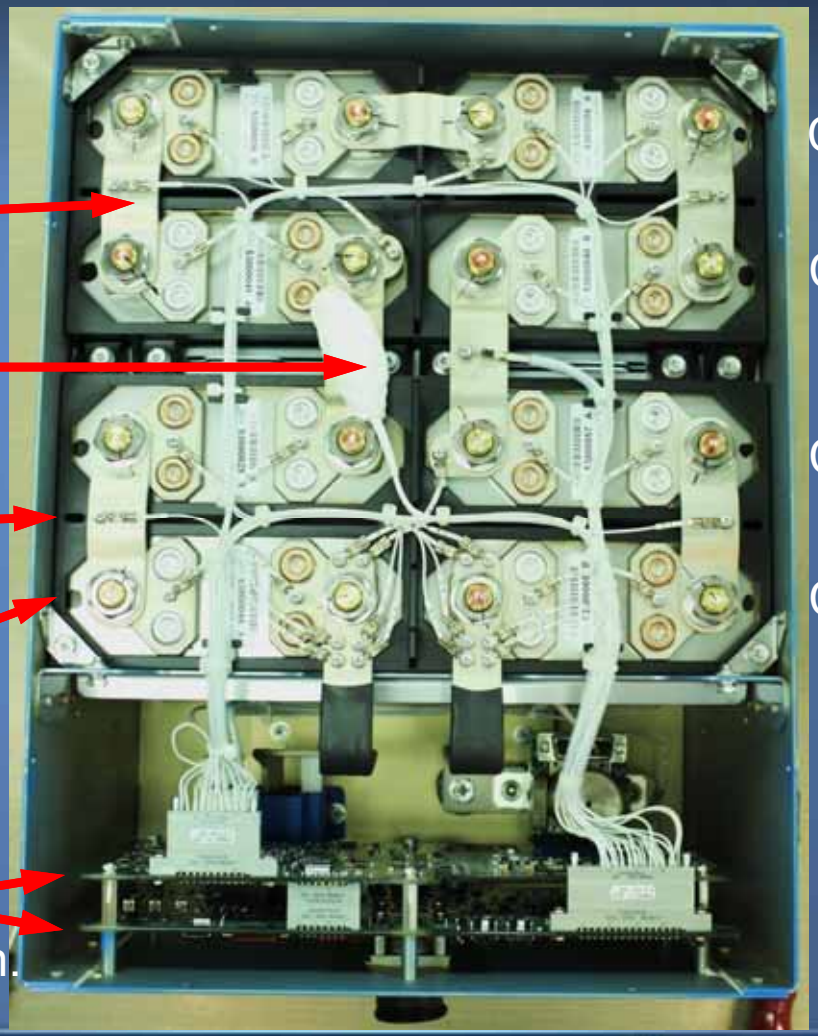
787 Battery Configuration

Eight cell cases electrically isolated in aluminum box

- Bus bars link 8 cells in series
- Temperature sensor (1 of 2) on bus bar
- Plastic spacers surround each cell
- Cell vents oriented outward
  - Original design vented into case
  - Revised design vents out of case
- Battery monitoring unit (BMU)
  - Four levels of overcharge protection



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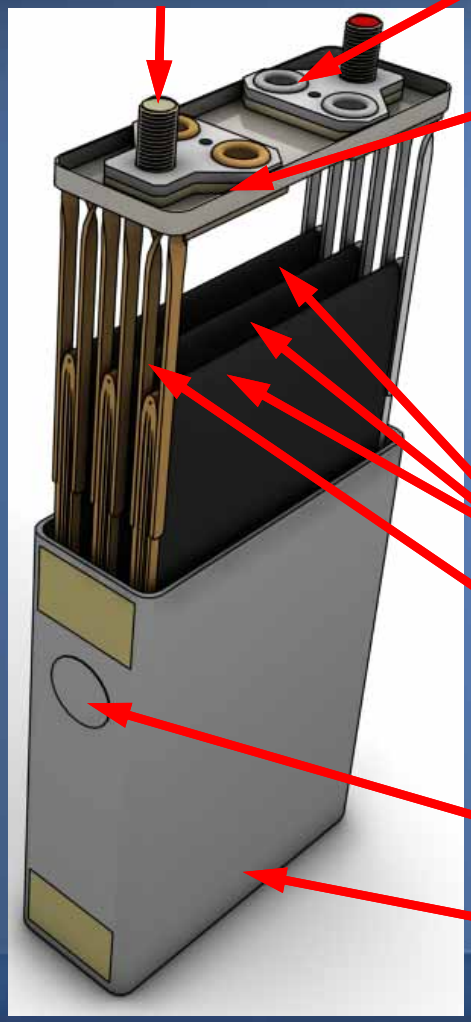
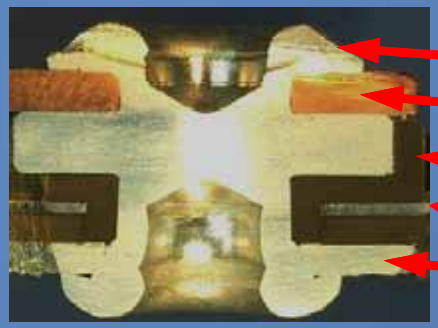
Configuration of Each 787 Cell

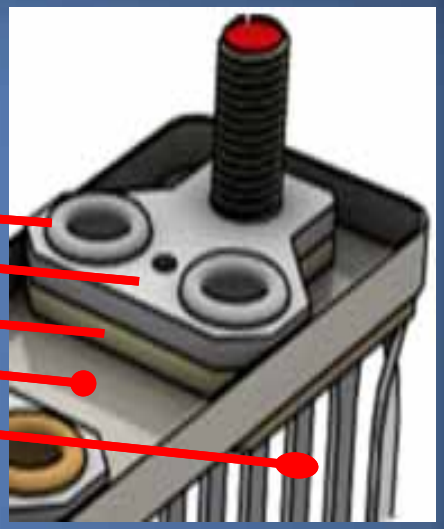
Threaded terminal lug



Rivets in conductive path are partially hollow. Fasten interior collector to exterior terminal plate.

Thermoplastic insulators seal cell and support terminal plate





Three windings are in each cell

Current collector fingers attach to upper portions of windings

Case vent

Stainless steel case

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Observations And Disassemblies

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Facts Known Soon After Boston Event

- Heat and smoke without large fire (3 inch flames at connector)
- No overcharge in data and BMU has 4 layers of protection
- Voltage data showed progressive loss of cells

  Began with one. Data did not show which failed first
- Battery had not been over-discharged
- No external sources damaged the battery case or cells

  Mechanical or heat
- No external pre-failure source of a short circuit

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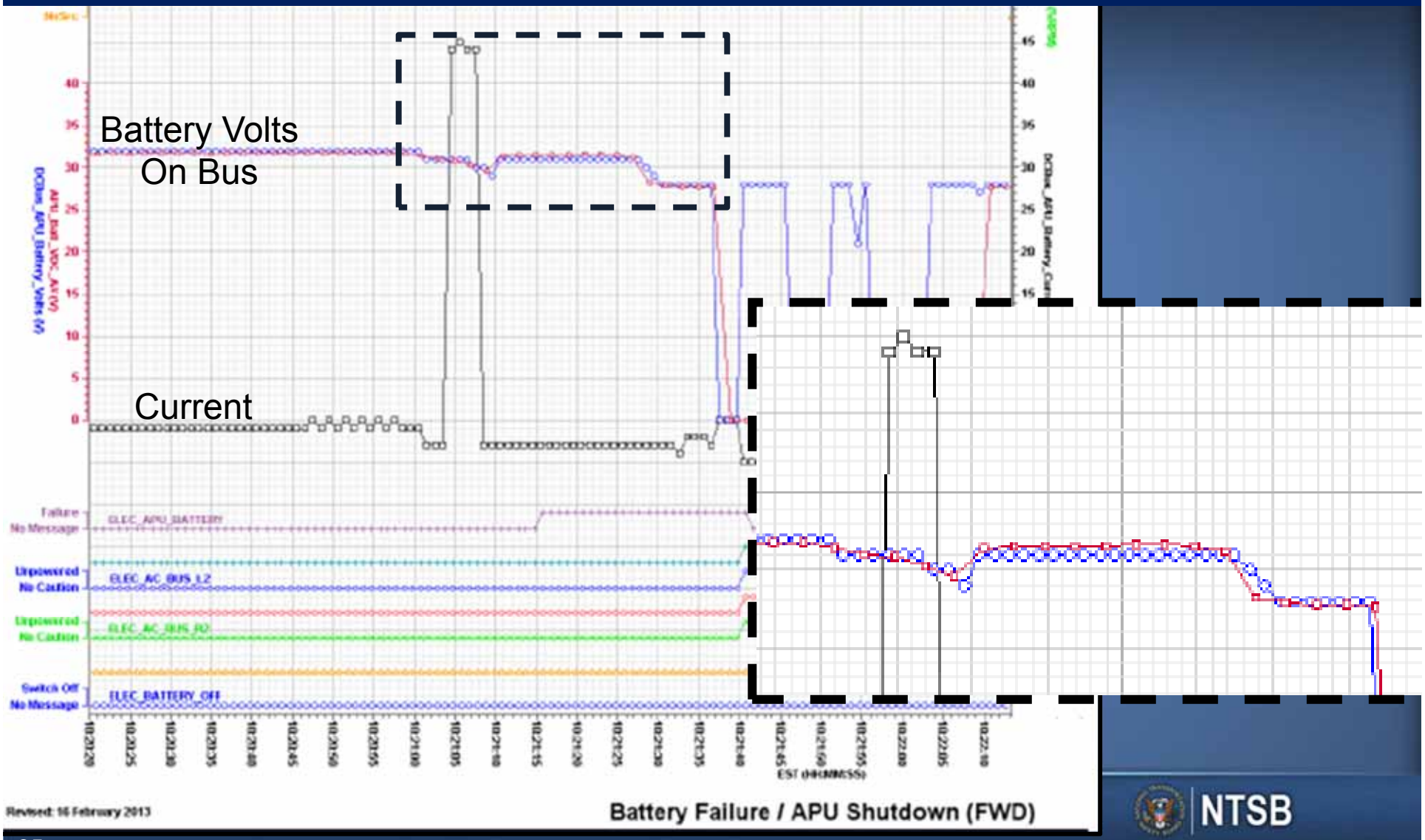
FDR Data Showed Initial Voltage Loss From a Single Cell



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Cold Weather

- JTSB noted that incident airplanes were based in Tokyo
- All three failed mid-January
- Japanese operators had minority of fleet
- Different operators at different Tokyo airports with different types of operation

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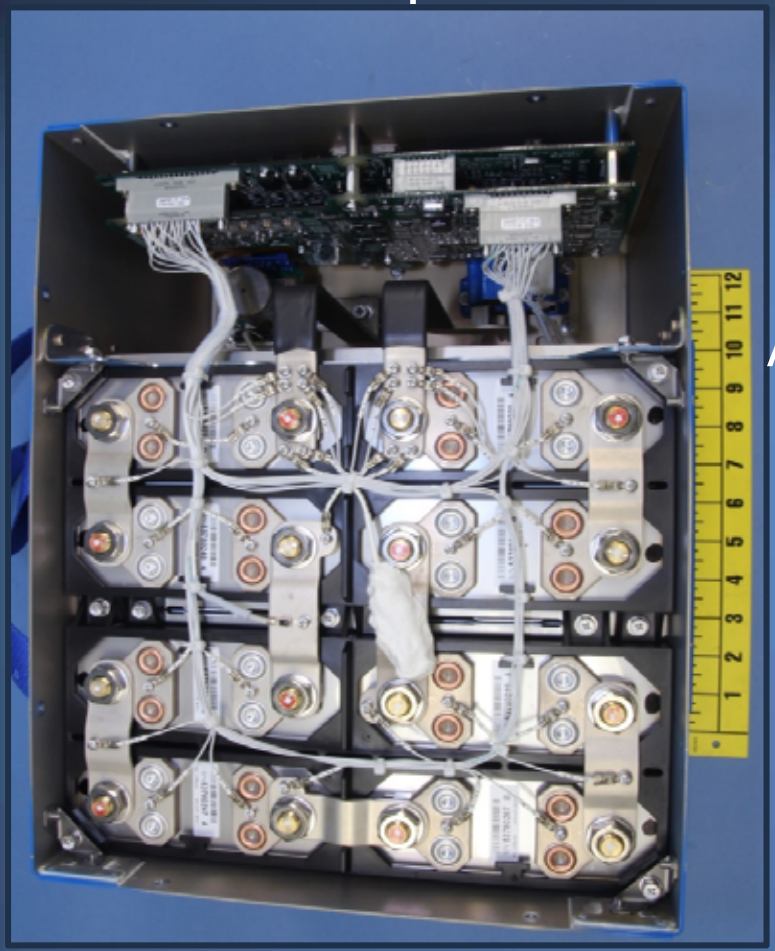
Forensics About Extent of Thermal Damage

