Lithium Ion Battery Safety
How Agencies and DoD Assess and Mitigate Hazards

SAFETY & HEALTH LEARNING ALLIANCE

Dial 1-844-467-6272 for audio and enter passcode 674294#

NSC
NASA SAFETY CENTER

SAFETY & HEALTH LEARNING ALLIANCE

Event Logistics

- Facilitator: Mike Lipka, Knowledge Management Officer
  NASA Safety Center
- The webinar will last approximately 2 hours
- To ask a question: Type your question in the chat box
- To get a closer look at the slides, select “Full Screen”
- Turn off the speakers and microphones on your computer
- NASA employees receive training credit in SATERN

NSC
NASA SAFETY CENTER

SAFETY & HEALTH LEARNING ALLIANCE

Agenda

- Goals of the Safety and Health Learning Alliance
- Today's Panel Speakers
- Discussion and key points
- Wrap-up and next event

NSC NASA SAFETY CENTER

SAFETY & HEALTH LEARNING ALLIANCE

Goals of the SHLA: The Four C's

- **COLLABORATE** Create an open forum for collaboration
- **CONCENTRATE** Accelerate learning by connecting people to people
- **CONTEXT** Learn from your peers about how and why
- **CONNECT** Establish networking opportunities

Learn more at https://nsc.nasa.gov/SHLA

NSC NASA SAFETY CENTER

SAFETY & HEALTH LEARNING ALLIANCE

Today's Panel Speakers

- **Bob Swaim**
  - National Resource Specialist, Aerospace Engineering Investigator
  - National Transportation Safety Board

- **Tamera Tucker**
  - High Energy Storage Systems Safety Program & Certification Authority
  - US Navy (NAVSEA)

- **Larry Valencourt**
  - Safety Engineer
  - US Army (CECOM) (Ret)

Today's Panel Speakers Cont'd

- **Penni Dalton**
  - ISS Battery Subsystem Manager
  - NASA Glenn Research Center

- **Eric Darcy**
  - Battery Technical Discipline Lead
  - Johnson Space Center

- **Mike Milbert**
  - Quality and Safety Analyst, Electrical Safety Subject Matter Expert
  - NASA Safety Center

SAFETY & HEALTH LEARNING ALLIANCE

Wrap Up and Next Event

- NASA employees receive training credit in SATERN
- Visit the SHLA Web site at nsc.nasa.gov/SHLA
  - Video of this presentation, slides, event summary
  - Submit ideas for events
- SHLA Event Survey: We'd like to hear your feedback

NSC NASA SAFETY CENTER

National Transportation Safety Board

787 Battery Investigation Summary

Robert Swaim

Airworthiness Group Co-Chairman, NTSB

787 Has Two Main Batteries

As originally installed

Auxiliary Power Unit (APU) Battery

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

Interchangeable With 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**.

Other lithium-ion batteries for flight Control backup, RIPS, ELT, emergency exit path lighting, EFB

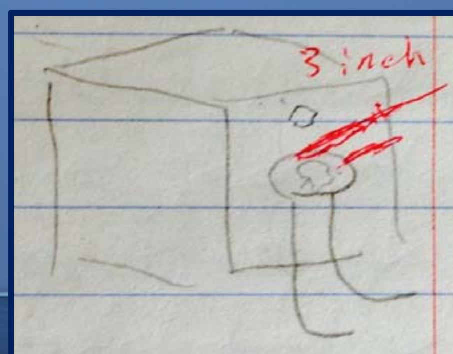
2006/07 Design Based In Evolutionary Predecessors

Examples of more than 11,000 LIM and LEV vehicle and industrial cells with no issues:

787 incident at Boston, 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



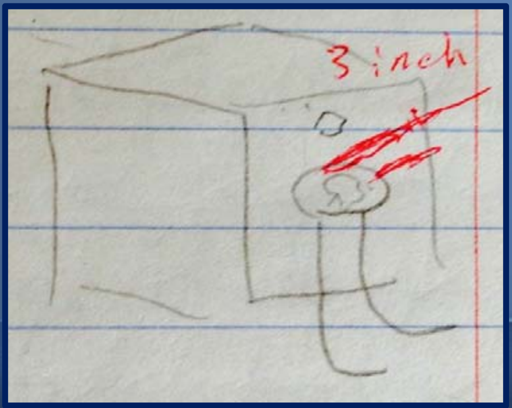
Sketch by mechanic who saw flame

NTSB

External Case Damage

Burned connectors at front of case

"Protrusion" melting at back of case

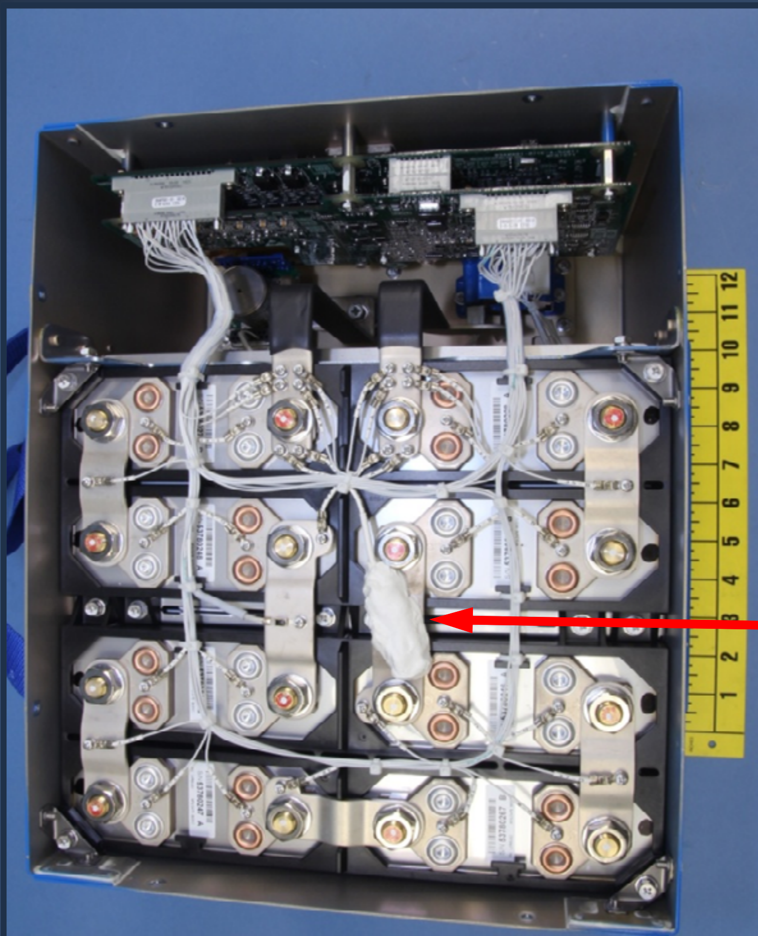


Sketch by mechanic who saw flame

Exemplar and Extent of Thermal Damage

Exemplar (Boston Main Battery)

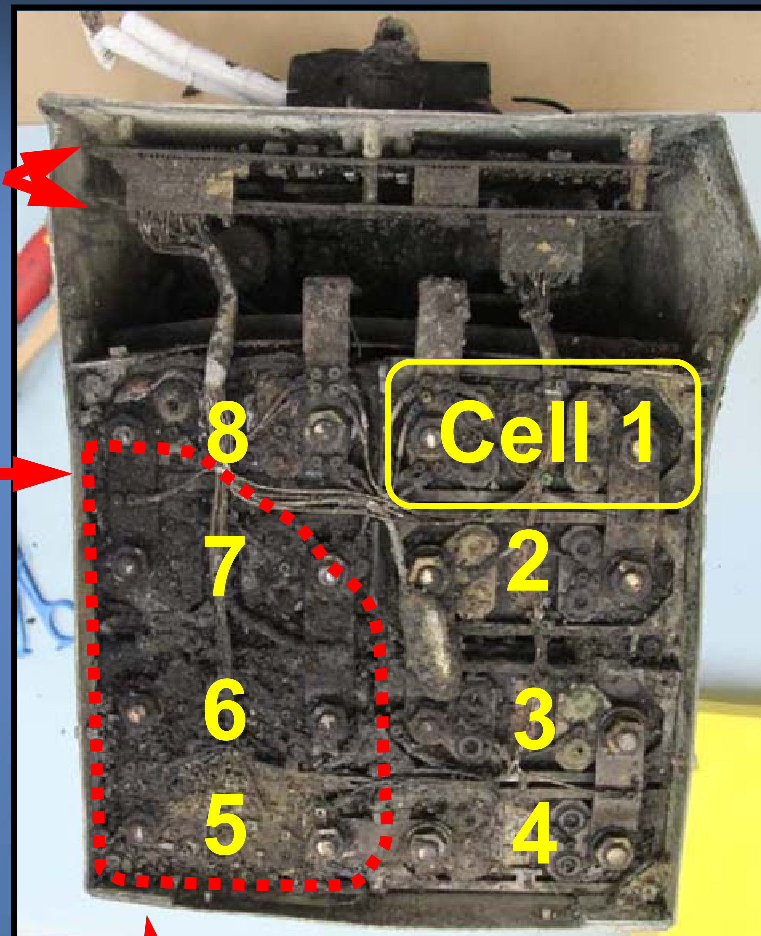
Boston APU Battery



BMU Cards

Area of most thermal damage

Temp sensor (1 of 2) on bus bar



(Boston Main Battery)

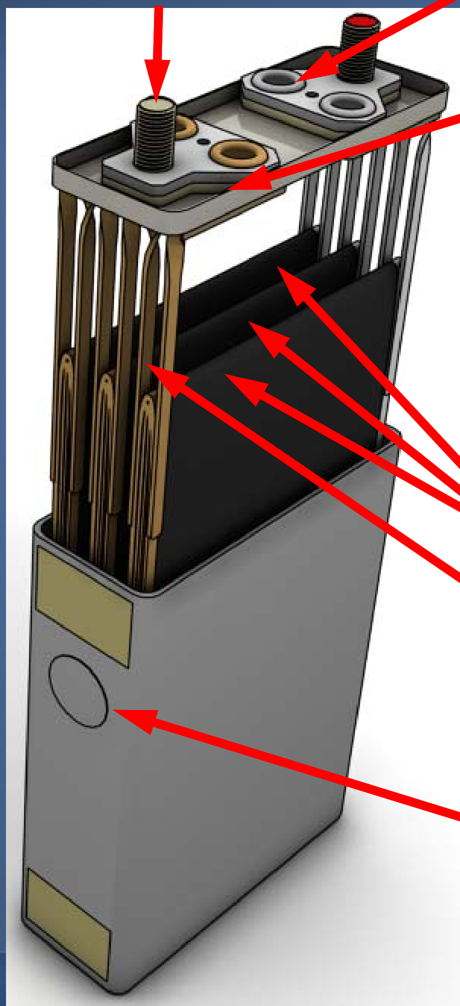
Protrusion

NTSB

1Apr15

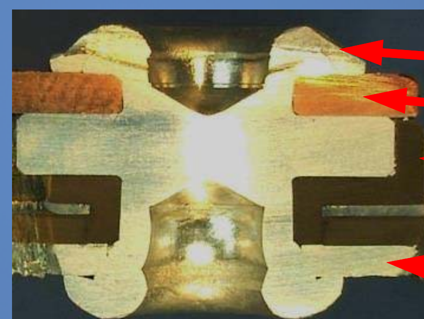
Configuration of Each Three Winding Cell

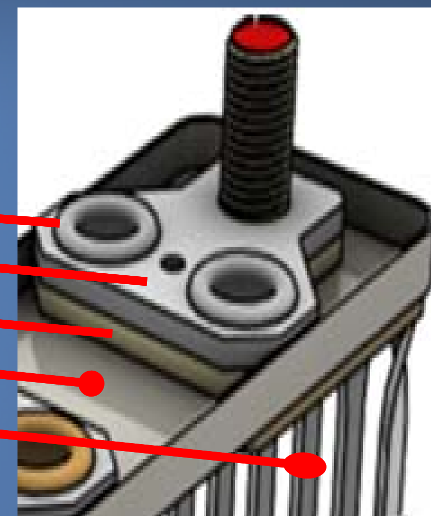
Threaded terminal lug



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 pressed into stainless steel case