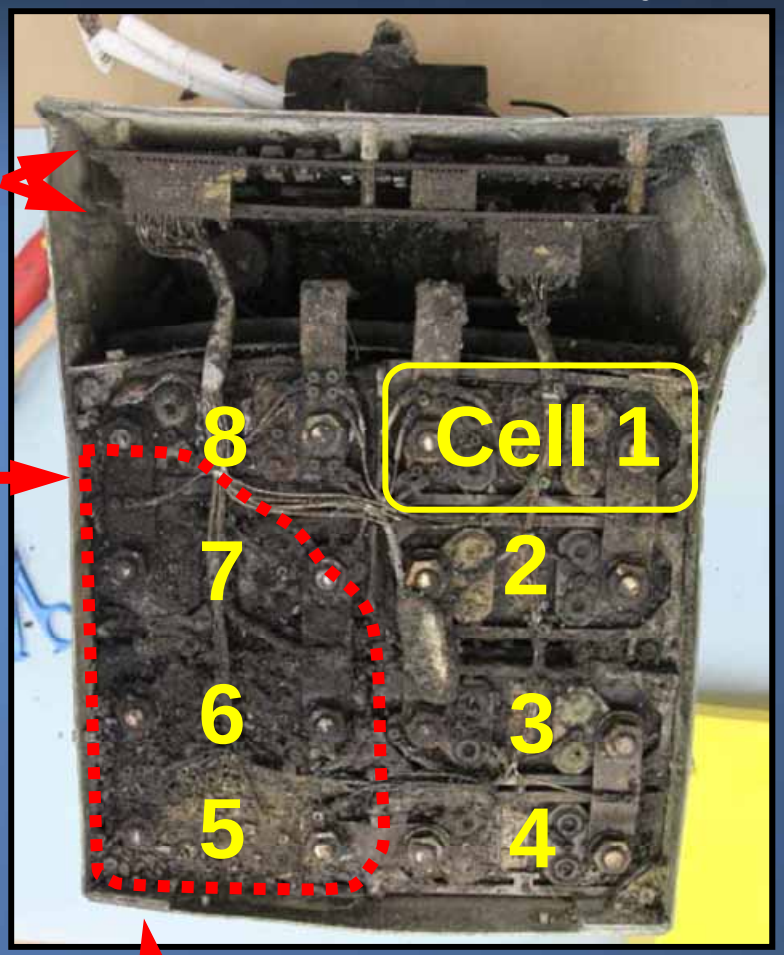
Exemplar



BMU Cards

Area of most thermal damage

Boston APU Battery



Protrusion

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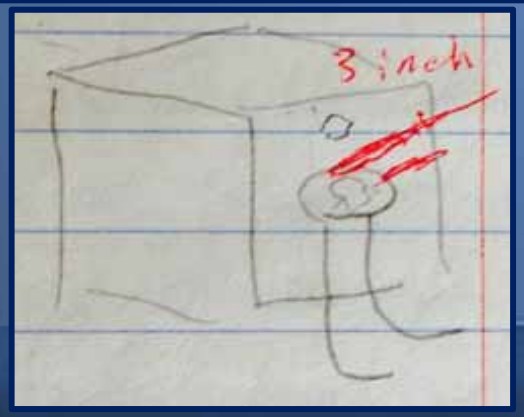
Forensics - External Case Damage

Connectors at front of case

"Protrusion" melting at back of case



Sketch by mechanic who saw flame

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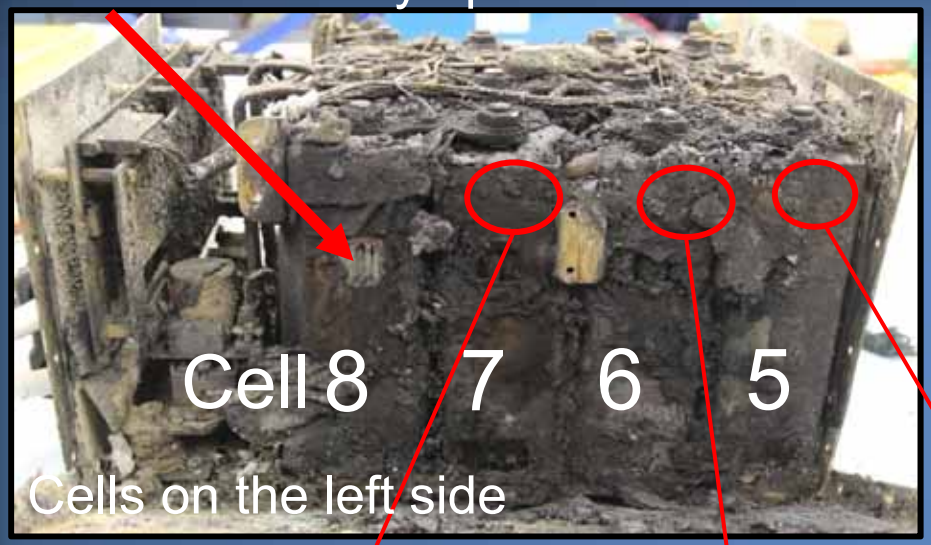
Internal Damage at NTSB Materials Lab

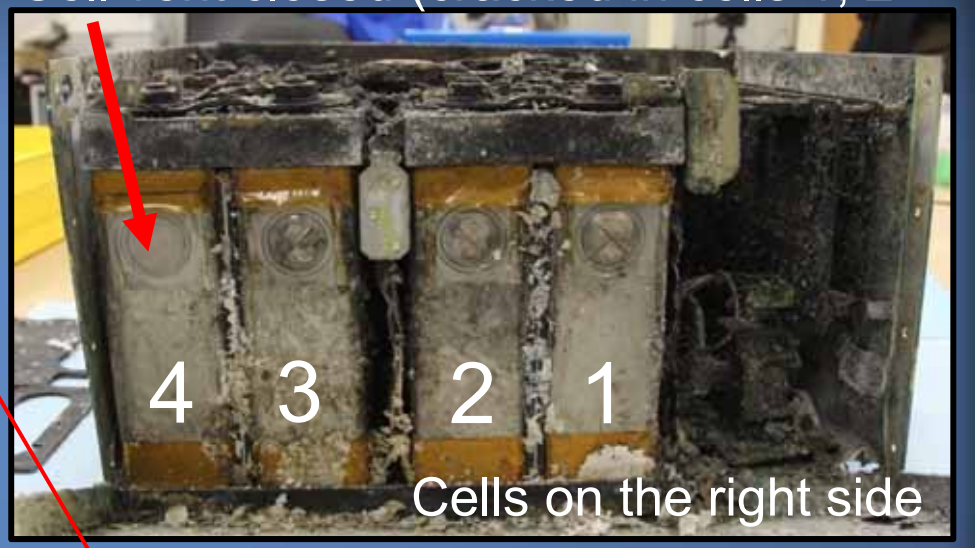
Substantial thermal damage

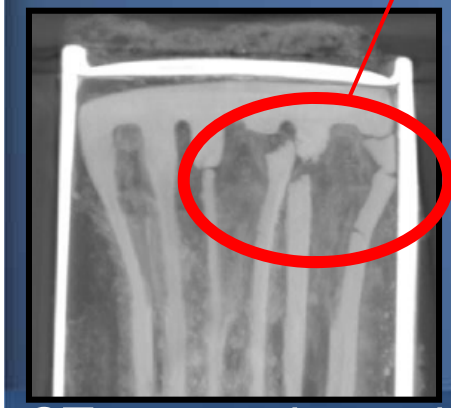
Cell vents visibly open in 5-8

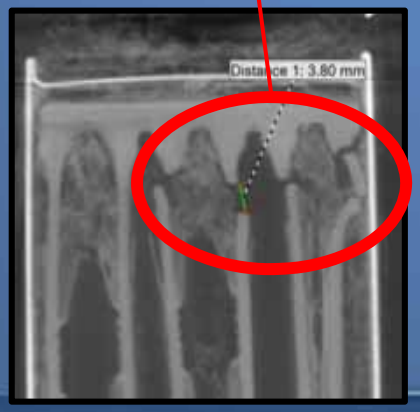


Moderate thermal damage

Cell vent closed (cracked in cells 1, 2







CT scans showed open current collectors in these three cells

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Forensics at NTSB Materials Laboratory

Two unwound electrodes (of 24)

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Forensics at NTSB Materials Laboratory

Detailed electrode inspections

Microscopic inspections
(example shows aluminum on copper)

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Wrinkles Observed in Windings

- Gold indicates charged material
- Dark indicates less-charged material

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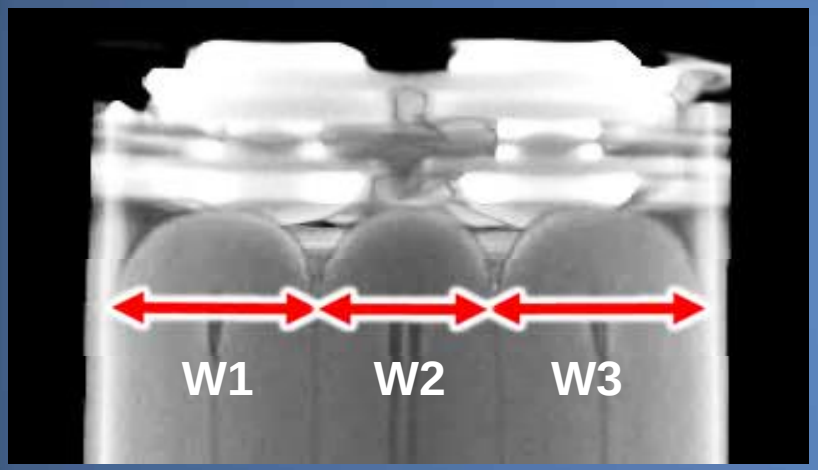
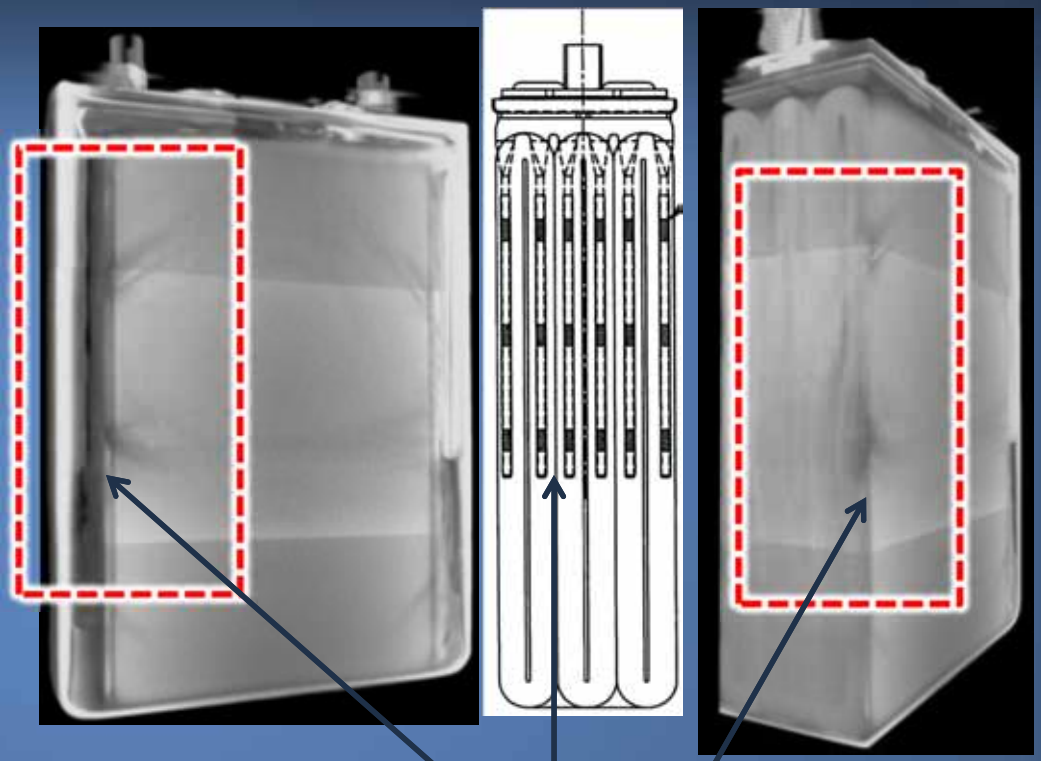
Stressors on Wrinkled Electrode Windings



W2 is 5-10% less than W1 and W3 in width. The collector fingers are evenly spaced, creating uneven stress on windings



Ends of collectors

Uneven stress can lead to poor contact between electrode(s) to separator

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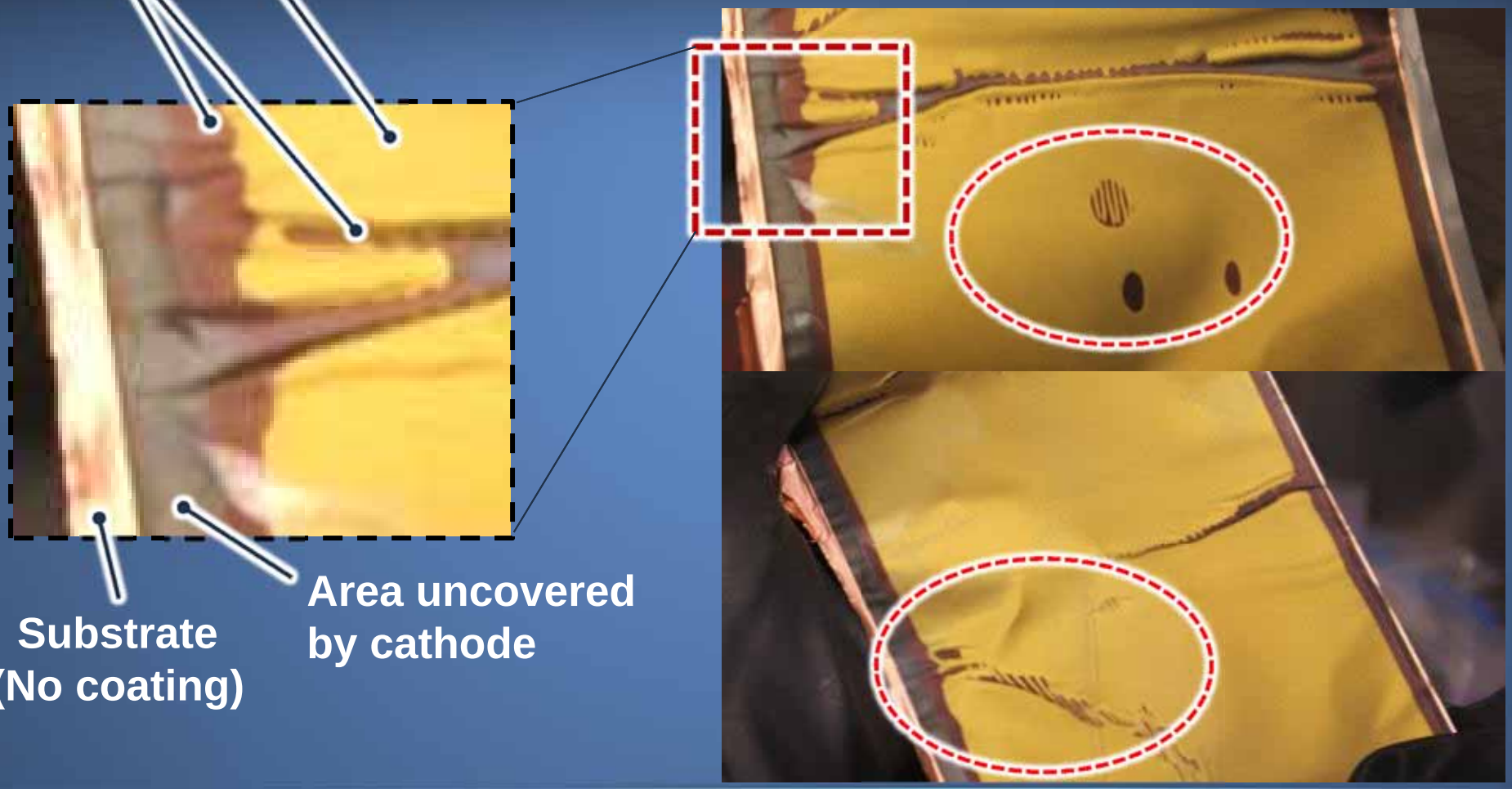
Tool-Like Patterns and Uneven Current Density