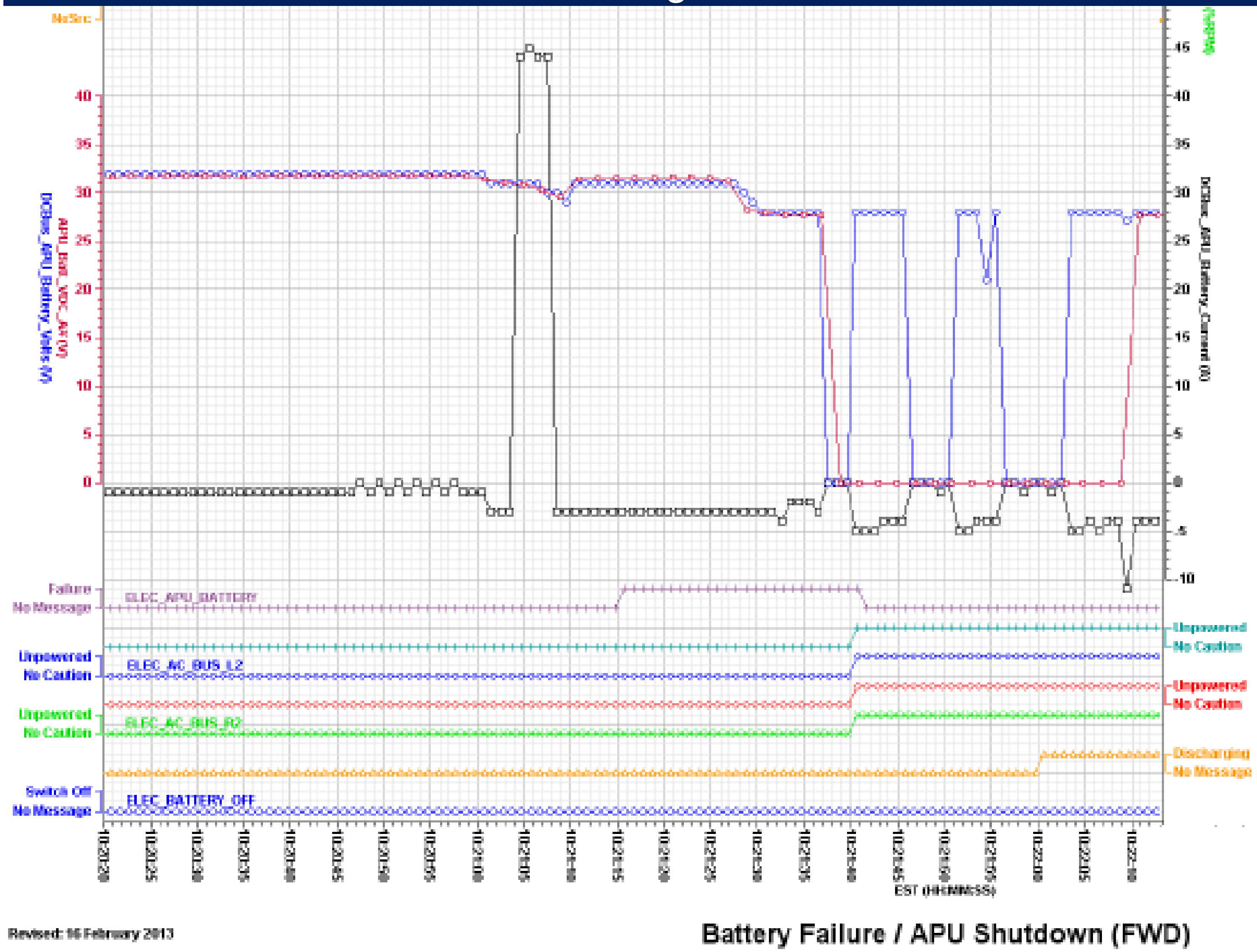
NTSB

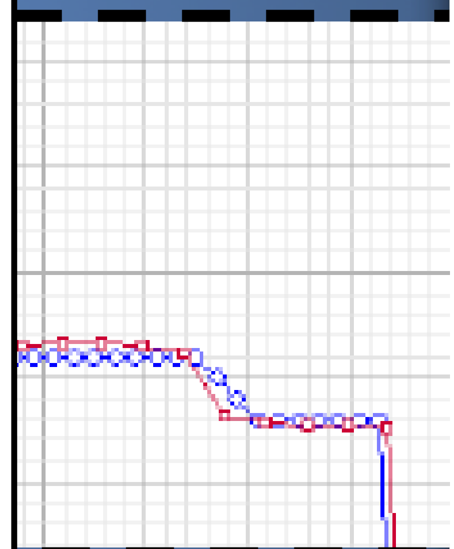
1Apr15

FDR Data Showed Initial Voltage Loss

Voltage of a single winding in a single cell

Took about 45 minutes for all eight cells to vent



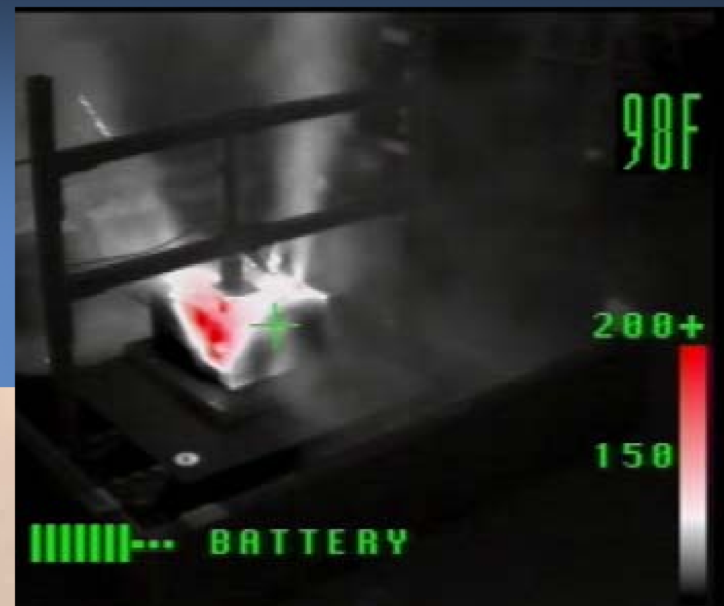


NTSB

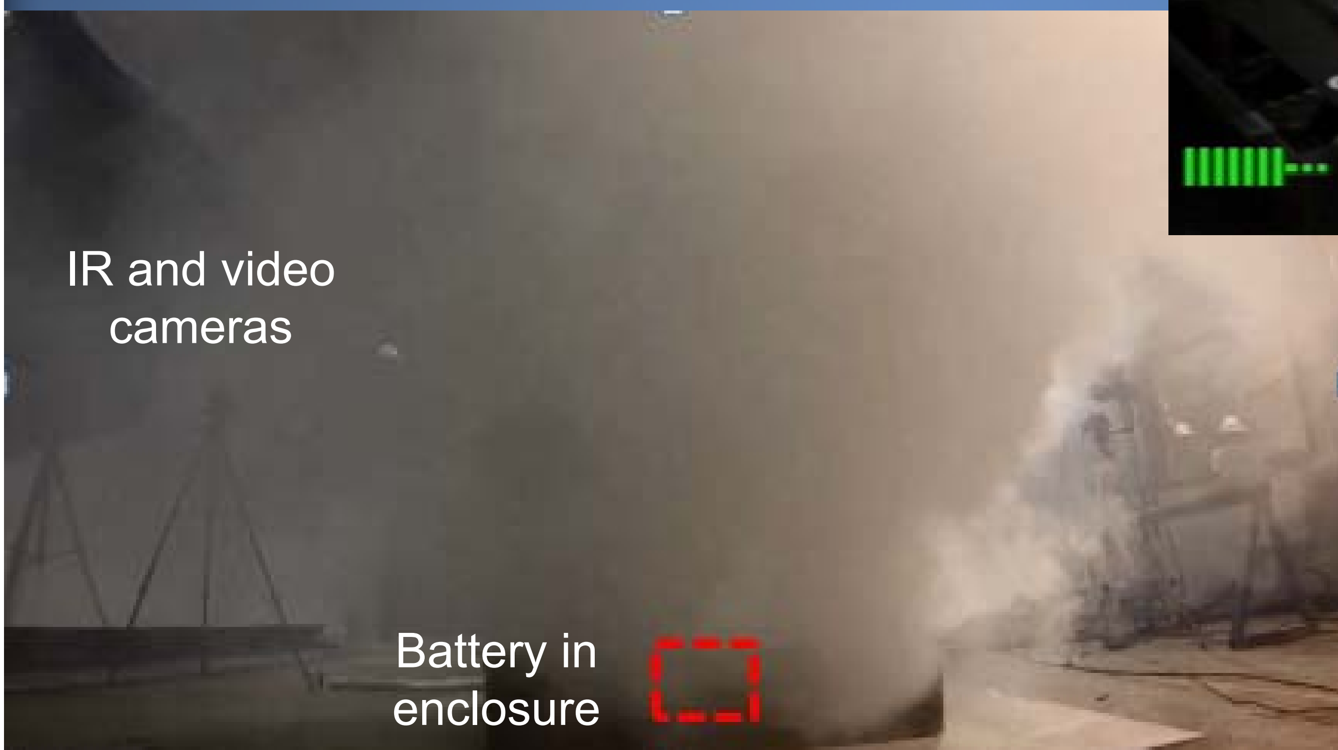
Hazardous Smoke Output of 787 Battery

Amount of smoke output from a single cell of battery test in UL lab nail test (below)

Sampling found acidic electrolytic smoke is hazardous to breath, potentially flammable, and highly corrosive.



IR image shows jets of venting electrolytic smoke and ejecta



Single 787 Cell During Nail Penetration Test

Shows door of vented thermal chamber after a single 787 cell ignited and blew door seal out

For scale, this strap is about 2 3/4" wide

Three 787 Airplanes

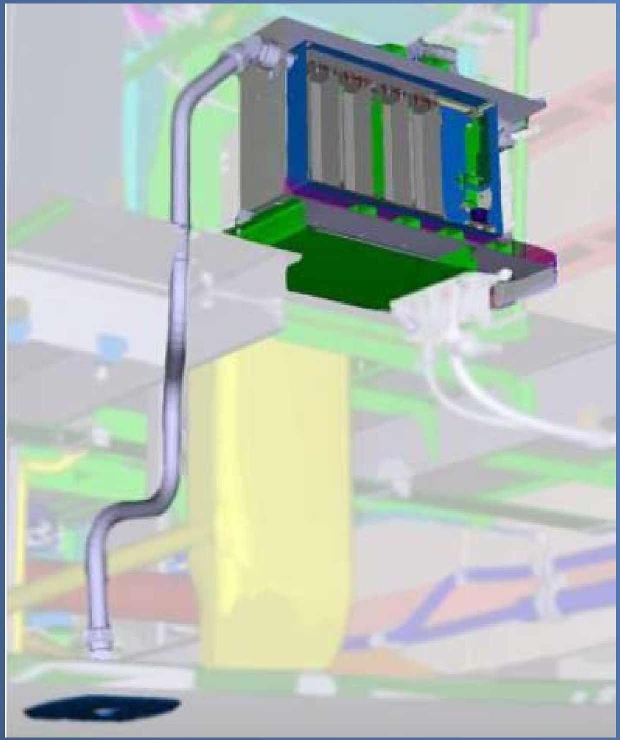
	Boston, Massachusetts	Takamatsu, Japan (“-901”)	Narita, Japan (redesigned “-902”)
Date	January 7, 2013	January 16, 2013	January 14, 2014
Battery version	“-901” (original)	“-901”	“-902” (redesign with containment box)
In-flight or on ground	Ground	Flight	Ground
Position	APU	Main	Main
Airplane-level result	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.

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.

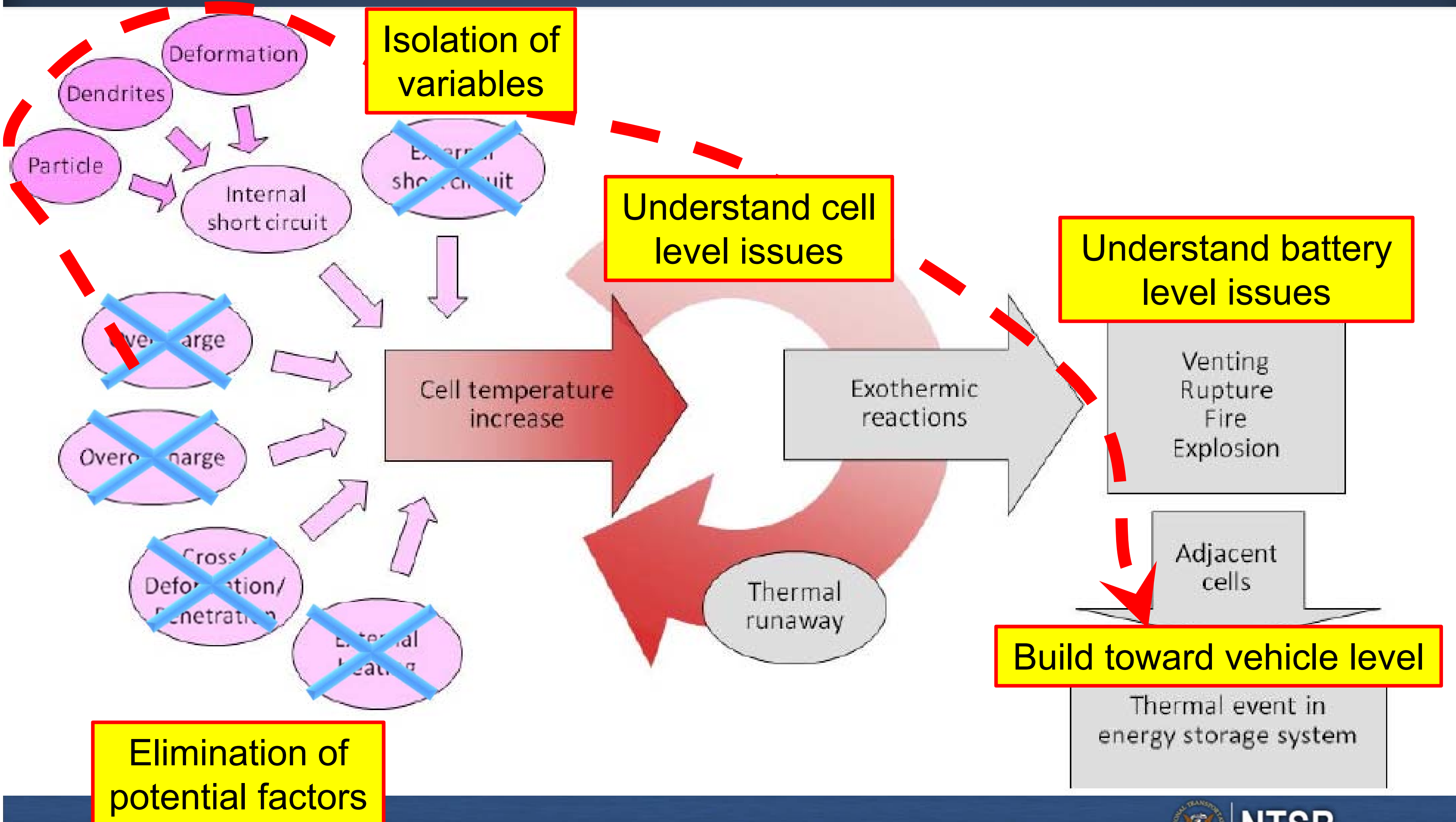
NTSB

Summary of Facts Known Soon After Boston and Takamatsu Events

- Heat and smoke without large fire (Boston connector burned)
- 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
- Other than being 787s in freezing temps, everything else was different. Operator, airport, type of routes, new versus year+ old,

NTSB

Scientific Process:
Eliminated Potential Issues To Isolate a Path



NTSB

1Apr15

Became World-Wide Investigation

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

Notable Physical Findings

- Steel particles found in bottom of welded stainless steel cell cases
- Cells with 3 electric parallel windings of unequal thicknesses
  - Wrinkles and unequal stress across electrode windings
  - Portions of electrode surface not charged at wrinkles and at tool-like marks. Dendrites found at edges of wrinkles.
- Mechanical gaps developed at rivets in cell terminals
  - GS-Yuasa vendor assembly of cell headers differed from Boeing and NASA specifications
  - Rivet seals leaked
  - In cold tests heat from rivets melted separator between anode and cathode layers
- Extensive improvements possible in monitoring.