Anode covered by cathode with poor charge transfer

Area covered by cathode with good contact



Substrate (No coating)

Area uncovered by cathode

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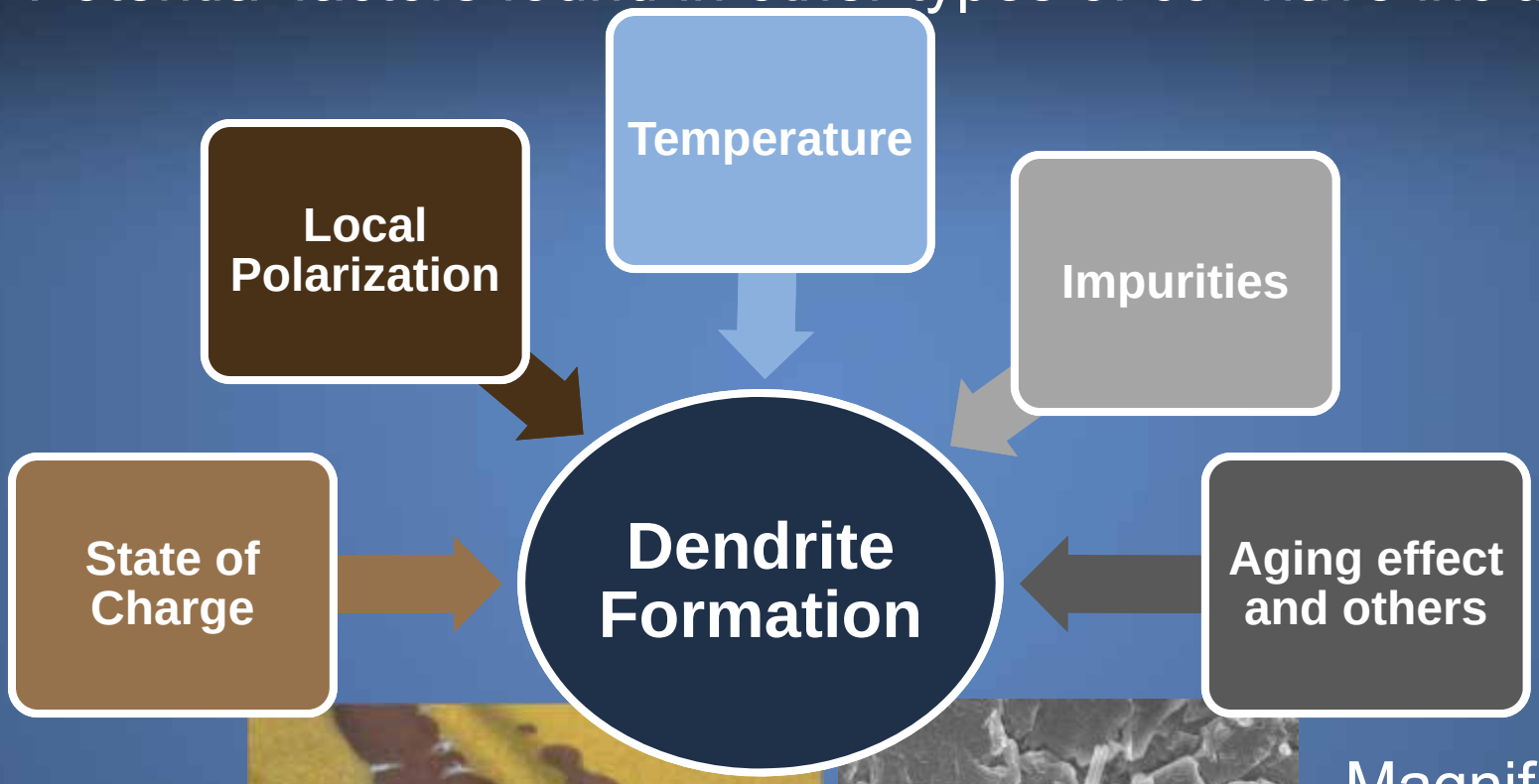
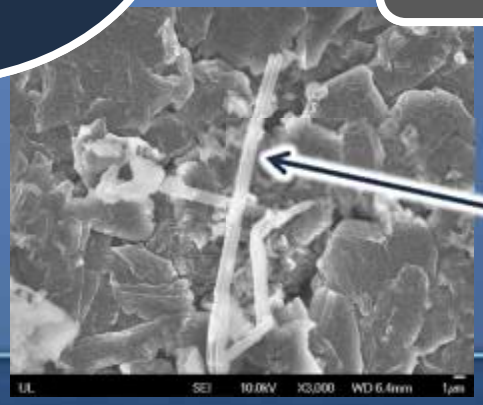
Dendrites Found at Wrinkles

Potential factors found in other types of cell have included



Dendritic material found



Magnified view shown on next slide

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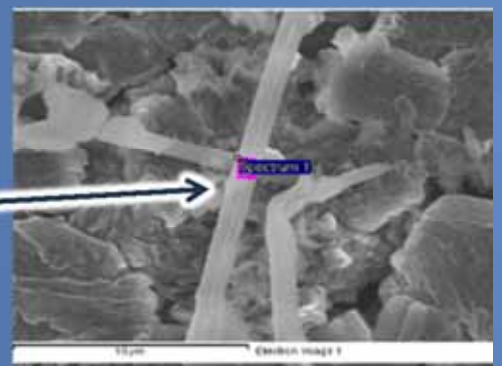
Elimination Indicates Dendrite is Lithium

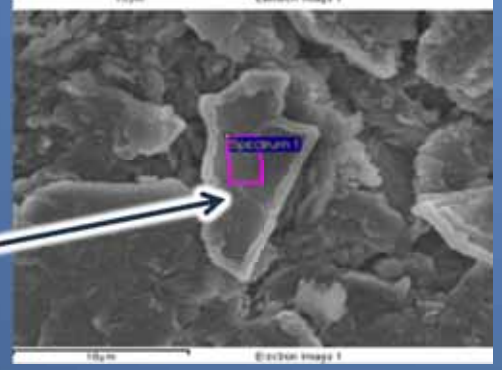
- EDX atomic number limited to ≤ 4, so can not directly state dendrite is Lithium
- EDX analysis on targets shown identify C, O, F & Cu
- Dendrite was very light in color and disappeared in air, so not carbon
- Elimination indicates lithium

EDX on the dendrite



Element	Weight%	Atomic%
C	53.23	60/72
O	43.57	37.31
F	2.54	1.83
Cu	0.66	0.14
Totals	100.00	

EDX of background material



Element	Weight%	Atomic %
C	39.49	47.10
O	55.66	49.83
F	3.74	2.82
Cu	1.11	0.25
Totals	100.00	

Note: Cold charging resulted in no thermal runaway in testing to date

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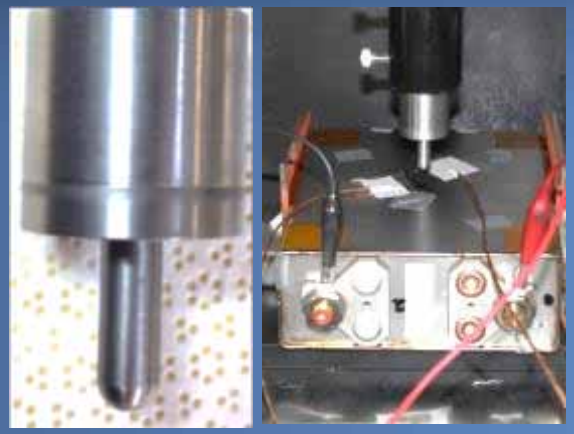
Tests and Results

Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

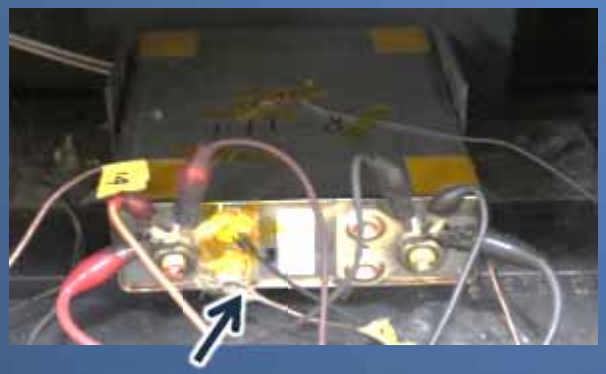
Cell Behavior Tested By Four Abuse/ISC Methods

UL Indentation Induced ISC test



Nail Penetration test

Hot Pad test



Heating source from 1 side

ARC Thermal Abuse test

Global heating by ARC system

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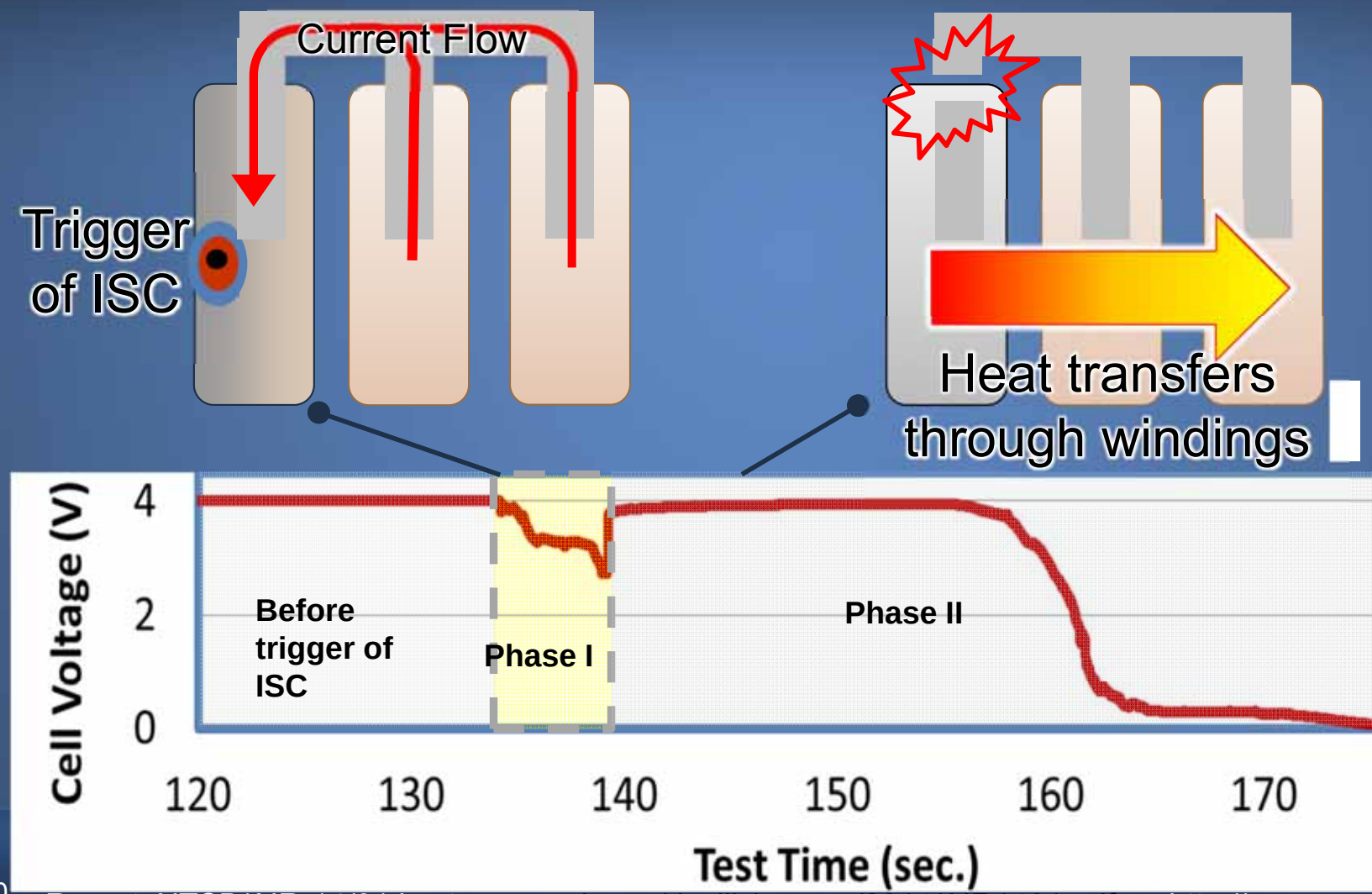
Cell Indentation Test (IIISC) in Slow Motion

Failure Sequence Through Cell Windings

W2 and W3 current into W1

Current from W2 and W3 melt W1 current collectors



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

50

Current Collectors Melt Nearest Initial ISC

One winding shorted first in:

- Hot pad test
- IIISC test
- Nail penetration test

Initial damage on this side

No collectors melted when cell was evenly heated in ARC test

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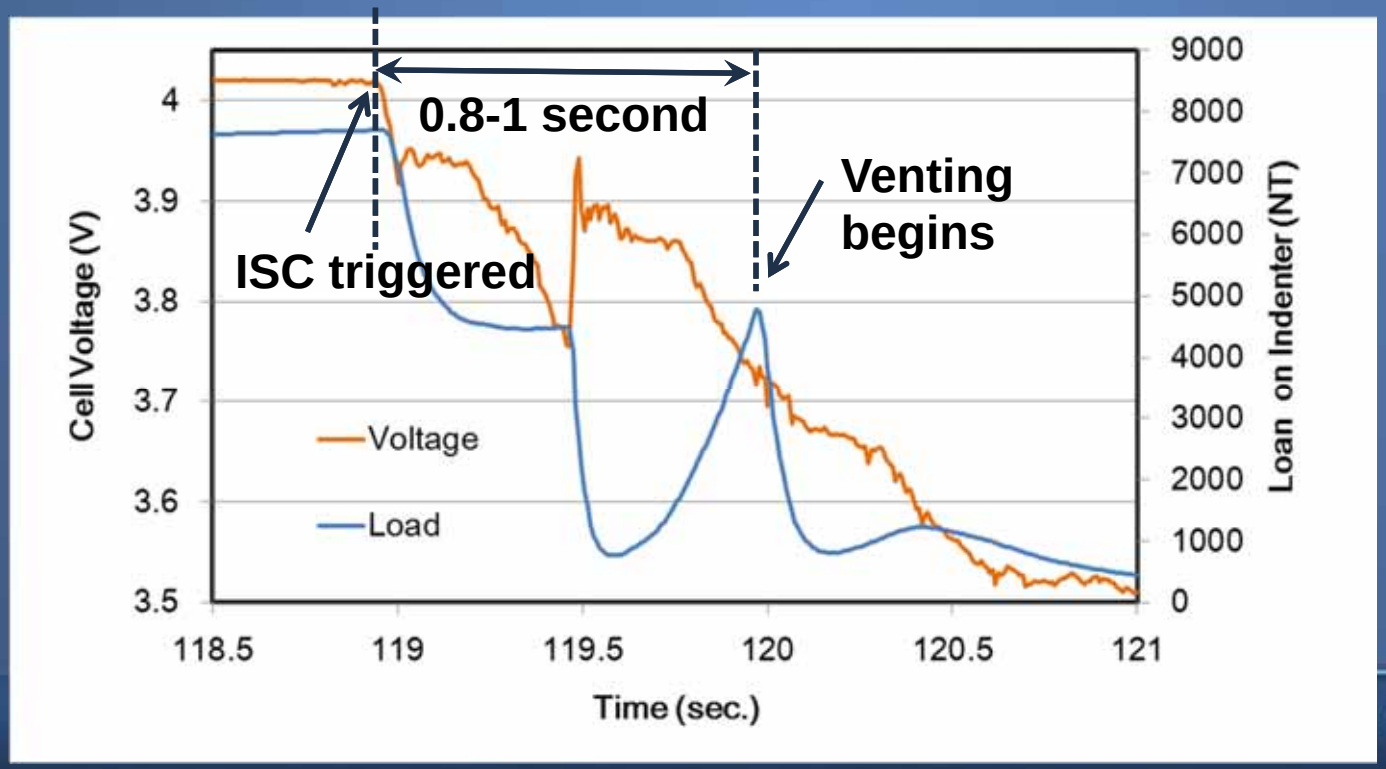
Ability to Respond to Impending ISC Identified

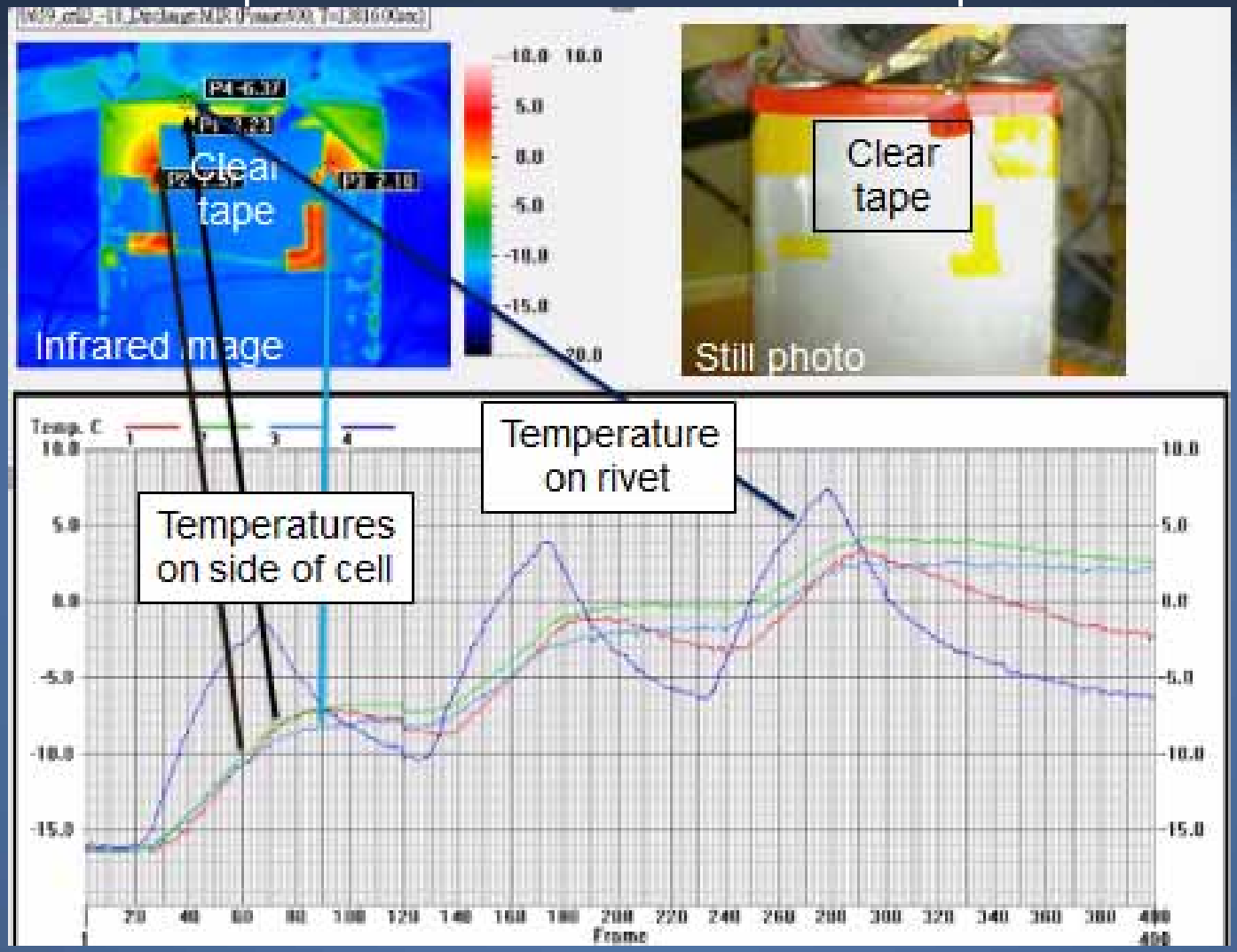
- Test cells were very slowly indented (0.1mm/sec) until open cell voltage (OCV) changed, then indentation stopped
  - Initial tests measured in 0.1 volts vented almost immediately
  - Halting indentation at 20 mV provided 0.8-1 second recognition
- Mitigation could isolate failing cell from energy of other cells in pack, allow cooling, or other potential responses



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

APU start – Cell Level Thermal Imaging

Substantial temperature differences between sample locations



Dark blue line is cathode rivet temperature with highest temperature reading

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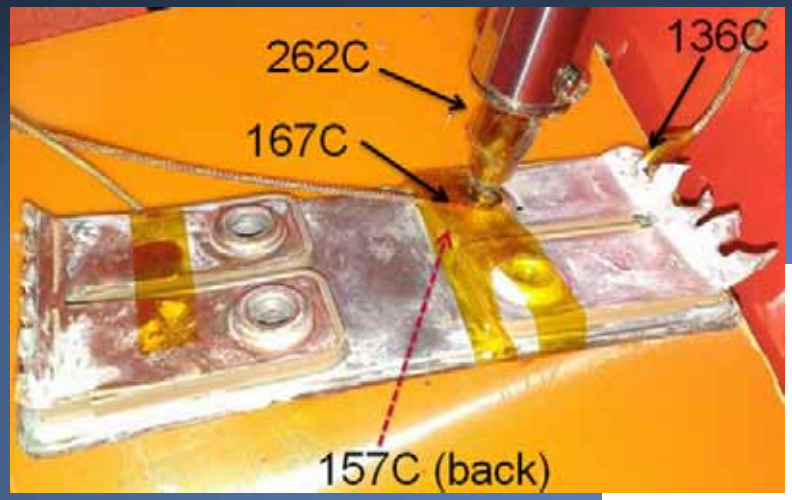
Temperature Variations in Cell

A soldering iron was used to increase rivet temp to 157°C, as found in battery test.

Thermocouples revealed range of temperatures



157°C, top of rivet, as in battery discharge

136°C Current collector

167°C bottom of rivet

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Two Temperature Sensors

Not located at points of most vulnerability

Temperature sensor on bus bar
(1 of 2)

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Battery and System Tests

- Battery failures initiated with control of:
  - Starting temperatures,
  - Electrical ground,
  - Initiation method (nail or hot pad)
- Data capture of numerous parameters, including:
  - High speed visual
  - Temperature by both infrared and thermocouple
  - Smoke particle and gas constituents,
  - High frequency electrical emissions,
  - Cell voltages,
  - Electrical currents,
  - BMU states and signals,
  - Etc.

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ISC in Full Battery Ejected Hot Material and Melted Ground Wire

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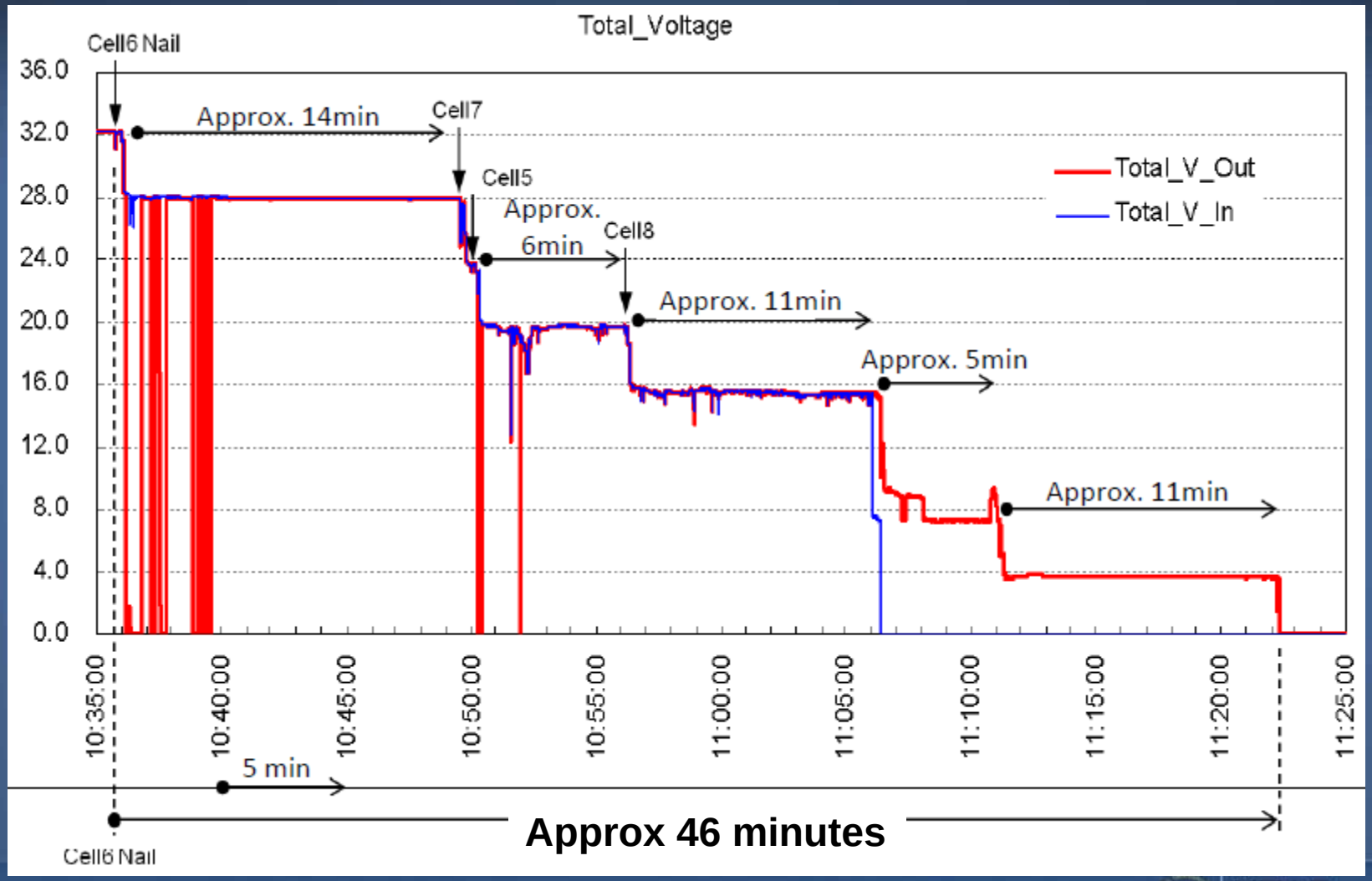
Example of Cell Voltages Decay in Test

(Source: JTSB report AI2014-4, September 25, 2014)