NTSB

Delegated Certification With Layers

FAA certifications - aircraft and production

- Boeing airplane - design and assembly
  - Thales DC power system - batteries and chargers
    - GSYuasa – lithium ion battery design and assembly
      - Vendors – battery sub-assemblies & components

Summary of Test Findings

Failure Mode Findings From Cell Abuse Tests:

- ISC starting in a single winding melted current collectors
  - Thermal runaway from overall heating did not melt aluminum collectors
- Radio frequency emissions found during runaway could be a potential issue for digital electronics
- Insufficient temperature and voltage monitoring
  - Measuring at millivolt level found time to potentially mitigate thermal runaway (TR)
  - About one second between 20 mV drop and thermal runaway permits cutting cell out of circuit

- Charger current oscillations not a factor

Hazard: Thermal limits vs temperature

Car surface temps on 93°F day:

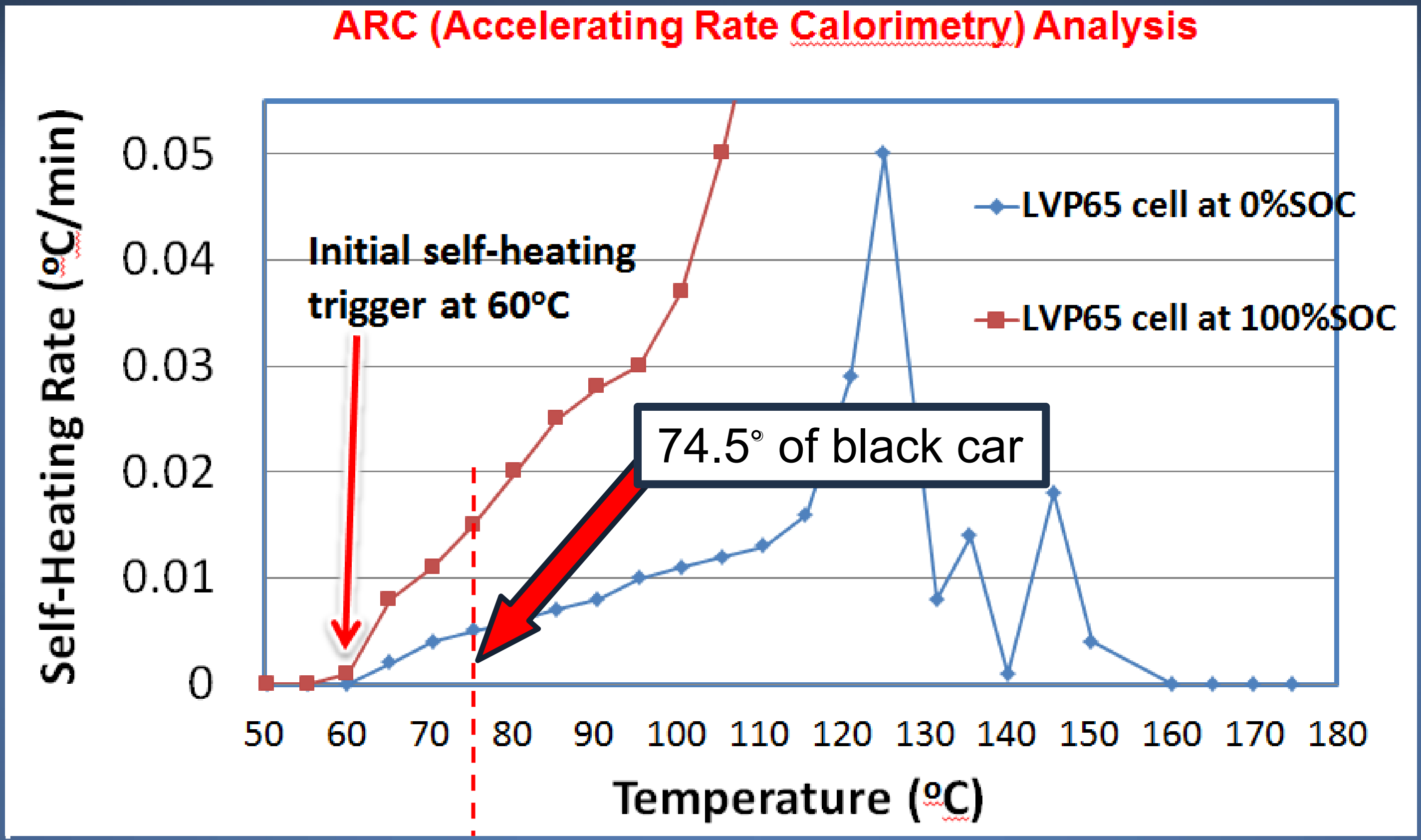
787 Max operational limit = 70°C / 158°F
Cellphone battery max 60°C / 140°F (Typ)

Black Corvette
74.5°C / 166°F

Blue Mustang
69 °C / 156°F

Silver gray Pontiac
62°C / 143.9°F

Cell Thermal Stability and Self-Heating
Cells may not be thermally stable after sun



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

Investigation and Test Results

2006 GS-Yuasa test

Release of electrolyte and smoke

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

- Change the certification requirements
- Create additional developmental testing
- Account for ISC and thermal runaway in certification tests
- Address lithium-ion battery issues
- Change FAA introduction of new technology into aircraft

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.

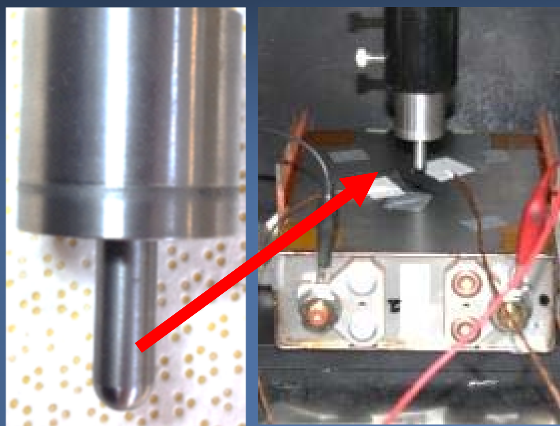
Investigation Results

- 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
- Findings are now being applied to surface vehicles and consumer products

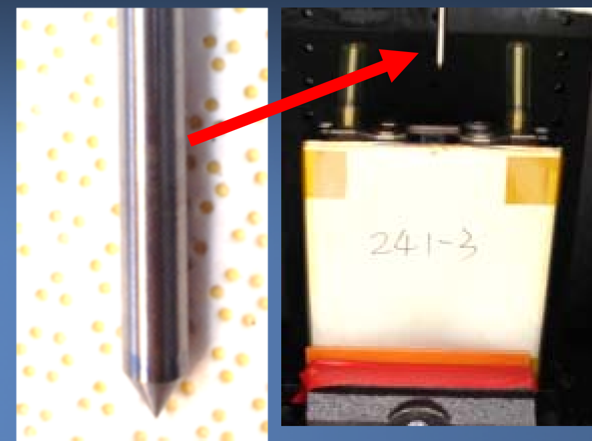
NTSB

Laser Ignition to Supplement 5 Abuse/ISC Methods

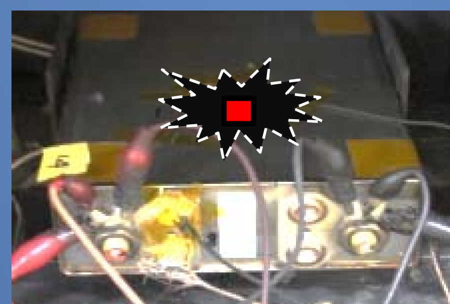
Indentation Induced ISC test



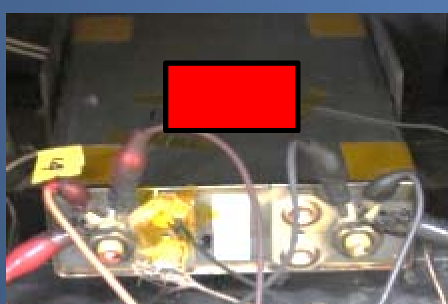
Nail Penetration test



FOD or heater built into cell



Hot Pad on cell exterior



ARC Thermal Abuse test

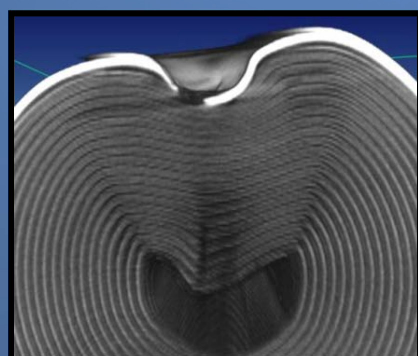
NTSB

Vehicle Manufacturer Objections to Abuse Tests

Vehicle manufacturers have called abuse methods invalid because actual batteries are typically a closed assembly and:

- Cell to ignite first is typically built into a case with wiring, cooling, etc.
- Test batteries are not production batteries if cell or battery construction requires building in foreign materials, heat pads, or other ignition sources.
- Nails and other intrusions are not typical of small flaws leading to thermal runaway.
- Precise flaws or damage for ignition source is not consistently repeatable.
- Access holes can release coolant and pressure.

Typical massive trauma to 18650 cell created by indentation test method

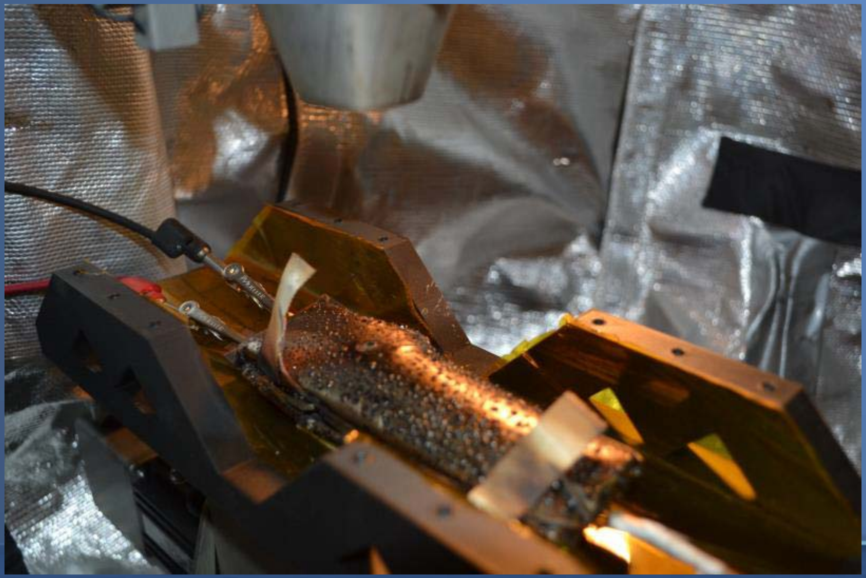


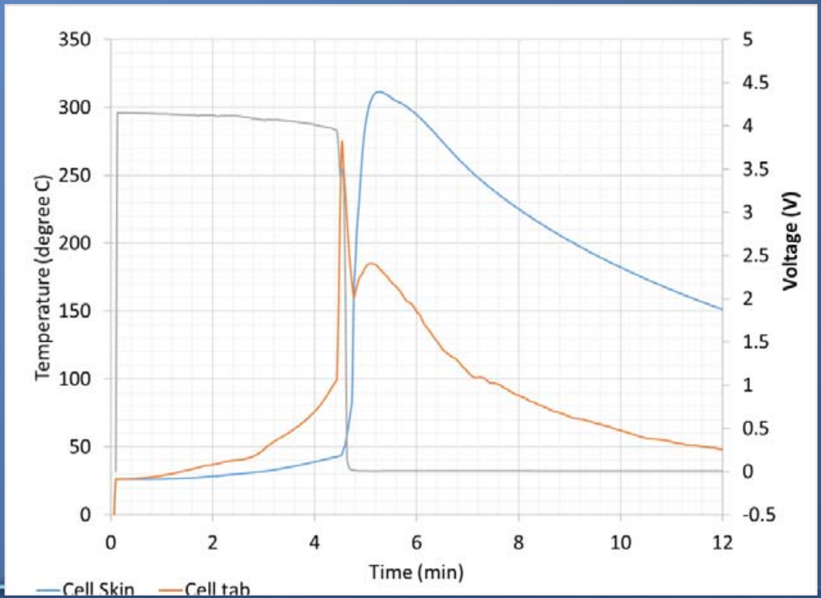
Assembled pack

Laser Ignition As An Abuse/ISC Method

Sandia Lab Proof of concept by Lamb, Steele, Orendorff in presentation to Battery Safety Council January 12, 2017

Single cell failure initiated using 40W pulse laser
~40 J total energy needed for failure (20 pulses)





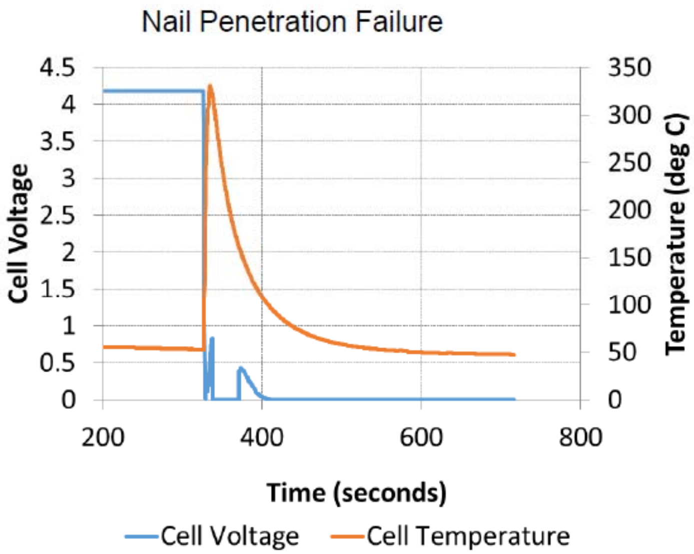
NTSB

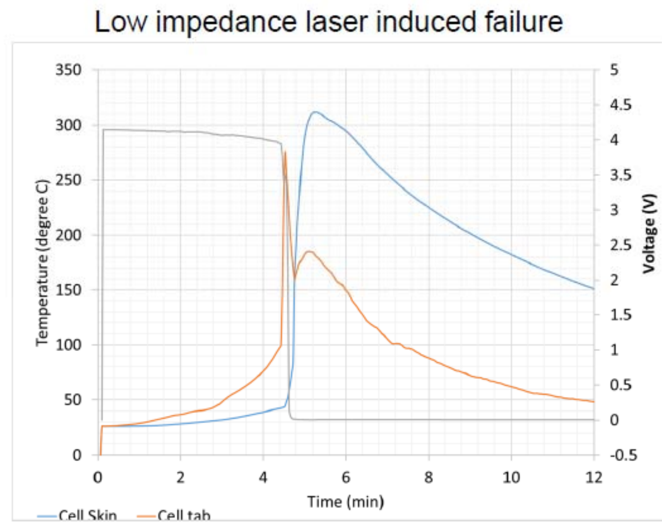
1Apr15

Sandia Results

Comparison to Mechanical Data

Sandia National Laboratories



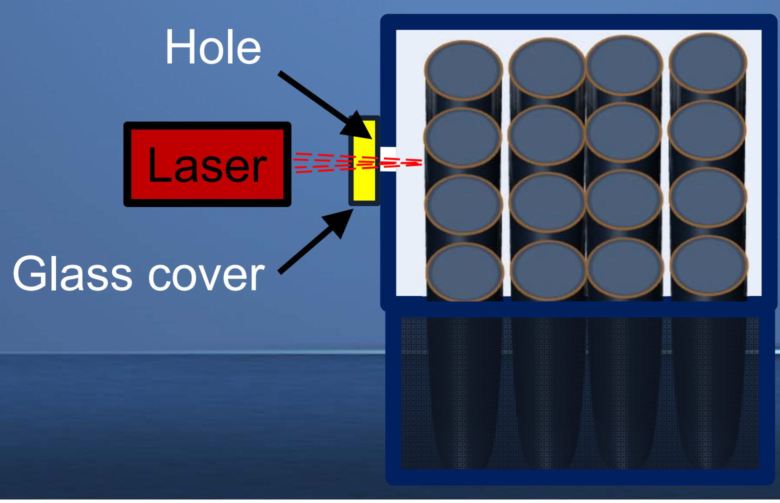


Comparison of failure to nail penetration of same model of cell.
Peak temperatures observed are similar, however the nail penetration shows much higher rate of failure after onset

NTSB

NTSB Testing Found Laser Ignition Issues at Assembly Level and Resolutions to Those Issues

- Potential to damage internal components
  - X-ray, CT, or drawings can be used to identify precise target spot and avoid wiring, coolant passages, etc.
  - Allows repeatability for a precise point on a cell
- Hole through armored casing of battery can release pressure or coolant
  - Laser requires hole of 1mm or less
    - 1-2 mm is minimal pressure release, or
  - Laser-transparent glass cover can retain coolant and pressure
- Reflectivity of cells changes energy absorption
  - Addressed with use of flat black paint or spot of printer ink
- Method limited to cells on pack wall



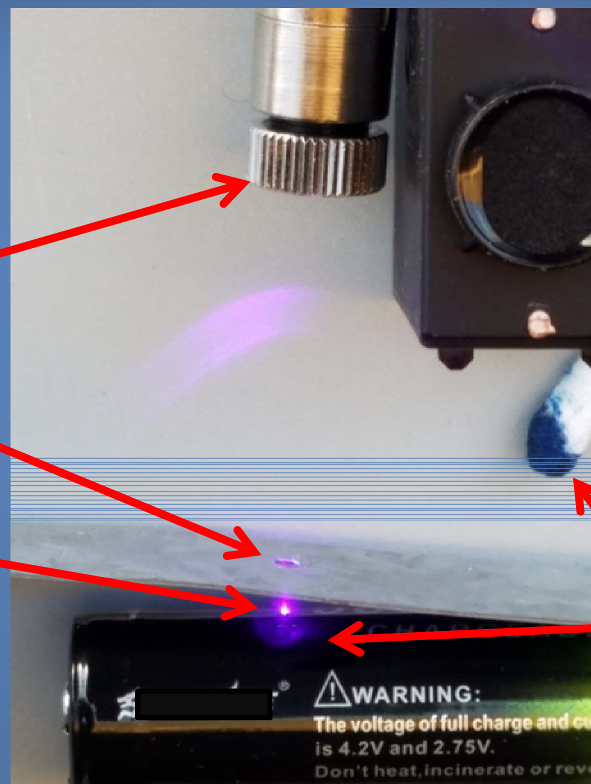
NTSB Laser Ignition Test Addressed Objections

Proof of concept ignited flat cells and 18650

500 mW engraving laser

1.5 mm (1/16”) hole
in steel barrier

Spot of laser illumination



18650 cell

Flat black paint or
printer ink spot
standardizes target
reflectivity

Items For Future Work in Laser Ignition

This test method was created to address repeated manufacturer objections.
This test method is not being patented or protected as intellectual property to encourage further development by the battery community. (safety improvement)

The proof of concept testing was performed outdoors with minimal instrumentation.
Repeat test with instrumentation of cells and in controlled environment.

The 500 mW engraving laser was barely adequate and not recommended.
The 18650 required pre-heating, full charge, and took almost 20 minutes.
The engraving laser was ultimately damaged by running at higher input voltage.

Suggest CT exam of cells post-test to compare with other methods of ignition.

Develop optimum combinations of variables, which are primarily:
- Laser power
- Distance/focus
- Time
- Initial cell temperature

Much higher power will be required for ends of cells.

No further NTSB development of this is currently planned.

NTSB

LITHIUM BATTERY SAFETY

Tamera Tucker

Marine Engineering
Naval Sea Systems Command

11 April 2017

About NAVSEA 05Z34

- **Who We Are:** NAVSEA 05Z34 provides High Energy Storage Systems engineering support to the Naval Sea Systems Command for :
  - Electrochemical, Thermal chemical, and Mechanical storage system

Primary & secondary batteries (AgZn, LI)	Electrochemical capacitors	Fuel Cells
Metal burner advanced energy systems	Ultra-capacitors	Fly Wheels
Mono/bi-propellant based thermal engines	Hybrid configurations	

- **What we do:** The Navy's technical authority for batteries and high energy storage systems
  - OPNAVIST 5100.23G assigned responsibility for Lithium Battery Safety to NAVSEA across all Navy Commands
  - NAVSEA 05Z manages, establishes and provide guidance for Lithium Battery Approval
- **Naval Surface Warfare Centers Crane and Carderock –** Technical Agents
  - Testing Facilities – Capabilities range from 10 mWh to 10kWh cells, up to MWh battery
  - R&D facilities, electrochemical development, rapid prototype development, forensics
  - Years of experience – Collectively over 2000 WY experience in power systems

Lithium Battery Incidents

- ASDS Lithium Battery Fire
  - Catastrophic cascading cell-to-cell failure of large high energy dense lithium-ion batteries
  - “Plasma jets" that led to lateral and longitudinal propagation through electrical, mechanical, and thermal effects to co-located battery strings, failure of an on-board high pressure O2 cylinder, and breach of the pressure hull
  - Damage deemed too expensive to repair
  - Local damage to the facility also occurred, no personnel injuries

RESULT

Creation & codification Navy technical manual SG270(-BV-SAF-010)

Lithium Battery Incidents

- UAV Armory Fire
  - UAV used for routine operations was cleaned with a fresh water wash-down, batteries were removed and inspected for damage, water intrusion, dried and then stored in a weapons cleaning & maintenance area
  - 2.5 hours later …

  - Lithium battery failure started the fire
  - Procedures issues for storage
  - Poor battery design

Lithium Battery Incidents

- Electronic Nicotine Devices – Not just a civilian issue
  - Approximately 12 incidents in 2016 involving Navy service members
  - Loose batteries shorting to other metal object
  - Device battery igniting in clothing pockets
  - Ignition while in use
- FDA Workshop – April 19
  - Regulated as a tobacco product
  - Currently no regulation or specifications for batteries
- Hoverboards – introduced 2 years ago – full recall on 1st release
  - New batch UL tested and released
  - Recent incidents with fire fatality with hoverboard as cause of fire

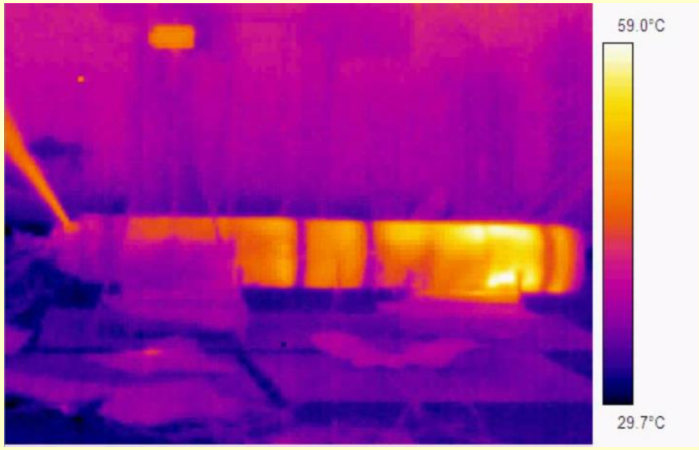
Lesson Learned

Navy technical manual SG270(-BV-SAF-010)

- Systems engineering and system level hazard analysis
  - Battery design, systems design, deployment and use scenarios
  - Placement of batteries in relationship to other stored energy devices
  - Hybrid systems and failure modes
  - Identification and engagement of risk acceptance authorities
- Expanded safety testing, characterization, and qualification
  - Battery chemistries vary, failure modes vary
  - Battery casualty behavior – vent, fragment, flame,
  - Electrical Safety Device, High Temp Abuse, Over Charge/Discharge, Short circuit, etc
  - Cascading effect, other unusual test (propagation, battery management system failure, un-ignited gases)
  - Analyze all data to conduct hazard and risk analysis
- Independent Safety Certification - NAVSEA INST 9310.1C
  - Performed independent of the design and technical reviews
  - NAVSEA 05Z ensures Certification Authorities have appropriate subject matter expertise

Best Practices

- Segregated storage – new, used, damaged, hazmat, charging
- Storage facility design – fire suppression capabilities, ventilation, fire proof
- Emergency Responders – informed and trained
- Use of protection devices – venting, thermal, cell to cell balancing, battery management systems
- Charging system design and use
- Insulated terminals
- Battery and system design:
  - Non-propagating
  - Solid lithium
  - Deluge/containment systems
  - Alerts, scan rates and BMS component redundancy



The Critical Link

Incidents Involving:
BB-2590/U Batteries & PP-8498/U Chargers
and
Other (CWB) US Army Batteries

NASA

Learning Alliance: Lithium Ion Battery

Safety and Health Safety

April 11, 2017

Dr. Lawrence R Valencourt

UNCLASSIFIED

U.S.ARMY

Incidents Involving:
BB-2590/U Batteries & PP-8498/U Chargers
and
Other (CWB) US Army Batteries

Agenda

- Latest [*known*] Incident
  - Equipment
    - BB-2590/U
    - PP-8498/U
  - Historic Timeline
  - 2015 investigation process and findings
  - Root cause
  - Conclusion
- Conformal Wearable Battery Information
- Some Other Army Incidents

NB: Any product shown or discussed in this presentation is NOT to be considered an endorsement by the US Army, CECOM Safety or the presenter.

The Critical Link

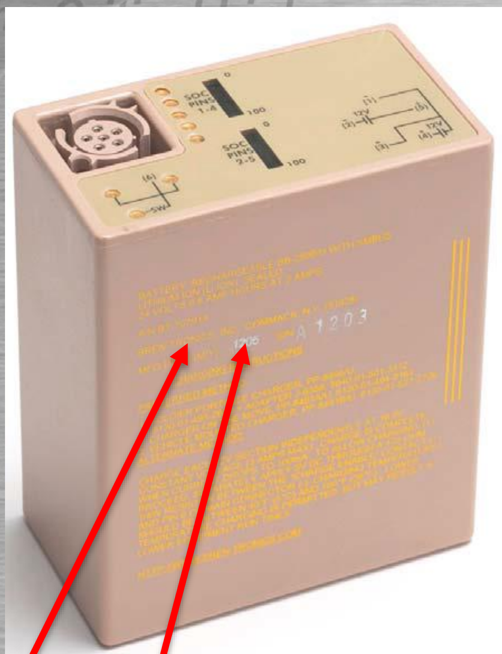
BB-2590

- Lithium-ion
- Used in many different systems (radios, robots, targeting systems, etc.)
- 24 18650 cells
- 2 independent packs of 3P4S
- End items can use in series or parallel mode
- Cells range from 2.2Ah to 2.6Ah depending on generation (higher capacities in COTS and specialty builds)
- Overcharge and over-temperature protected
- In addition to US Army testing, ALL batteries MUST pass UN testing criteria
- On site @ Manufacturer is a Government QA test witness

The Critical Link

PP-8498/U Soldier Portable Charger (SPC)

- Universal charger, capable of charging multiple battery types and chemistries
- 300W power input
- 2 independent charge channels with 4 stations each
- Can charge either sequentially or in parallel
  - BB-2590/U's are charged sequentially.



Contract number is above the date code.

Date code, Month/Year is here;
Battery should be less than 5 years old.

Contract Number is on the faceplate

Software Update Label is here. Latest Revision (H) should be indicated.

The Critical Link

Historic Timeline

- There are 3 know incidents of fires occurring while charging BB-2590/U batteries on the PP-8498/U
- The first incident happened in 2010
- After this incident, a charger firmware update was issued

Historic Timeline, continued

- The second incident occurred several months later
- Following the this incident a Ground Precautionary Action (GPA) was issued in early 2011 requiring all chargers to be updated

Details of 2015 Investigation

- On 16 April 2015, in preparation for an early morning EOD training exercise, BB-2590/U lithium ion batteries were being charged PP-8498/U chargers.