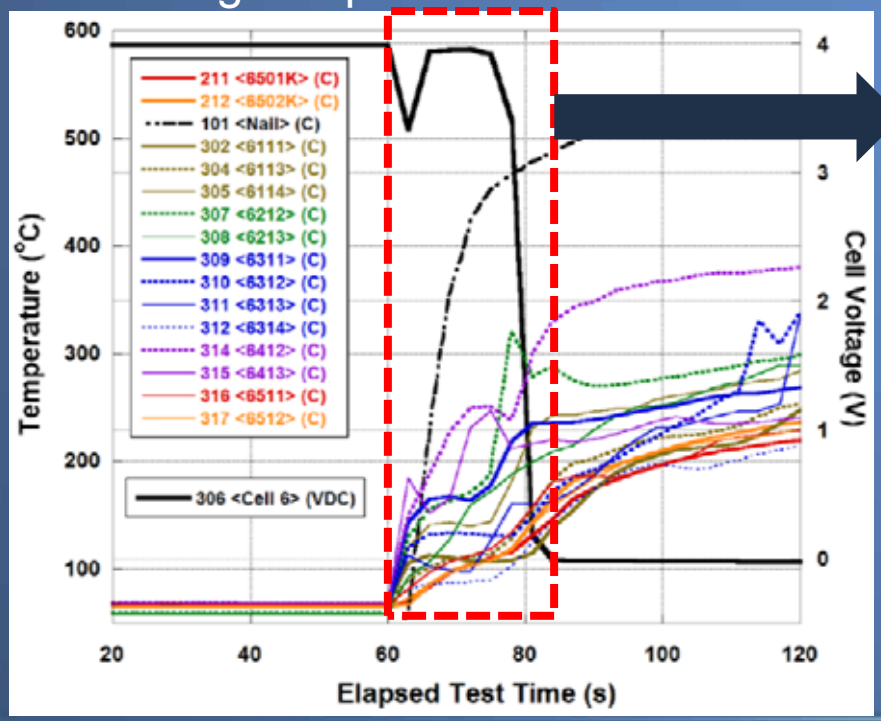


Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

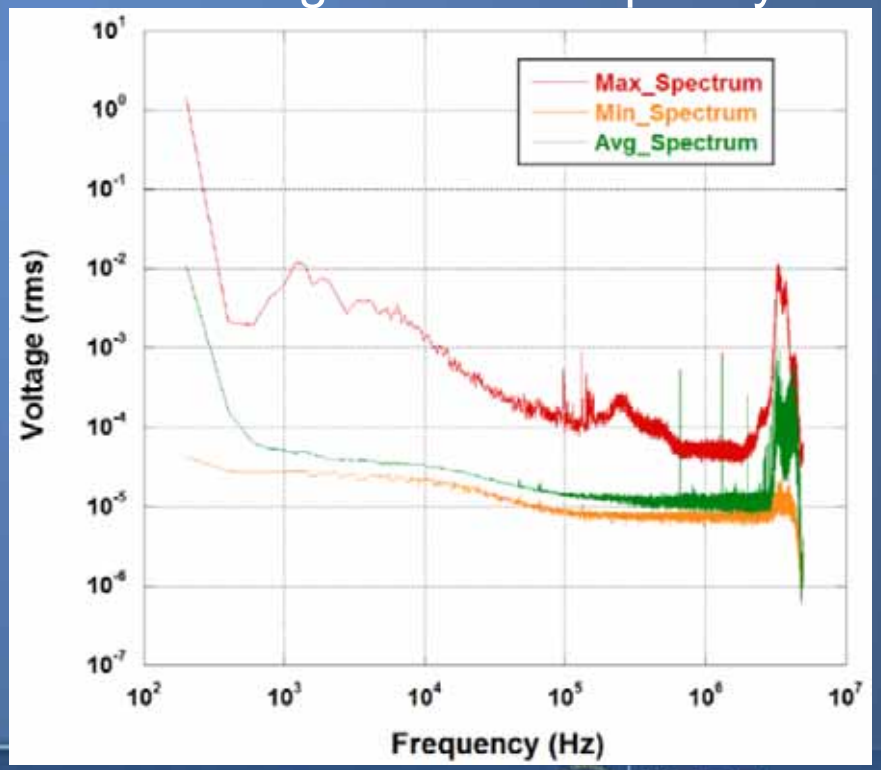
Broad Frequency Transients in Voltage

- Thermal runaway results in broadband energy releases
- Some cell discharge spikes exceeded 100% cell State of Charge.
- Typical digital avionics frequencies within this range

Voltage and temp data from cell 436-6 during nail penetration test at 70°C

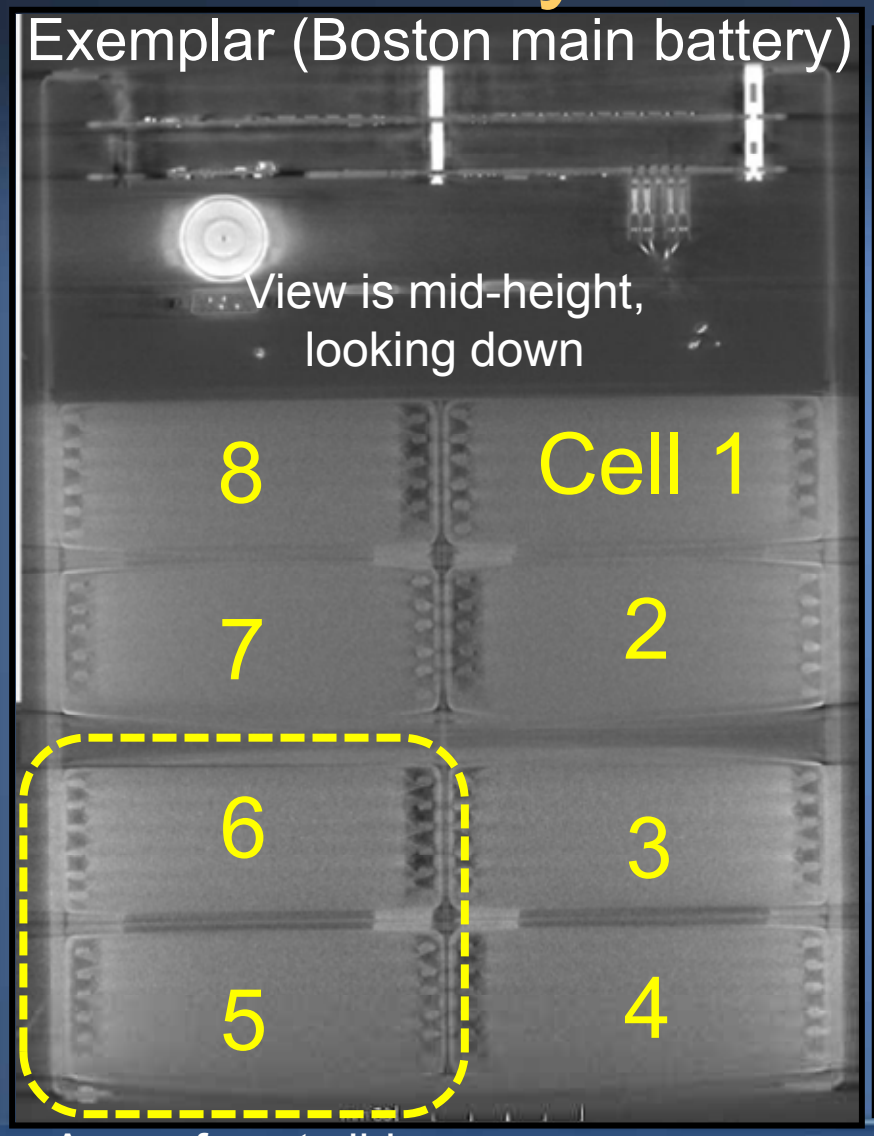


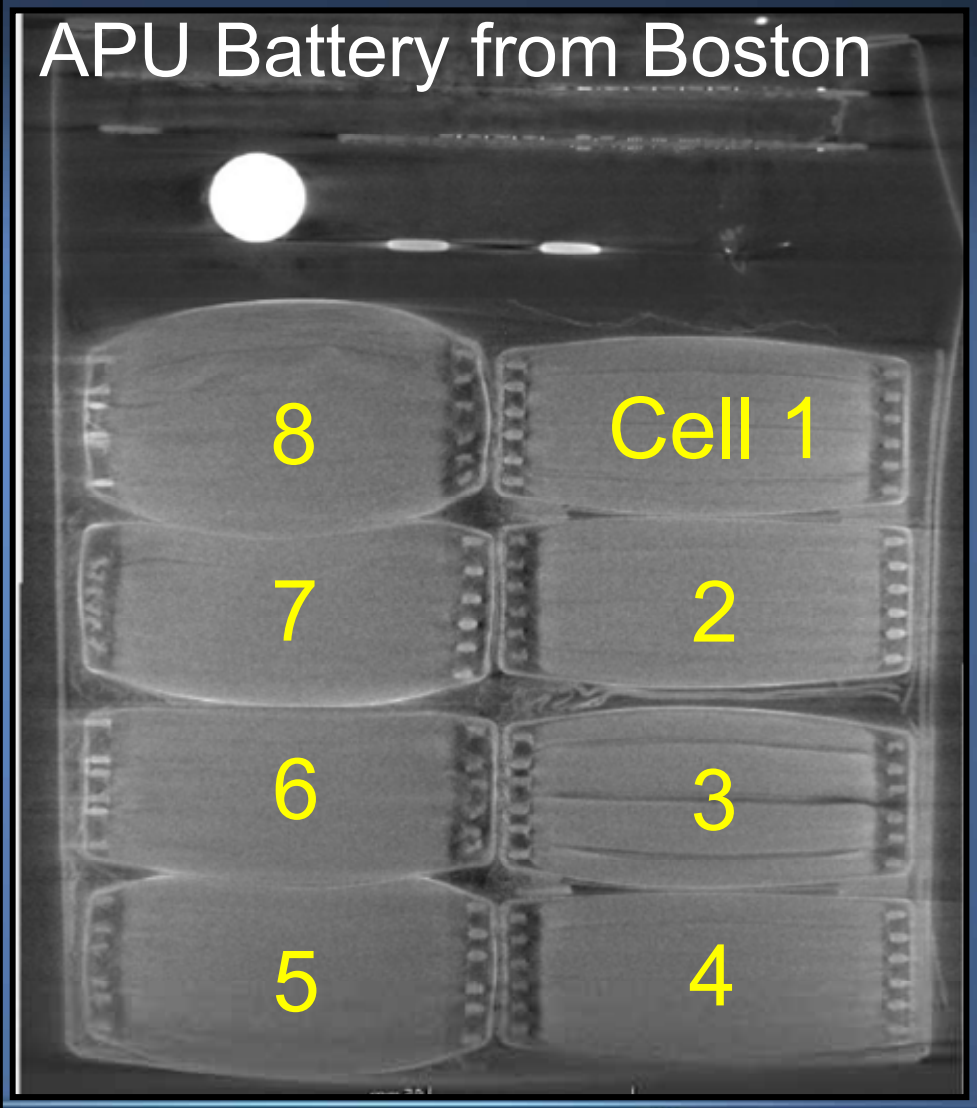
Voltage versus frequency



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Full Battery CT Images





Area of next slide

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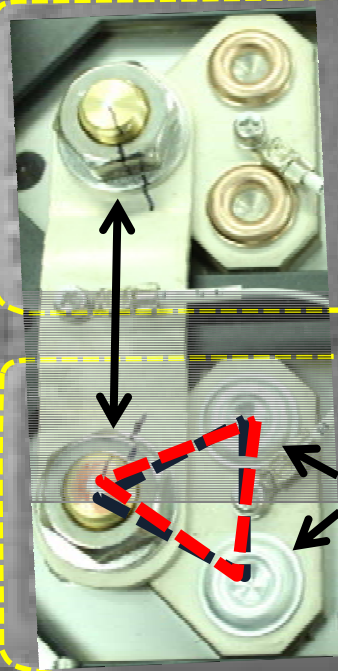
Strain On Cells And Rivets

Cell dimensions and strain change with charge and temperature

Potential strain on rivet seals

CT view is mid-height, looking down



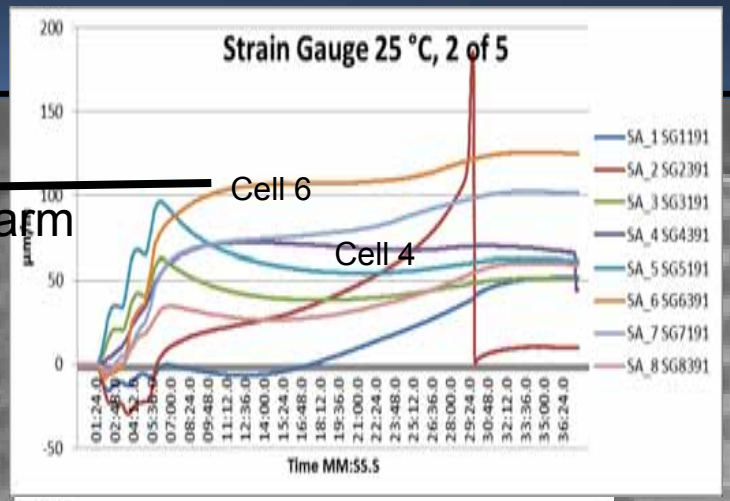
Most strain when warm

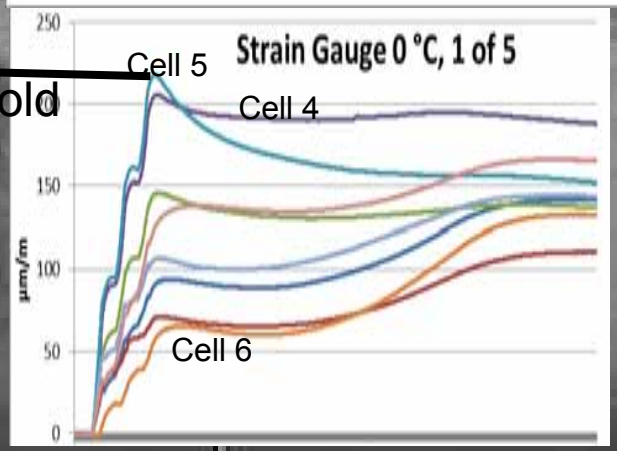
Cell 6

Most strain when cold

Rivets

Cell 5





Cell and box walls displaced at full charge

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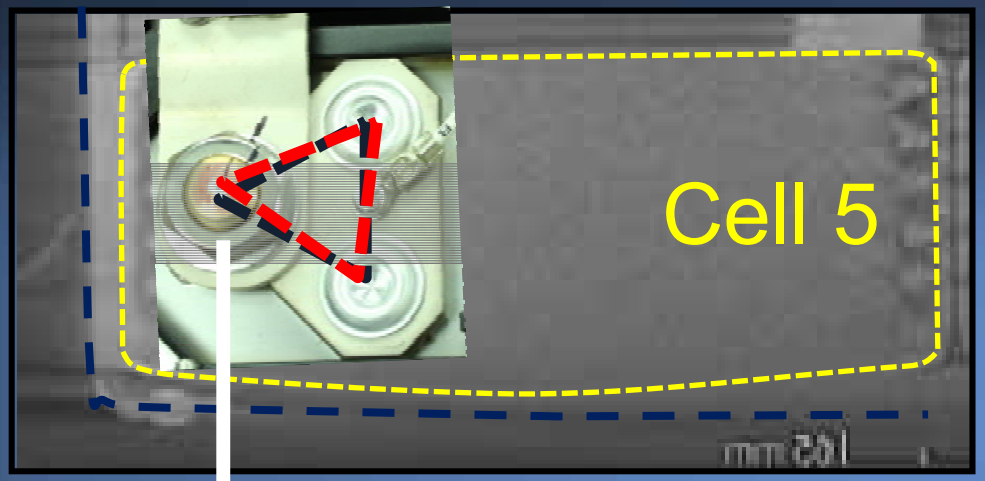
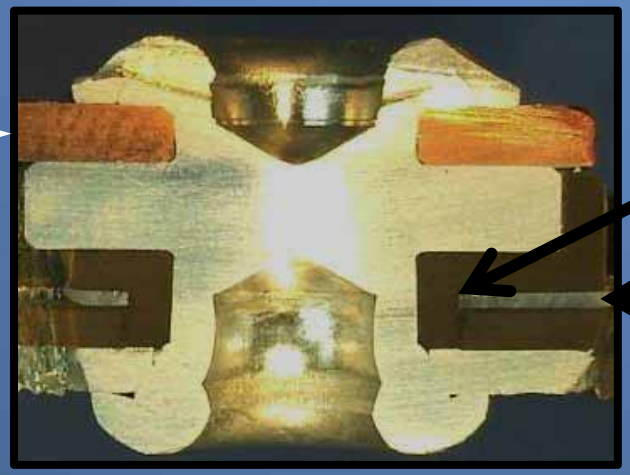
Strain On Cells And Rivets



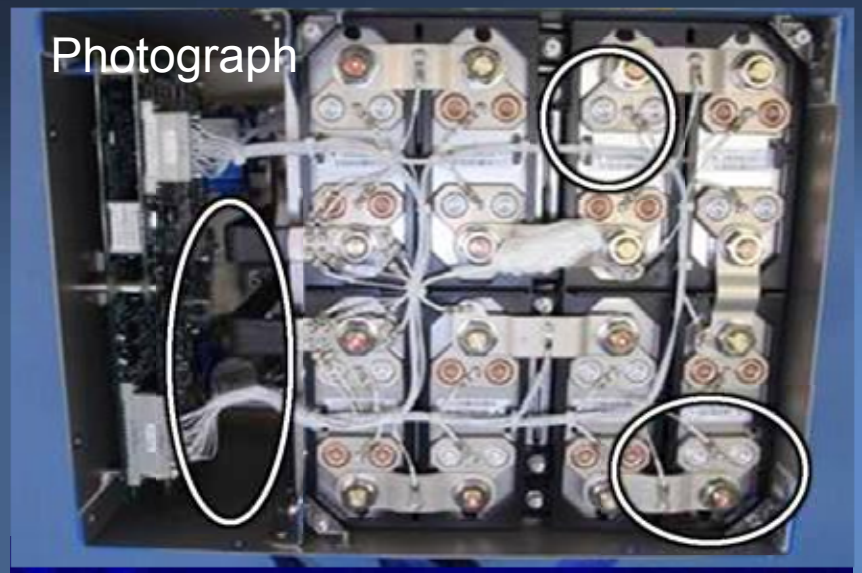


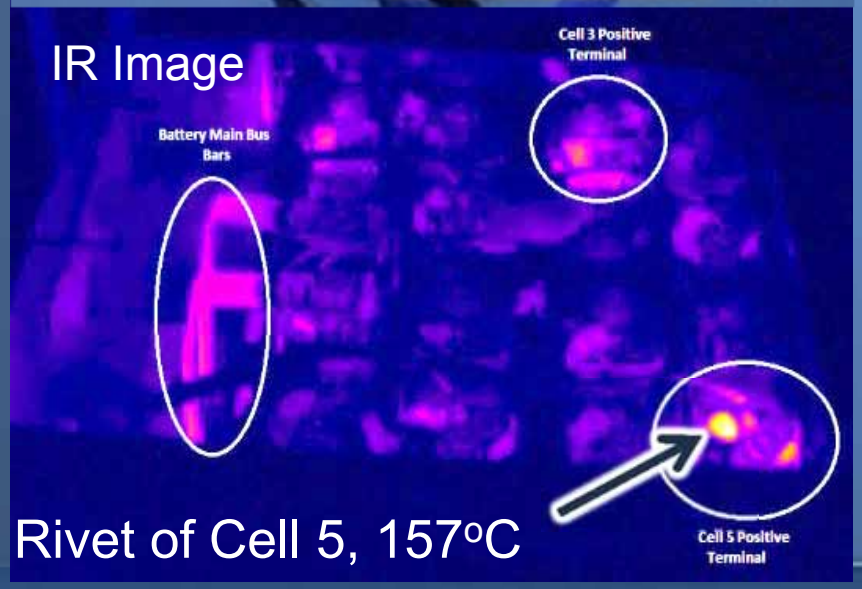
Plastic Rivet Seal and Insulator

Top of cell

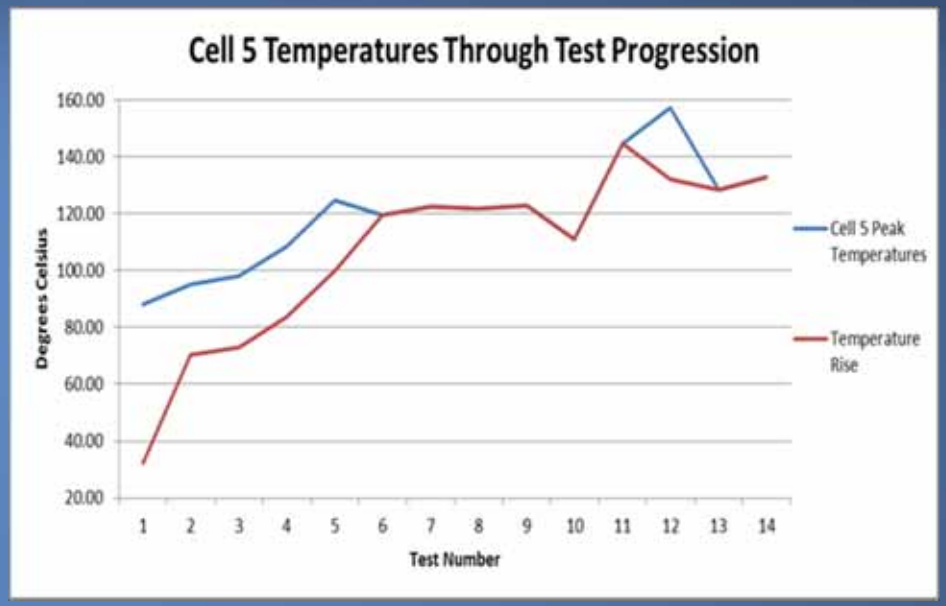
 Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Rivets Heated in APU Start Test Sealing





Rivet temp increased during a series of start cycles



Battery passed initial test cycle.

Each cycle was 3 APU starts at Boeing specified max power followed by return to ambient temp before next cycle

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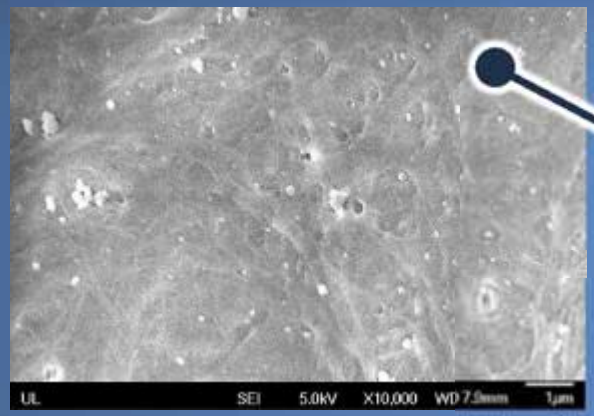
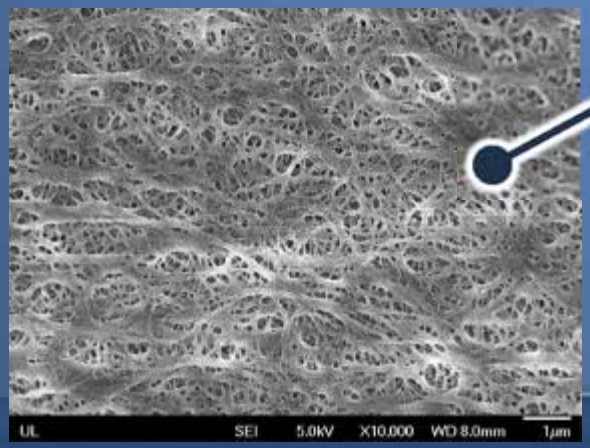
Separator Found Partially Melted