  - 6 chargers, each charging 4 batteries

- Due to the early training start time, Soldiers were sleeping in the building

  - The fire alarm and sprinkler systems functioned properly and there were no injuries to any personnel

- Damage total was in the millions of dollars due to water (sprinkler) and soot damage to EOD equipment

  -Considered a Class A incident per AR 385-10 and an Accident Investigation Board was convened

The Critical Link

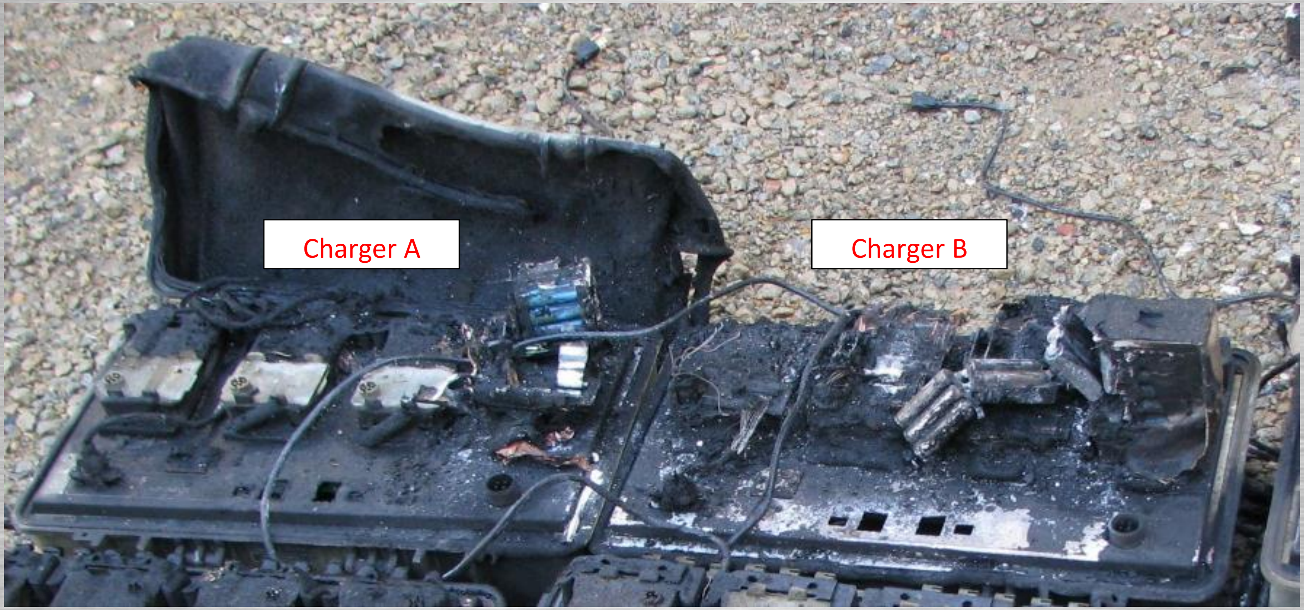
Details of 2015 Investigation, continued

- Chargers arranged as they were preceding the fire

The Critical Link

Details of 2015 Investigation, continued

- Chargers with most damage

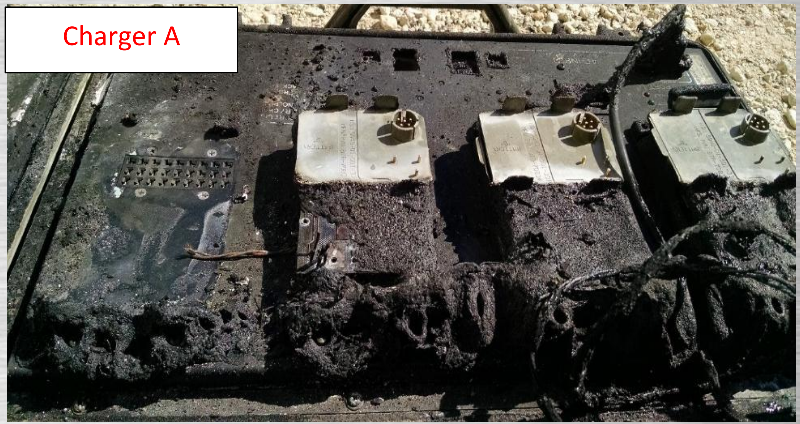


The Critical Link

Details of 2015 Investigation, continued

- Rear views of the chargers.
  - Damage indicates fire started where they met

Damage decreases ←



Damage decreases →

Details of 2015 Investigation, continued

- Charger A did not have a label indicating it had been updated
  - Labels are to be marked with an indelible marker when the firmware is updated. (A new label was provided when revision H was released)

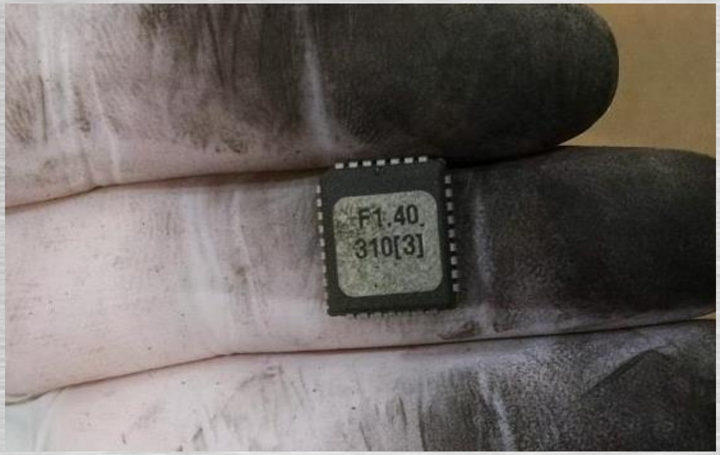
Details of 2015 Investigation, continued

- Charger B's firmware label was damaged beyond recognition, as was its nameplate with manufacture date
- Taking charger B apart revealed that its power supply was manufactured after the updated firmware was implemented by the OEM
- Investigation/autopsy was conducted at Manufacturer's site with 2 Government witnesses/participants at every step; From opening the shipping box to securing them after the investigation until permitted to dispose of them at the conclusion of the investigation (Trail of custody)

The Critical Link

Details of 2015 Investigation, continued

- The EEPROM's (**E**lectrically **E**rasable **P**rogrammable **R**ead-**O**nly **M**emory) from both chargers were recoverable
- Using specialized equipment at the OEM's facility to read the EEPROMs it was confirmed that
  - Charger A had firmware version D
  - Charger B had the correct version H

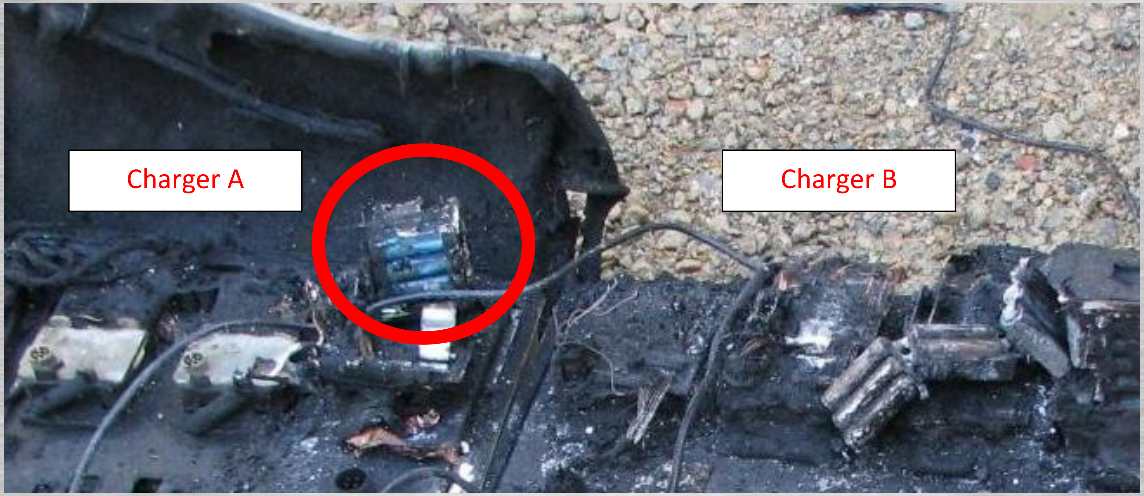


The Critical Link

Details of 2015 Investigation, continued

- Conclusion is that fire originated in the circled battery

  - Cell pack is believed to have survived the fire due to its low energy state (i.e. battery was over-discharged)



The Critical Link

Root Cause of Incidents

- All batteries involved in the 3 incidents were believed to be in over-discharged states due to lack of use
- Some may have been COTS
- When a low voltage BB-2590 battery is placed on the SPC it will attempt to pre-charge the battery with approximately 400mA of current per section (12 cells 3P4S)
- If the battery does not ‘wake-up’ the charger will proceed to the next battery station
- Prior to the latest firmware, revision H, the charger used battery voltage to determine if a battery has been removed

Root Cause of Incidents, continued

- When the charger sequences away from the over-discharged battery the voltage dropped leading the charger to consider that the battery was removed
- When it sequenced back to the same station, the charger once again attempted to ‘wake-up’ the battery
- The revision H firmware update used an alternate method to recognize that the battery had been removed

The Critical Link

Conclusion

- New GPA was issued reinforcing requirement to upgrade chargers and properly maintain batteries
- As with most safety incidents, a number of factors were involved.
- There were multiple missed opportunities to have broken the chain of events

  - Original firmware was flawed
  - Batteries were not maintained / discarded
  - Communication breakdown led to the operator not receiving update

Conformal Wearable Batteries (CWB)
An Exemplar CWB

The Critical Link

Approximate Parameters

(Varies by capacity/end use)

85Wh to 185 Wh

2.5 lbs (+/-)

¾” x 7 ¾” x 8 ¾‘”

Conformal Wearable Batteries (CWB)

The Critical Link

CWB Attributes

- Conformal, flexible
- Fits in SAPI Vest
- Complies with ALL US Army Battery tests; (including live fire/ballistic testing)
- Has survived such testing and continues to operate in ‘911 mode’
- Have been several ‘reported’ battery failures in field evaluations but all (to date) have be determined to have been caused by abusive conditions
- Constructed to mitigate catastrophic failure (Fire/thermal runaway)

The Critical Link

Battery Safety: Lithium Batteries

Back Up/Supporting Materials

COMBAT POWER FOR LEADERS

The Critical Link

U.S. Army: Publications, Processes and Processes

Publications:

MIL PRF's [Battery 'type' specific] Examples:

MIL PRF 32383, BATTERY, RECHARGEABLE, SEALED, LITHIUM-ION, BB-25xx and BB-35xx (Conformal Wearable Battery : CWB);

MIL PRF 32271, BATTERY, NON-RECHARGEABLE, LITHIUM

MIL STD's Examples:

MIL STD 882E, DEPARTMENT OF DEFENSE STANDARD PRACTICE, SYSTEM SAFETY

AR Regulations Examples:

DA Pam 385 -16, System Safety, Management Guide

DA Pam 385 - 30, Risk Management

DA Pam 385 – 40, Army Accident Investigation and Reporting

These publications describe US Army safety policies, risk assessment, mitigation/acceptance criteria, testing protocols (pass/fail), approval processes, reports, approval authority, design requirements, documentation requirements,….

U.S.ARMY

The Critical Link

US Army Battery Safety Contacts

Linda M. Seubert P.E., CSP Safety Engineer
CECOM Directorate for Safety, ATTN: AMSEL-SFS-I
Building 3200, 6630 Raritan Avenue,
Aberdeen Proving Ground, MD 21005-1850
(443) 395-3823; linda.m.seubert.civ@mail.mil

Lawrence R. Valencourt, PhD, Safety Engineer, Contractor
CECOM Directorate for Safety, ATTN: AMSEL-SFS-I
Building 3200 , 6630 Raritan Avenue
Aberdeen Proving Ground, MD 21005-1850
(443) 395-3820; Lawrence.r.valencourt.ctr@mail.mil

The Critical Link

Some Other U.S. Army Incidents involving Conformal Wearable Batteries (CWB)

U.S. Army Incidents Involving CWB's

Three recently (known) incidents:

(1)"Just thrown in Stryker"

Crease/Crushed cells diagonally across base

(2) Single Cell penetrated by apparent needle (Map pin?)

Upon battery autopsy found an additional 22 pin pricks on back side, Cactus penetration (?)

(3) Numerous CBW's 'caught fire' – investigation continuing

U.S. Army Incidents Involving CWB's

The Critical Link

In each of these cases (Except for incident #3) the batteries performed as specified:

- A single cell or two cells failed
- They vented as designed/specified (Soldiers described them as 'exploding, smoking, on fire')
- The other cells continued to provide power
- Battery autopsies at the manufacturer examined the battery 'history' and current capability (With Government witness present)
- Battery performed as designed
- No injuries or other equipment damage

- **As I have often said when discussing battery safety and testing with our manufacturers, "Never under estimate the ingenuity of the American Soldier when it comes to finding ways to abuse a battery:"**

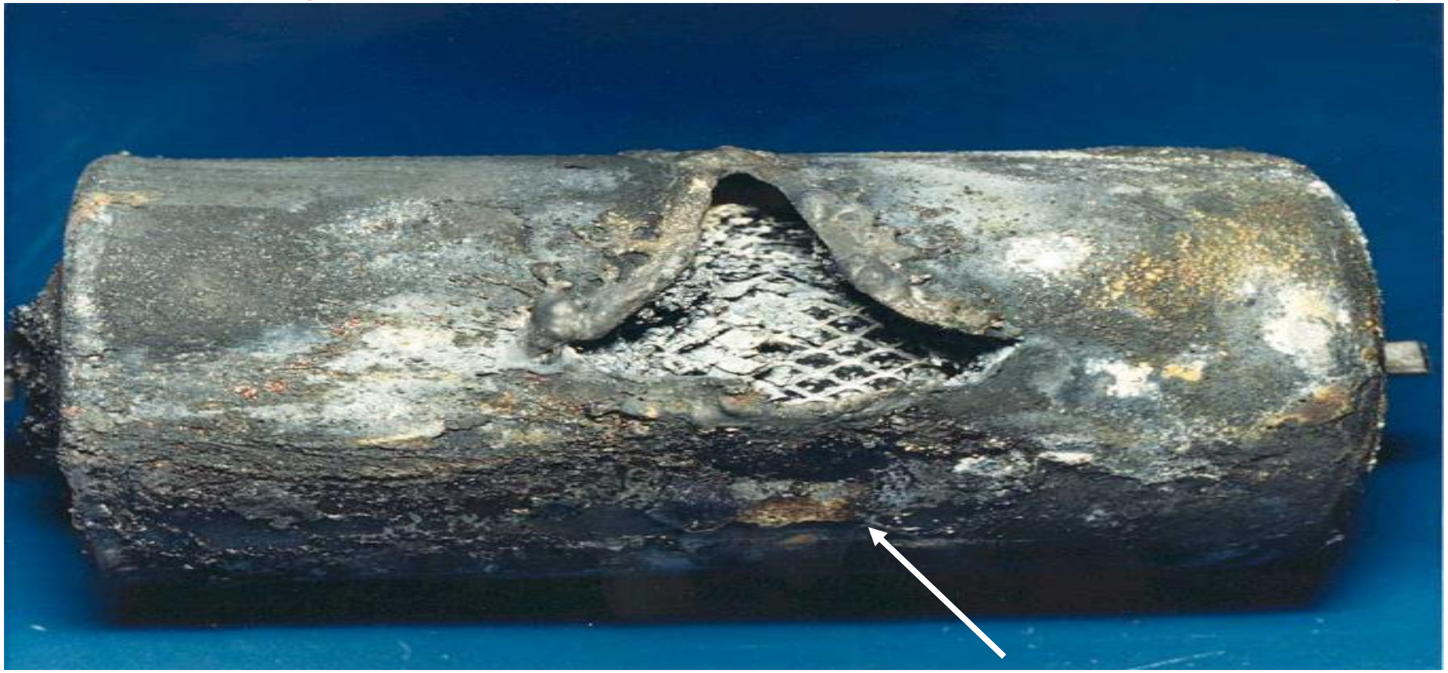
Some "Examples" of Battery Damage/Incidents

Battery Safety: Lithium Batteries

This is a ***Blow Hole***; the vent did not open.

Iron melts at 2,795°F

Aluminum melts at 1,220°F



The vent

UNCLASSIFIED

28

Battery Safety: Lithium Batteries

The current SINCGARS radio;
The *ASIP*

The result of using a “deadlined” battery in the SINCGARS ASIP.

Battery Safety: Lithium Batteries

BA-5590/U, SAFT, Found in trash can

UNCLASSIFIED

30

Battery Safety: Lithium Batteries

It's not just 10-cell batteries: A BA-5347/U. The burnt box below was in storage in a CONNEX container. The box was discovered inside the container after the fire had burned out. The location of the event was ***classified***; no investigation was possible.

UNCLASSIFIED

Battery Safety: Government/Military Lithium Batteries

BB-2590/U

Lithium ion Battery

'Carcass'

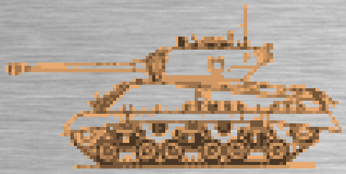
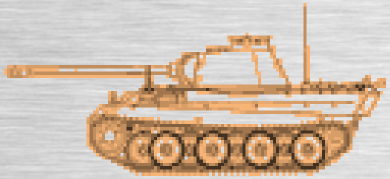
UNCLASSIFIED

Battery Safety: Lithium Batteries

UNCLASSIFIED

33

T’anks


At the End of the Day…

The Critical Li

It’s all about the Warfighter!

International Space Station Lithium-Ion Battery Safety Considerations

for NSC, April 11, 2017

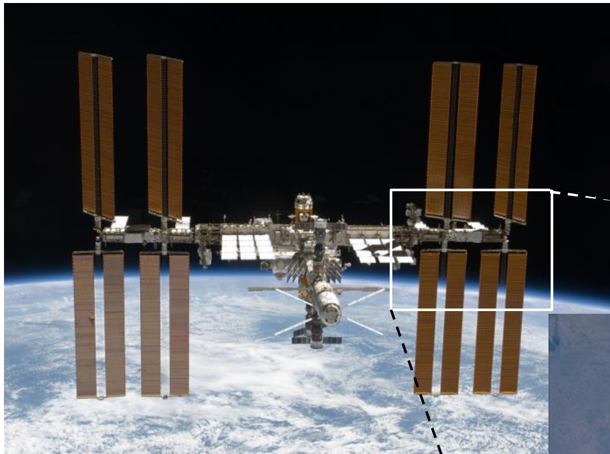
Penni J. Dalton, NASA Glenn Research Center

ISS Li-Ion Battery Safety Considerations

- ISS battery is the largest Li-Ion battery to be flown on a manned mission
  - 30 134 Ah Li-Ion cells in series
  - Approximately 15 KWh
  - Direct replacement for the existing, aging Ni-H_2 batteries on-orbit

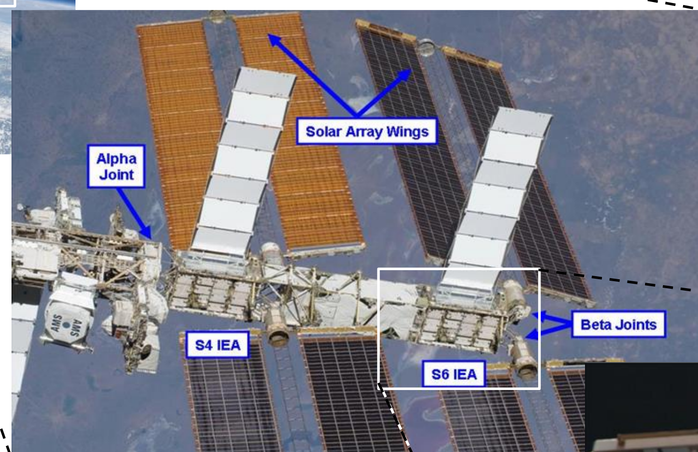
- Safety was a prime concern and was designed in from the very beginning of the project
  - Cell Production Processes and Screening Controls to help reduce the occurrence/likelihood of failures
  - Internal Battery ORU Controls to achieve 2-fault tolerance or design for minimum risk (DFMR)
  - External System Safety Controls to achieve 2-fault tolerance

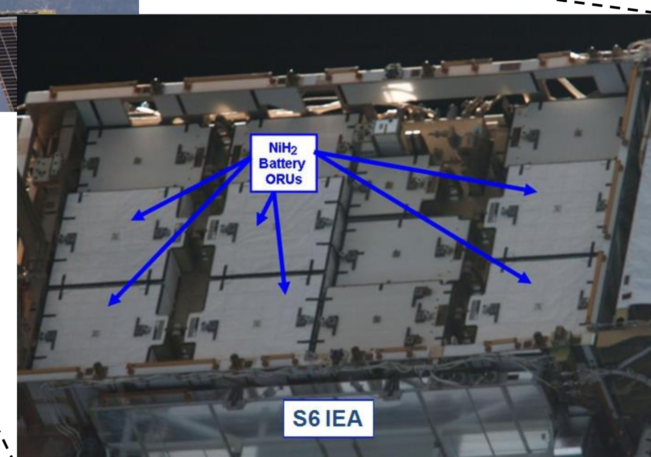
ISS Configuration - Battery Locations



Batteries are located in the 4 Integrated Equipment Assemblies (IEAs)

2 Power Channels per IEA





6 Ni-H_2 Orbital Replacement Units (ORUs) per channel – 48 total

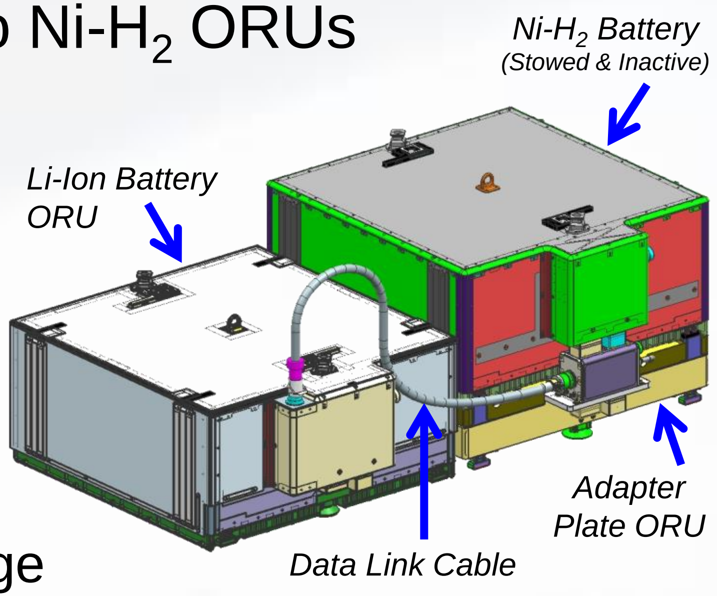
One Li-Ion and one Adapter Plate to replace two Ni-H_2 – 24 total Li-Ion batteries

Timeline of ISS Li-Ion Development

- **2009-2010 -** Preliminary risk and feasibility studies
  - Test/analysis of 6 different cells designs/vendors
- **December 2011 -** ISS Program Authority To Proceed with design, development and the fabrication of 27 Li-Ion ORUs and 25 on-orbit Adapter Plate ORUs
- **Jan-Jun 2012** - Cell Safety Testing and Cell Qualification
- **July 2012** - Final cell down-select
- **December 2012** - System Preliminary Design Review
- **November 2013** - System Critical Design Review
- **December 2016** - 6 Li-Ion batteries delivered to ISS via Japanese HTV Exposed Pallet
- **January 2017** - Li-Ion batteries installed on ISS and started up

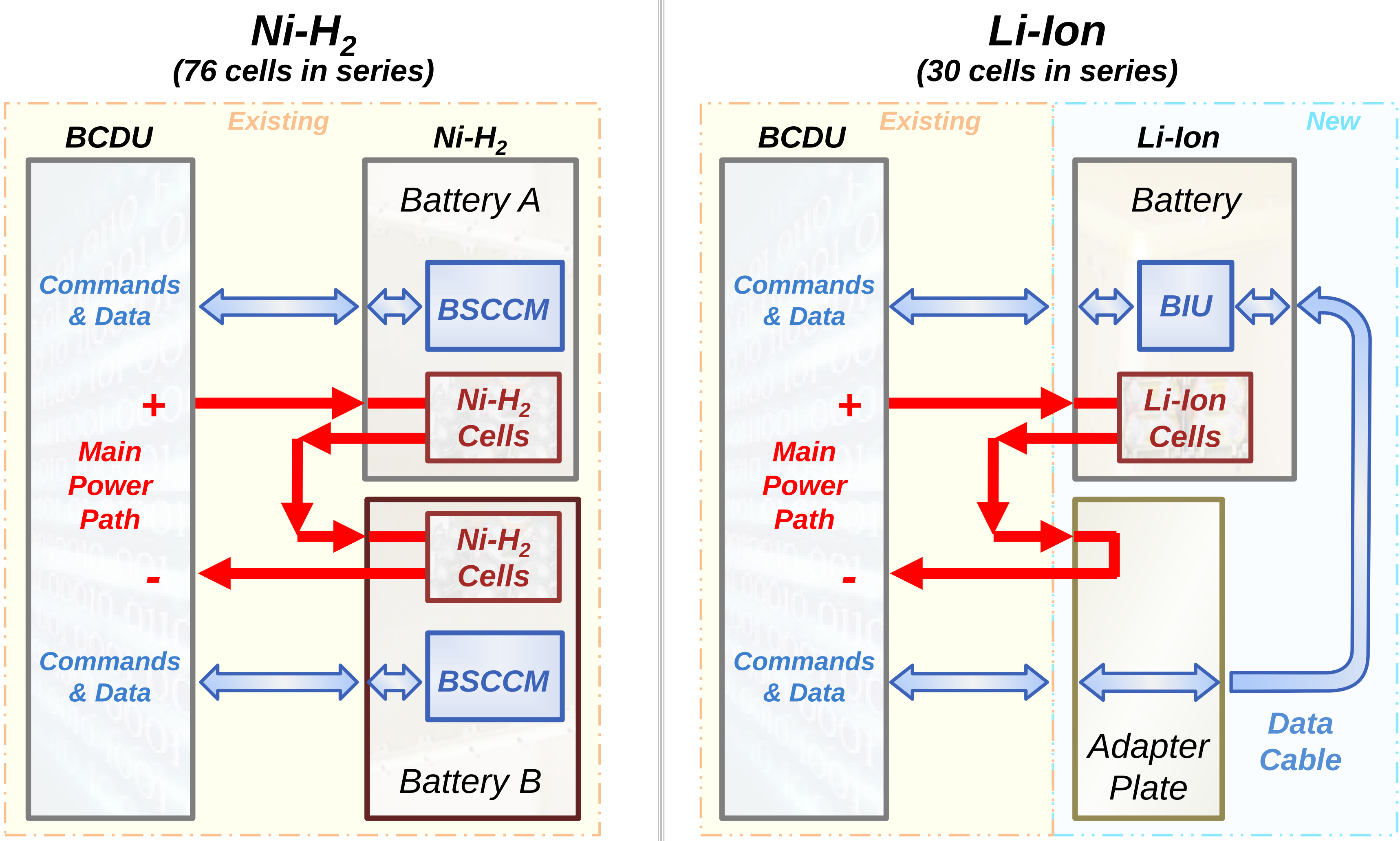
ISS Li-Ion Battery Key Design Drivers

- One Li-Ion battery ORU replaces two Ni-H_2 ORUs
- Launch on Japanese HTV
- Six year battery storage life requirement
- Ten year/60,000 cycle life target (minimum 48 A-hr capacity at end of life)
  - ORU will have cell balancing circuitry
  - ORU will have adjustable End of Charge Voltage (EOCV)