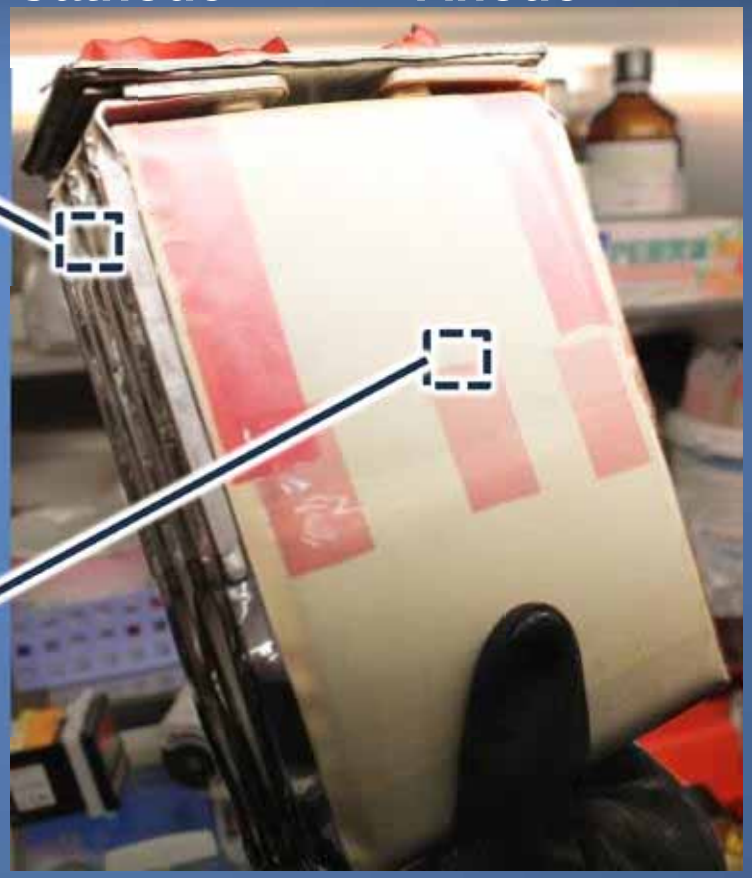
Following APU Start Test

Melted separator at edge of center winding next to collector finger



Intact separator material





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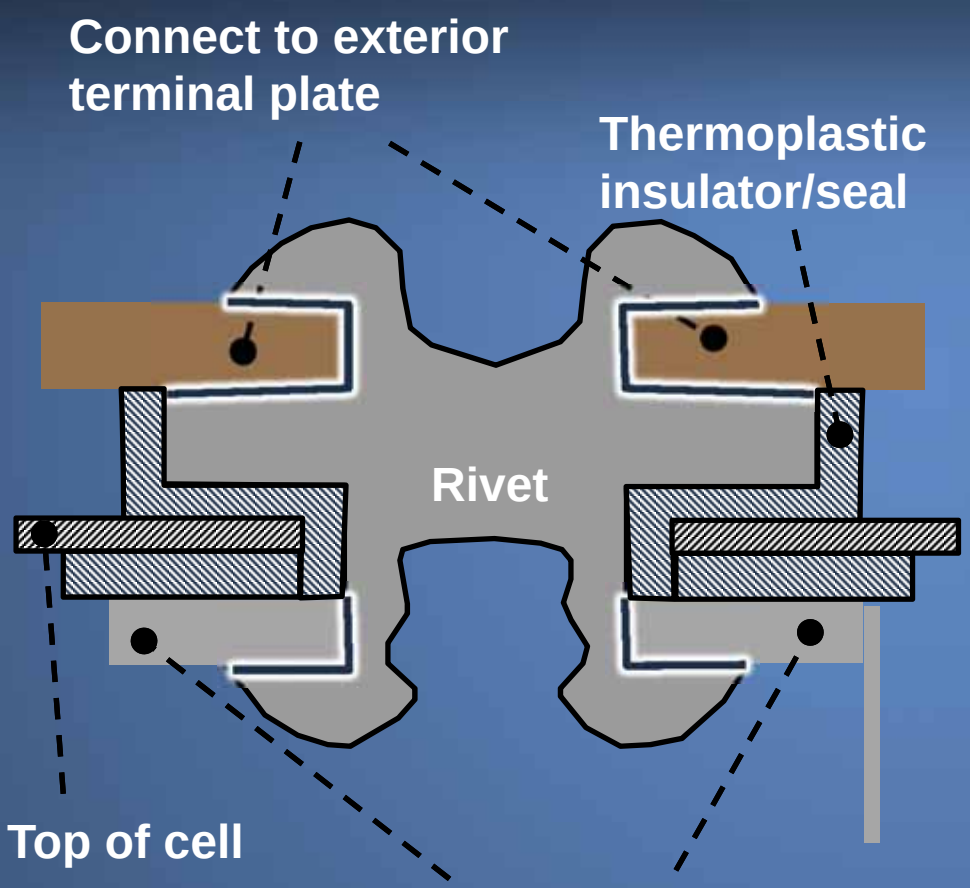
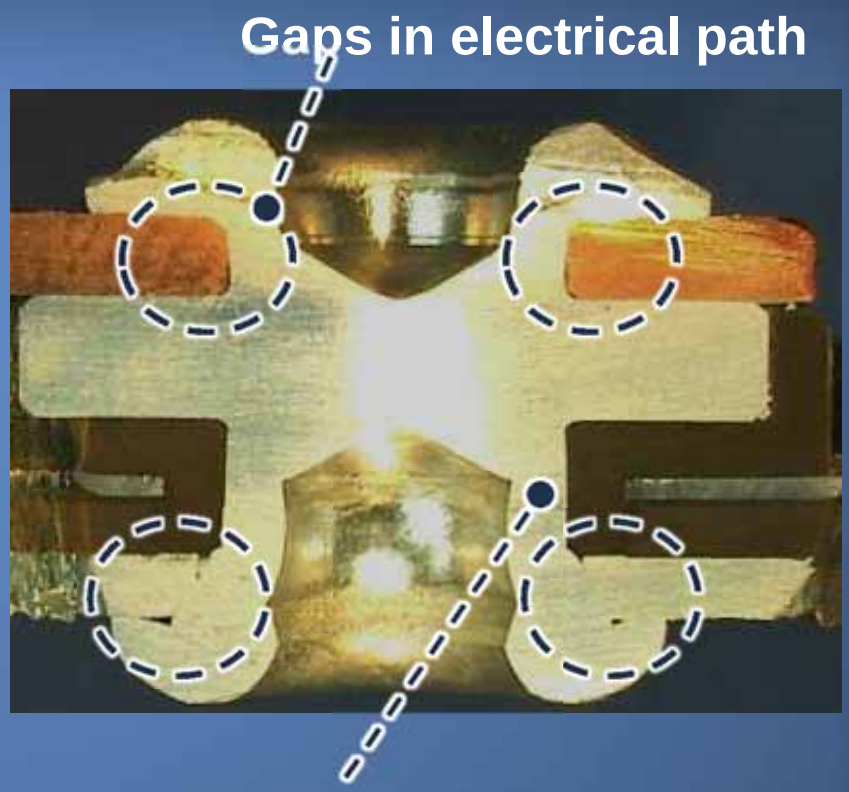
Rivet Gaps, Heating, Seal Leakage





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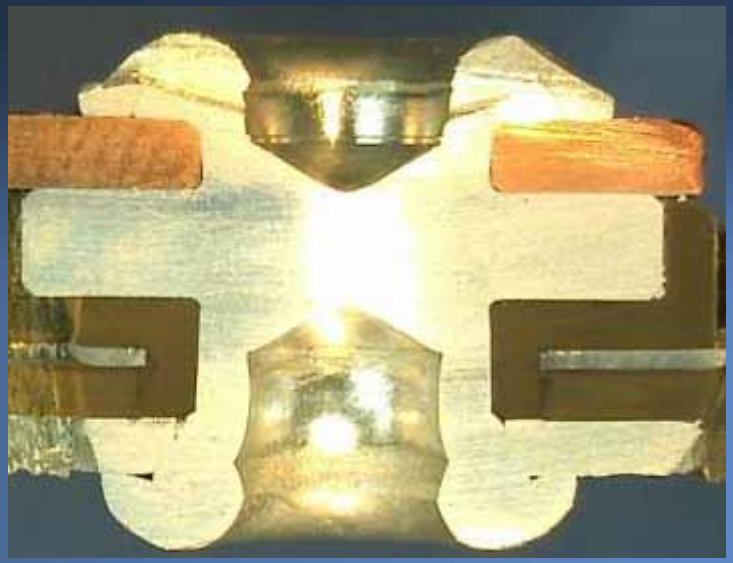
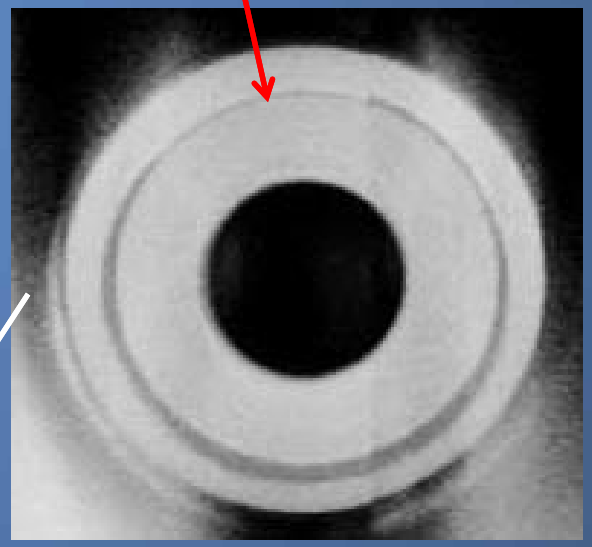
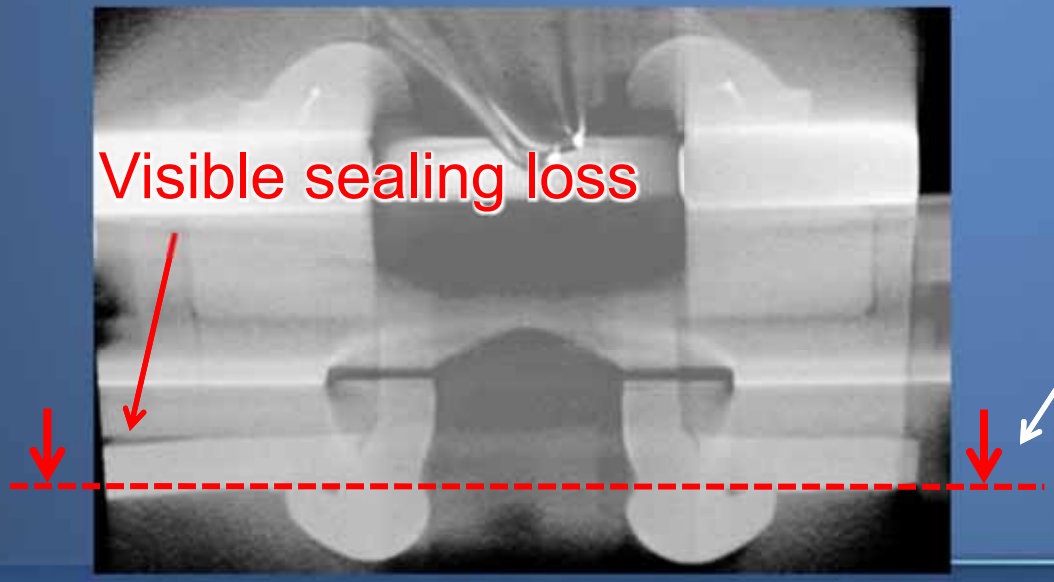
Rivet Gaps, Heating, Seal Leakage



Small contact area that may cause localized high resistance heating





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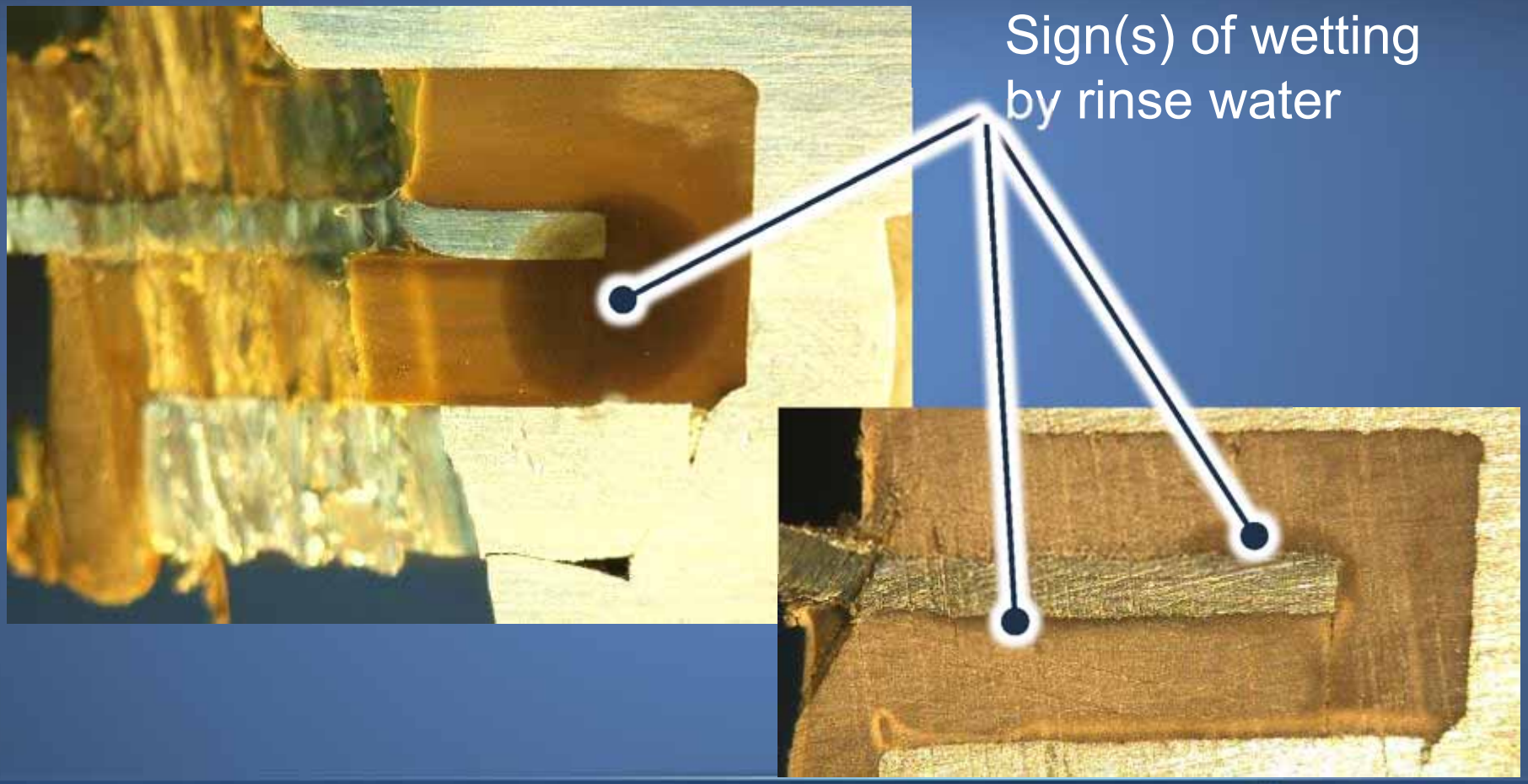
Seal Leakage Path

Trapped rinse water after cutting made leakage path visible



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Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

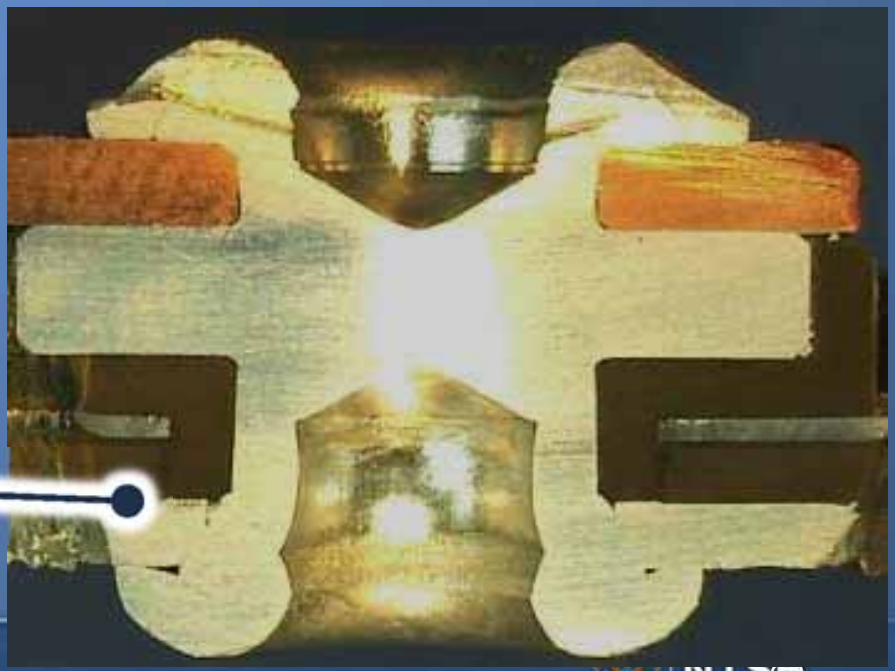
Rivet Joint Clamping Force

Specifications:

Boeing's battery specification: "The terminal attachment shall have a complete metal-to-metal compression system"