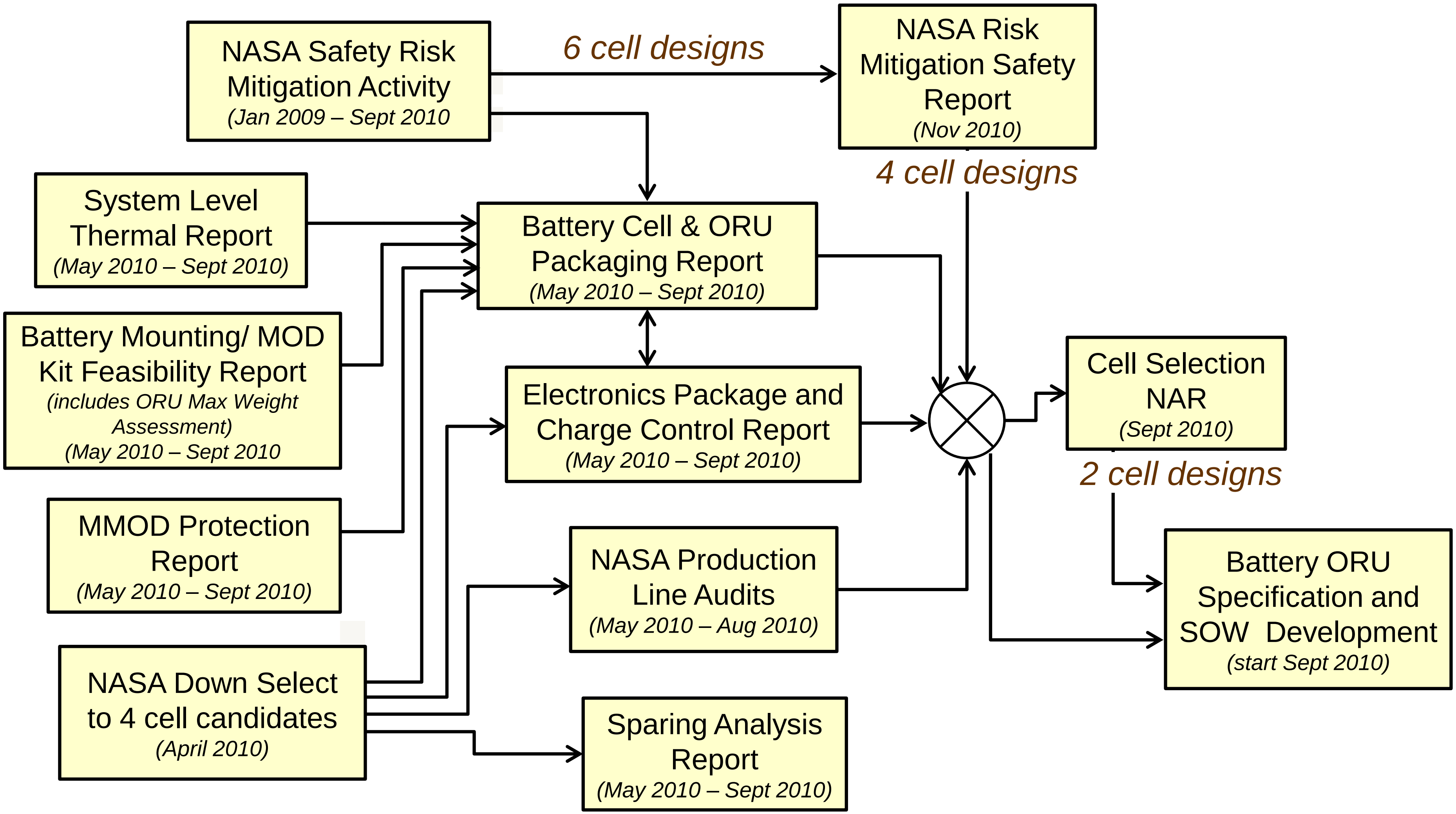
- Maximum battery ORU weight ~430 lbs
- Non-operating temperature range (Launch to Activation): -40 to +60 °C
- No changes to existing IEA interfaces and hardware
  - Use existing mounting, attachment, electrical and data connectors
  - Use existing Charge/Discharge Units and Thermal control systems

ISS Upgrade to Li-Ion



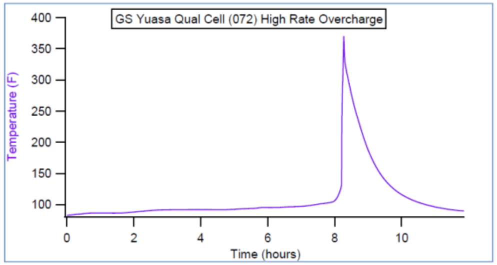
BCDU: Battery Charge / Discharge Unit
BIU: Battery Interface Unit
BSCCM: Battery Signal Conditioning and Control Module

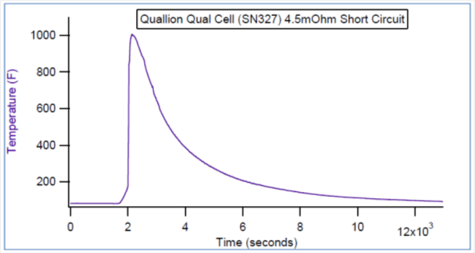
ISS Li-Ion Technical Definition Studies



ISS Li-ion Cell Safety/Abuse Testing

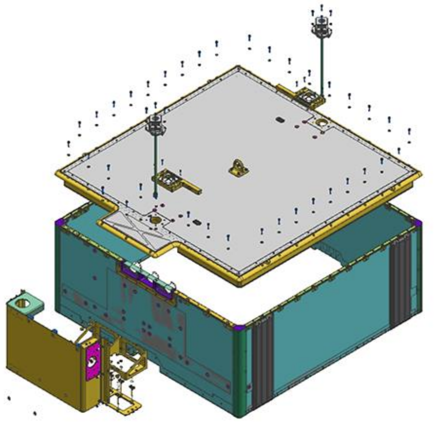
- Cells from two vendors were subjected to safety and abuse tests
- No pass/fail:
  - Cells were deliberately stressed into catastrophic events
    - External short circuit
    - Heat to vent
    - Overcharge
    - Overdischarge
    - Vent pressure determination
    - Burst pressure determination

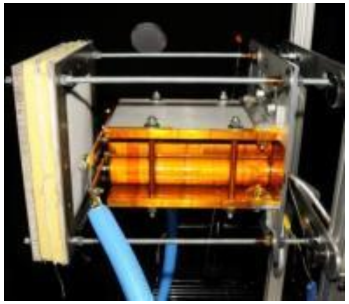




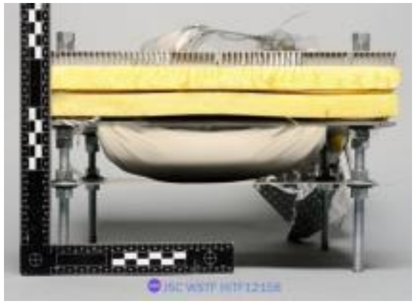
- Test results used in the design of the battery ORU and operational inhibits and protections

MMOD Shield Testing





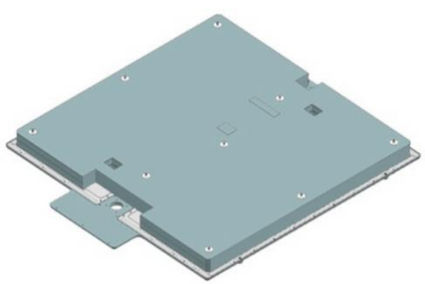
MMOD test setup



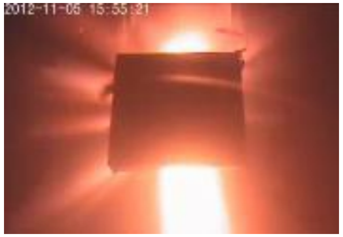
Ballistic Limit Testing

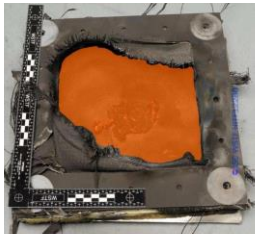
Over Match - Penetration testing

10 mm 2017-T4 Aluminum Sphere @ 6.86 km/s



MMOD Shield



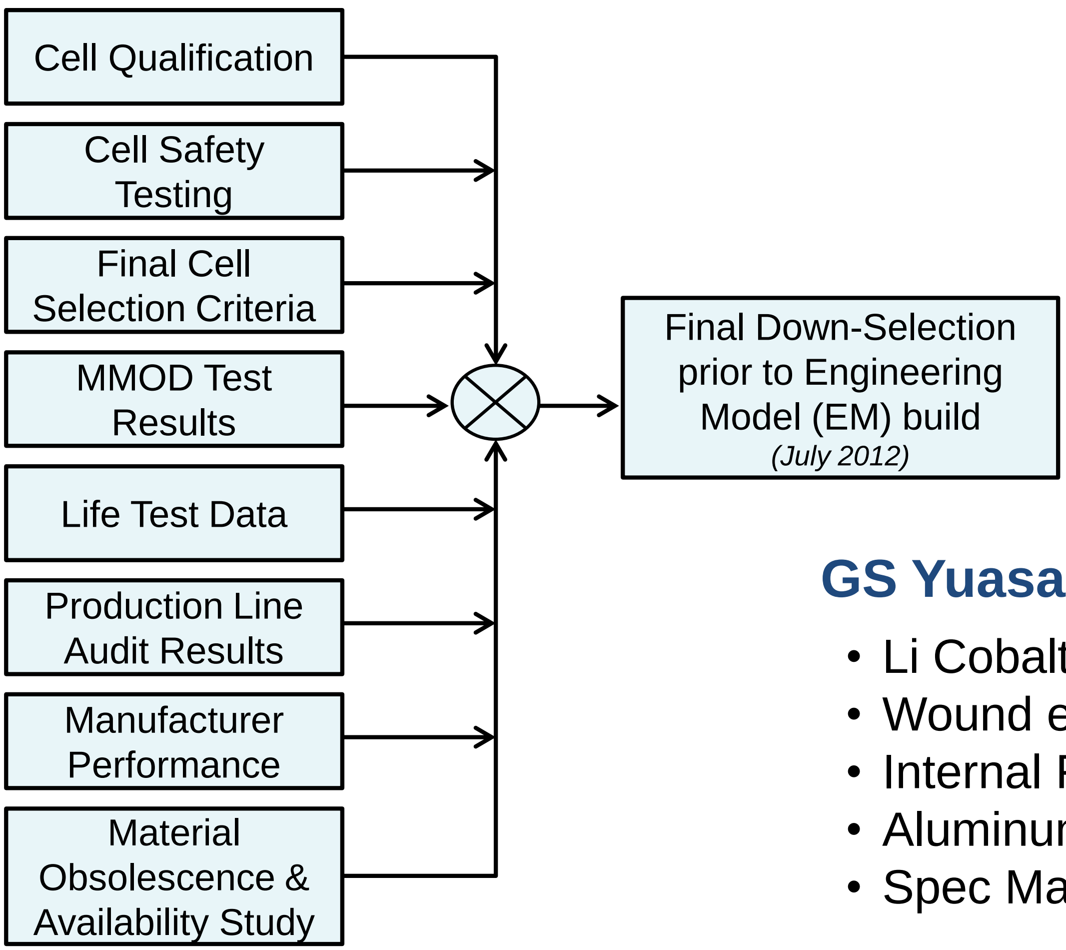


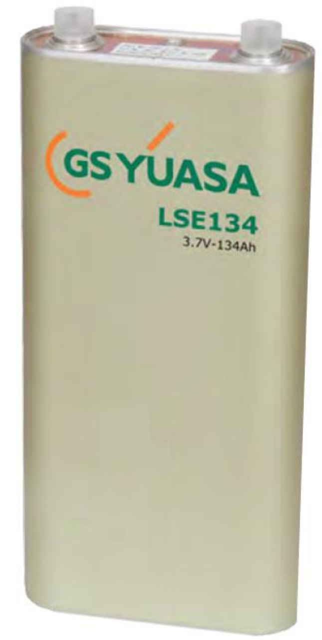
Overcharge Containment Testing

Note: Existing Ni-H_2 does not have MMOD (Micro-Meteoroid Orbital Debris) protection

ISS Li-Ion Cell Final Down-Select

- Two designs taken through qualification, with down-selection made prior to EM build





GS Yuasa, Japan 134 A-hr cells

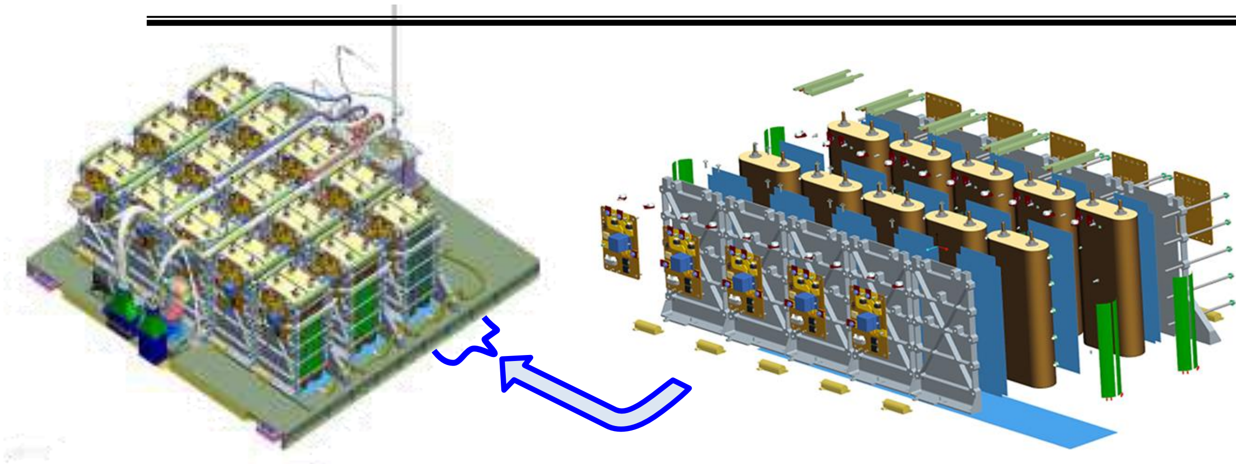
- Li Cobalt Oxide / Carbon Graphite
- Wound elliptical prismatic electrode
- Internal Fusible link
- Aluminum Case, 50 x 130 x 263 mm
- Spec Mass: 3530 grams (~7.8 lb)

ISS Li-Ion Battery Safety Features

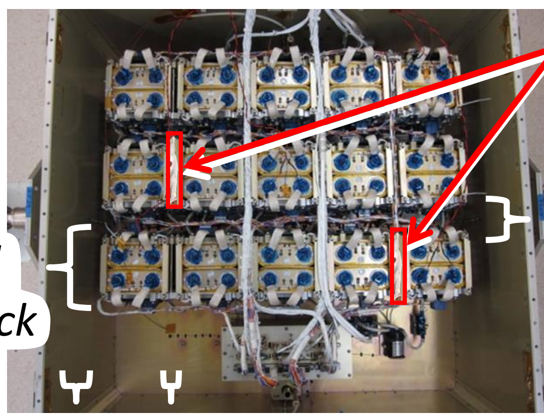
Battery-Level Safety Features

- Two independent controls vs. thermal runaway (two fault tolerant)
- Voltage and temperature monitoring of all 30 cells
- Circuit protection/fault isolation at the individual cell level for both high/low voltage and high temperature
- Physical separation between cell pairs and 10 packs
  - Thermal radiant barriers between cell pairs
- Controlled direction of cell vents - prevent damage to cold plate, adjacent cells and IEA hardware
  - ORU pressure relief/flame trap to prevent ORU over-pressurization but contain flame in the event of a cell vent
- MMOD shielding in ORU
- Dead face device to remove power from output connector during ground or EVA handling
- Non-propagation of failures beyond Battery ORU