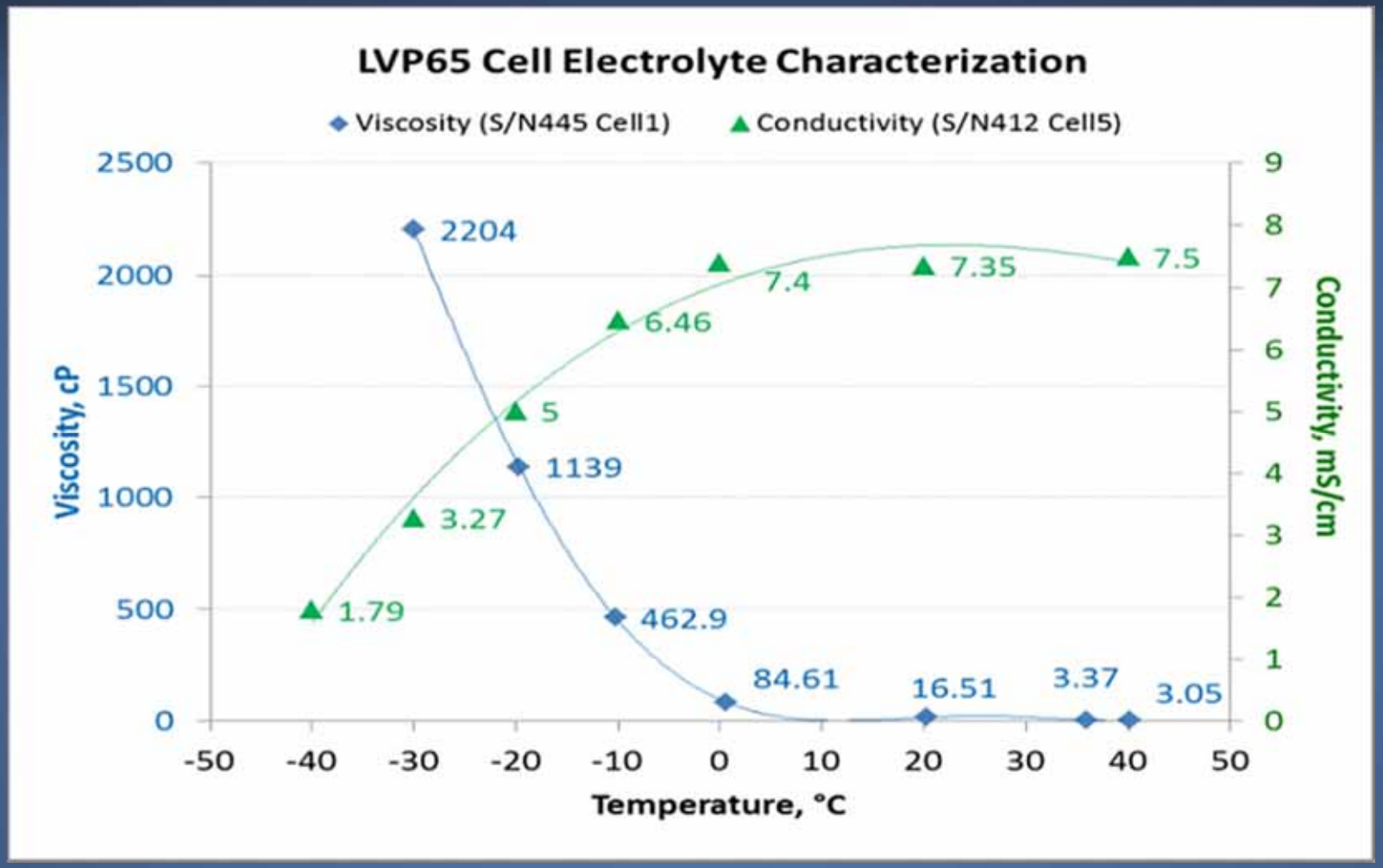
Similar call-outs in NASA Technical Standard, NASA-STD-4003A, UL Standard 857, and others

Finding:
No Belleville washers or other devices were found to prevent reduction of clamping force



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

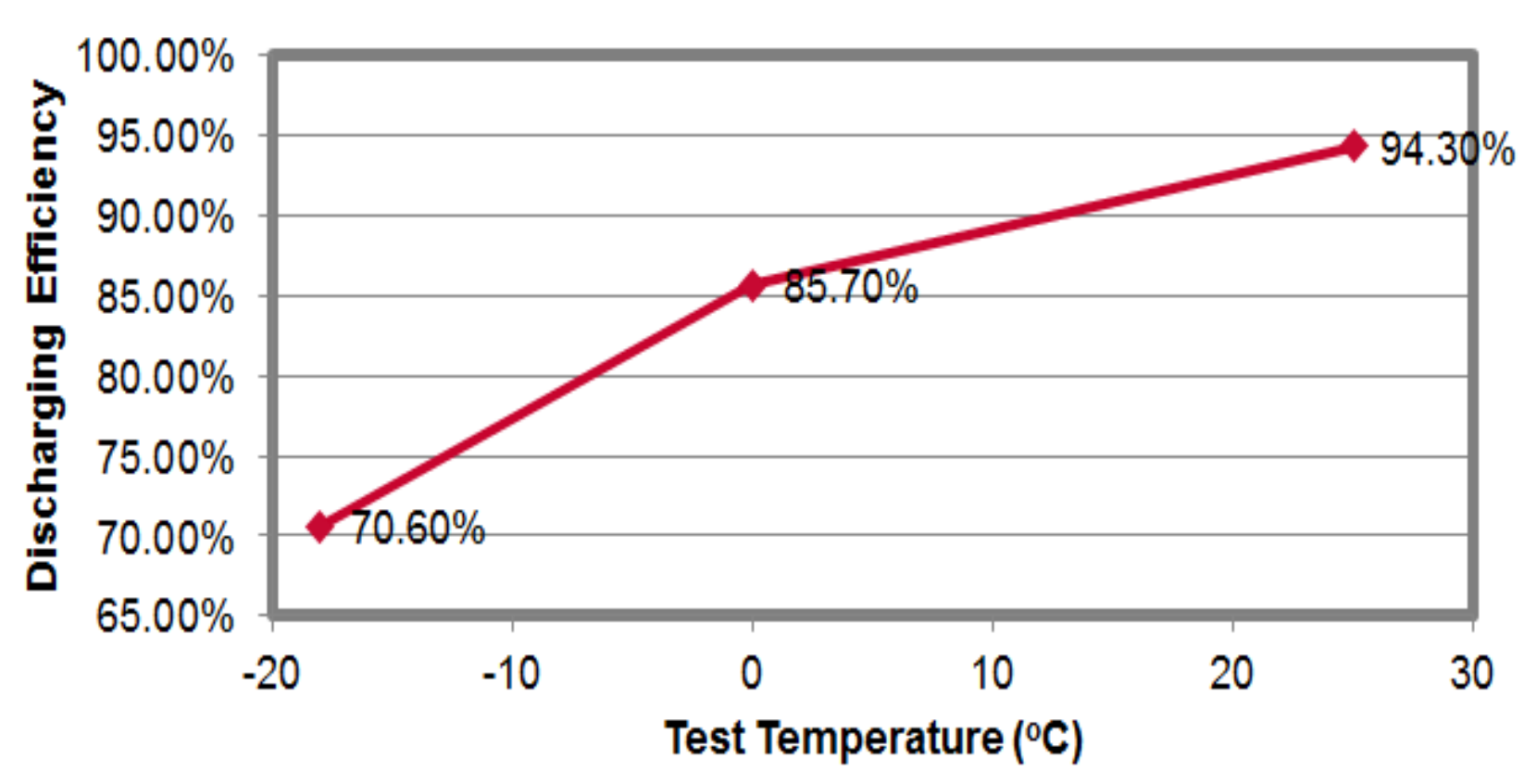
Electrolyte Related to Temperature and Heat Generation Within Cell



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

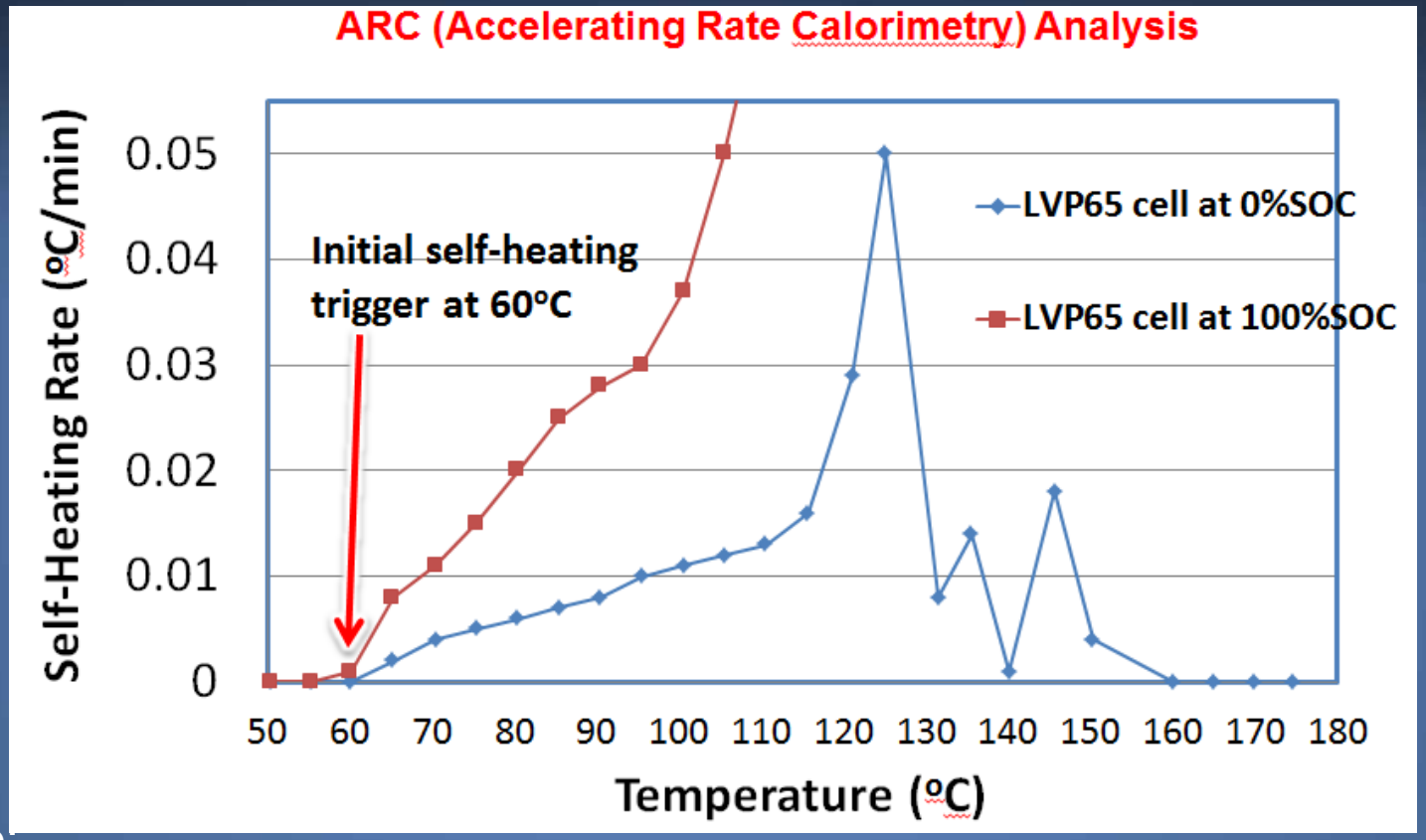
Discharging Colder Cells Resulted in Additional Energy Becoming Heat

30% of discharge energy becomes heat within cell at -18C during maximum discharges



Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Cell Thermal Stability and Self-Heating



Note:

1. The accuracy scale according to the calibration data is 0.01ºC/min
2. 0.02ºC/min is usually the setting of threshold to trace the self-heating on test sample. However, it can be set as low as 0.01ºC/min minimum.
3. The resolution of temperature reading of the system is 0.001ºC

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Summary of Key Findings With UL

- Aluminum rivets as part of electric path loosened, heated, and seals leaked
  - Rivet design had no retention of clamping force
- Separator melted in testing
  - Thin rivet shank cross-section resistively heated
  - Loosened joint of collector to rivet resistively heated
- Cold electrolyte decreased conductivity, increased heat during discharge
- Self-heating began within operating range (-18°C to 70°C)
- Winding wrinkles found with dendrites

NTSB

Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Summary of Key Findings With UL (Continued)

Failure Mode Findings From Cell Abuse Tests:

- ISC starting in a single winding melted current collectors
- General overheating did not melt current collectors
  - Thermal runaway from overall heating did not melt aluminum. Internal short circuits did.
- Radio frequency emissions found during runaway could be a potential issue for digital electronics
- Measuring at millivolt level found time to potentially mitigate thermal runaway (TR)
  - 0.84-1.0 second time between 20 mV drop and thermal runaway

NTSB

 Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

General Battery and Cell Findings Include

- Multiple design and manufacturing issues
- Cells create heat when discharging at cold temperatures
- Two sources create heat at rivets
  - Separator melted in test exhibiting hot rivet
- Thermoplastic rivet seals developed leaks
  - Potential for grounding cell to battery case
- Foreign material in cells
- Cells at rear of case had highest strain
- Wrinkles developed in cells
  - Dendritic formations at edges of wrinkles result in cell fade
- Charger current oscillations not a factor
- Usable battery and cell characteristics during runaway
- Insufficient temperature and voltage monitoring

NTSB

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Investigation and Test Results

2006 GS-Yuasa test

Release of electrolyte and smoke

Safety recommendation letter to the FAA on May 22, 2014:

- Certification requirements
- Developmental testing
- Accounting for ISC and thermal runaway in certification tests,
- Lithium-ion battery issues
- FAA introduction of new technology into aircraft

NTSB

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Probable Cause

The National Transportation Safety Board determines that the probable cause of this incident was an

internal short circuit within a cell of the auxiliary power unit (APU) lithium-ion battery, which led to thermal runaway that cascaded to adjacent cells, resulting in the release of smoke and fire.

The incident resulted from Boeing's failure to incorporate design requirements to mitigate the most severe effects of an internal short circuit within an APU battery cell and the Federal Aviation Administration's failure to identify this design deficiency during the type design certification process.

Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Investigation Results

- Investigation complete and NTSB report is in public docket
- Multiple potential causes for cell internal short circuit
  - Each is being addressed for existing and future designs
  - 23 safety recommendations include:
    - **To FAA:** approach to new technology, certification process, certification requirements, basis of key assumptions and validation, oversight of manufacturers and suppliers, engineer training, requirements for new standards
    - **For designers:** BMU monitoring of temp and voltage at cell level, data retention, identification of individual heat sources and impact, adoption of industry design standards, worst case testing/validation at aircraft level, data recorder improvements,
    - **Future research needs:** development of new design and safety standards, cell isolation/mitigation, battery failure impact on digital avionics

NTSB

Report: NTSB/AIR-14/01 is at www.ntsb.gov/doclib/reports/2014/AIR1401.pdf or http://go.usa.gov/HJtJ

Questions?

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And at http://go.usa.gov/HJtJ

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