Safety Feature - Radiant Heat Barriers



- ORU Layout – three Cell "10-Packs" and 12 Radiant Barriers

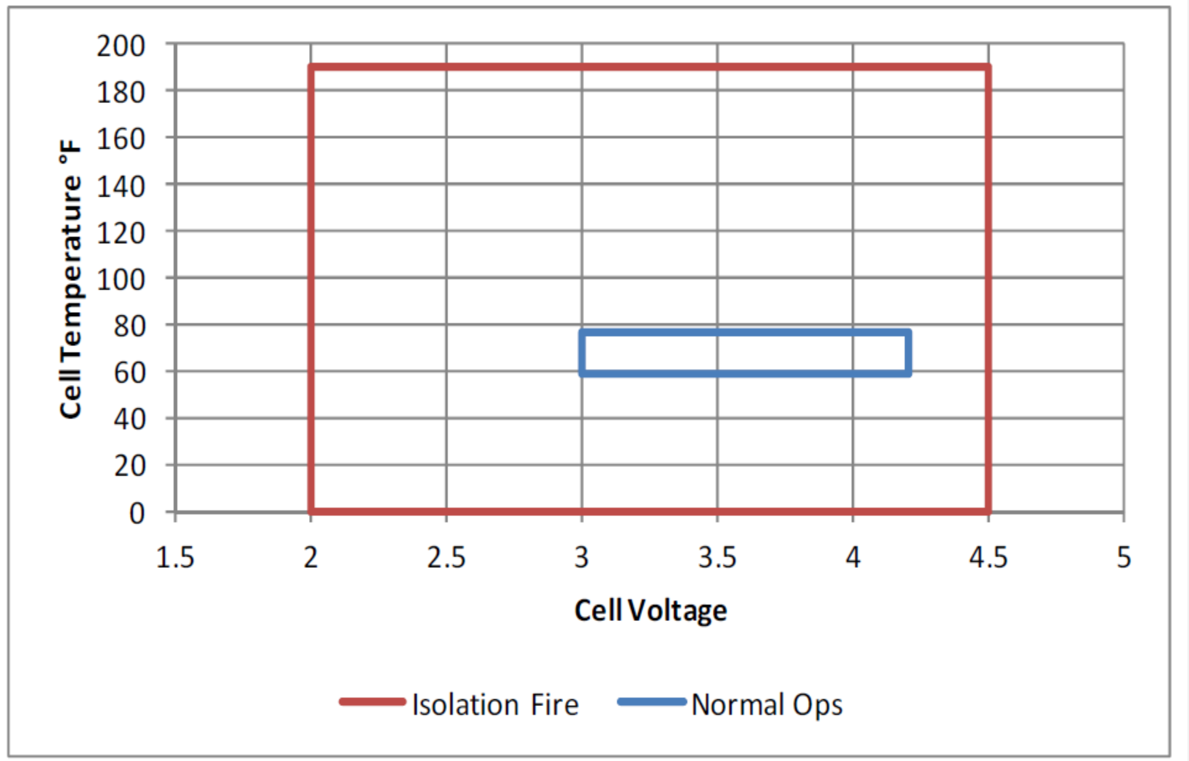


Radiant Heat Barrier (12 per ORU)

- Higher margin against thermal runaway propagation
- One barrier between each cell pair
- Reflects 787 reach-back safety additions (lessons learned)

Safety Feature – Cell Isolation

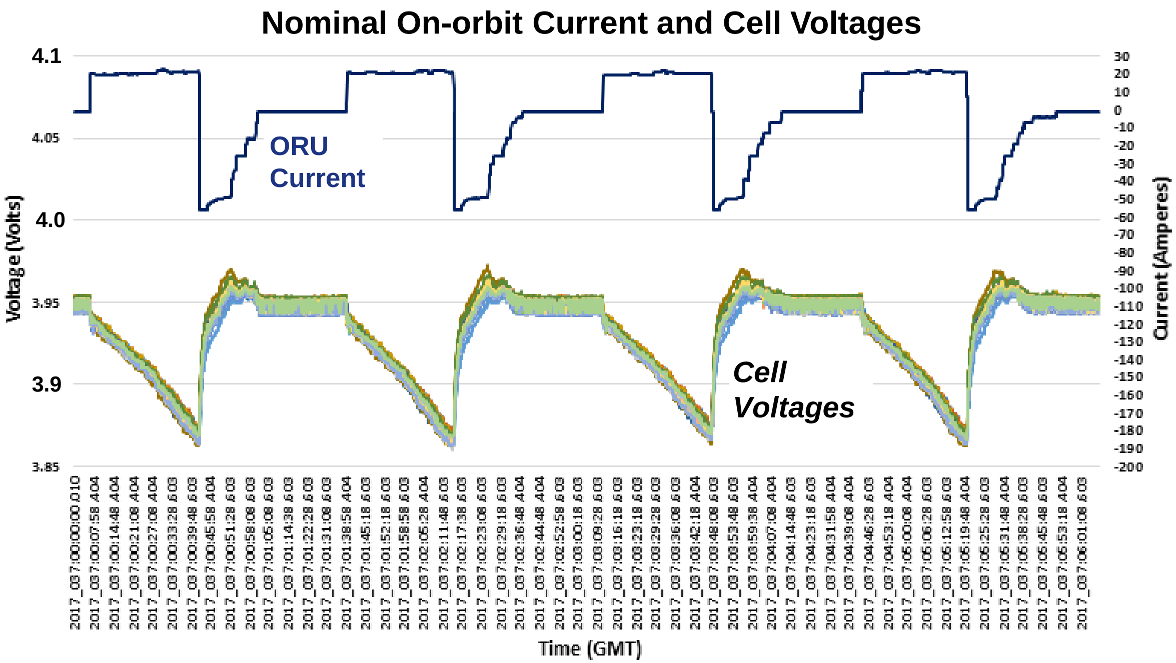
- Three thresholds for permanent cell isolation
  - High voltage = 4.5 V
  - Low voltage = 2.00 V
  - High temperature = 190^0 F

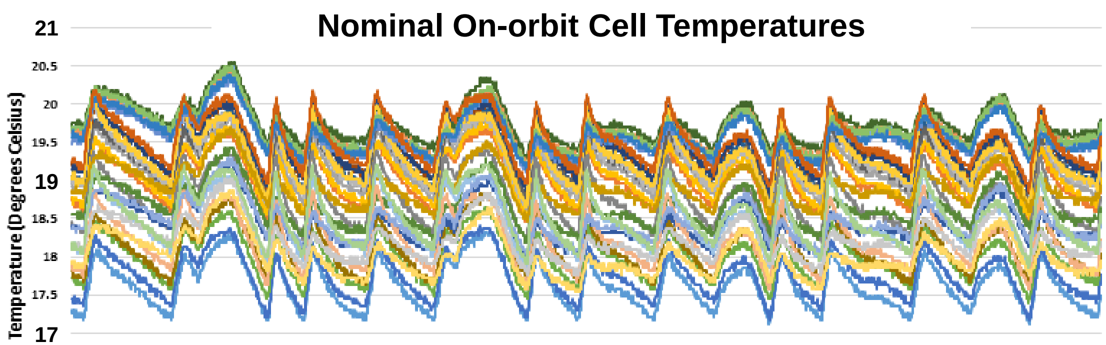


ISS Li-Ion Charge Control and Cycling

- Li-Ion charge current profile is based on cell voltages
- Cell bypass/balancing at EOCV every orbit
- EOCV ground command-able

Charge Current Profile		
	Highest of the Cell Terminal Voltages	Charge Current
Point 1	EOCV + 19mV	55
Point 2	EOCV + 19mV	49
Point 3	EOCV + 18mV	44
Point 4	EOCV + 17mV	39
Point 5	EOCV + 16mV	36
Point 6	EOCV + 15mV	33
Point 7	EOCV + 14mV	30
Point 8	EOCV + 13mV	26
Point 9	EOCV + 12mV	22
Point 10	EOCV + 11mV	19
Point 11	EOCV + 10mV	16
Point 12	EOCV + 9mV	13
Point 13	EOCV + 8mV	10
Point 14	EOCV + 7mV	7
Point 15	EOCV + 6mV	4
Point 16	not applicable	1





Data for Battery Channel 3A after ~30 days operation

ISS Li-Ion ORU Detailed Safety Features (Failure Risk Mitigation)

- Cell Terminal/Bus Bar
  - Terminals are torqued to specification
  - Terminal bus connections are epoxy staked (prevents loosening)
  - Terminal /bus bar joints are conformal coated (reduce potential for contact corrosion)
  - Flexible (braided wire) bus bars (reduce mechanical and thermal stress)
- Cell External Short and thermal Management
  - Cell internal insulation (electrode assembly in polyimide insulator wrap)
  - Double layer of external cell insulation (Polyimide wrap & Comeric Mil-I-49456A, Type III, Grade 3)
  - Cell top/header (double coat of conformal coating)
  - Cell holding fixtures (sync heat to base plate and prevent cell swelling)
  - Active thermal management to tight control band (cell heaters and IEA ammonia loop)
  - Cell spacing reduces cell pair to cell pair thermal communication
  - Actively controlled charge profiles (charge current control based on State of Charge)
- Over Charge / Over Discharge and Temperature Controls
  - 2 fault tolerant safety controls
  - Isolation of individuals cells prior to cell damage or thermal runaway thresholds (see backup)
  - Every cell individually monitored for temperature and voltage (2 voltage and 2 temp sensors per cell)

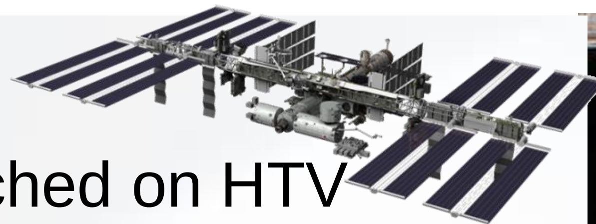
ISS Li-Ion Detailed Safety Features (cont)
(Failure Risk Mitigation)

- Cell Internal short circuits - 2-fault tolerance cannot be achieved, therefore DFMR utilized
  - Manufacturing Process Controls
    - Processes and documentation under configuration control
    - Manufacturing control documentation review and approved by NASA, Boeing, and PWR Team
    - Perform 100 % screening and chemical analysis for incoming raw materials
      - Analysis independent of raw materials' supplier analysis/certificate
    - Production Readiness Review
    - Annual battery cell production line audits
      - Modeled after Safety Risk Mitigation Tasks Audits
  - Cell Screening
    - 100% cell acceptance testing will be conducted for cell performance and reliability screening
    - Cells must undergo ISS specific screening. Including:
    - X-ray inspection - Open circuit voltage stand - Soft short recovery test
    - AC impedance - DC resistance at 50% State of Charge – Capacity tests
    - Nominal and off nominal cycling charge/discharge rates – Leak Checks
    - Workmanship vibration screening per SSP 41172 at the ORU level
    - 1% of randomly selected cells in each production lot (minimum of 1 cell per lot)- 100 charge/discharge cycles at 100% DOD followed by capacity test followed by a DPA
    - Periodic health and charge maintenance of ORU during ground storage

ISS Li-Ion Detailed Safety Features (cont.)
(Failure Risk Mitigation)

- Cell Internal short circuits (Continued)
  - Cell and ORU Physical Design
    - Physical controls to prevent cell penetration and contain flame as a result of cell vent
      - MMOD shielding built into ORU enclosure
        - Prevents MMOD from breaching a cell
        - MMOD shielding doubles to provide flame/energy absorption
    - Additional physical controls to prevent fault propagation
      - Cell vent before burst and directional vent away from base plate and adjacent cells
      - Header/vent test on each lot
      - ORU pressure relief/flame trap prevents overpressure but contains flame in the event of a cell vent
      - Physical separation between cell pairs
      - Individual cell fusing (internal fusible link)
      - Cells utilize shutdown separators between electrode windings
      - Cells are case neutral and are electrically insulated from ORU structure

ISS Li-Ion Flight Battery Status



- 6 Li-Ion batteries launched on HTV December 2016
  - Each IEA will have three Li-Ion ORUs and three Ni-H_2 ORUs (not electrically connected) stored on top of three On-Orbit Adapter Plate ORUs
- Installation and start-up on ISS: January 2017
- 17 of 27 Li-Ion batteries have been built and delivered
  - 6 on orbit, 11 in storage
  - ~1200 cells delivered
  - No failures
- Future launches in 2018, 2019, 2020

Backup

Safety Feature - Overcharge Control

Battery ORU

4.5 V Battery Isolates Cell → PVCA sets CW on isolation

4.45 V Battery sets Isolation arm status data → PVCA sets CW on condition

Battery Bypass controls each Cell Voltage to EOCV ± 25mVdc Battery Sinks current up to 4 amps as cell reaches EOCV

2.1 V Battery sets Isolation arm status data → PVCA sets CW on condition

2.0 V Battery Isolates Cell → PVCA sets CW on isolation

BCDU

Unusable Region

BCDU Shutoff 130V max (4.33 cell v)

Overcharge

Charge

Batteries

Discharge

BCDU LVC 76V approx

Overdischarge

Unusable Region

PVCA Software

No Cell voltage should ever be more than 4.5 V_{DC}

Cell Voltage = 4.3 V→ PVCA FDIR → Off

Bus Voltage = 126 V→ PVCA FDIR → Off

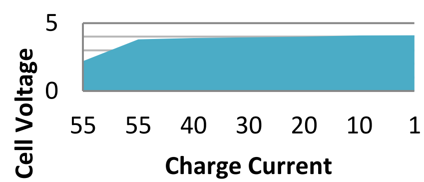
EOCV + Level 2 → PVCA FDIR → Off

EOCV + Level 1 → PVCA FDIR → 1 Amp

PVCA Sets Charge Current to ≤ 4 amperes

BOL EOCV 3.95 V (note: commandable3.2V→ 4.2V)

GS YUASA Nominal Charge Profile

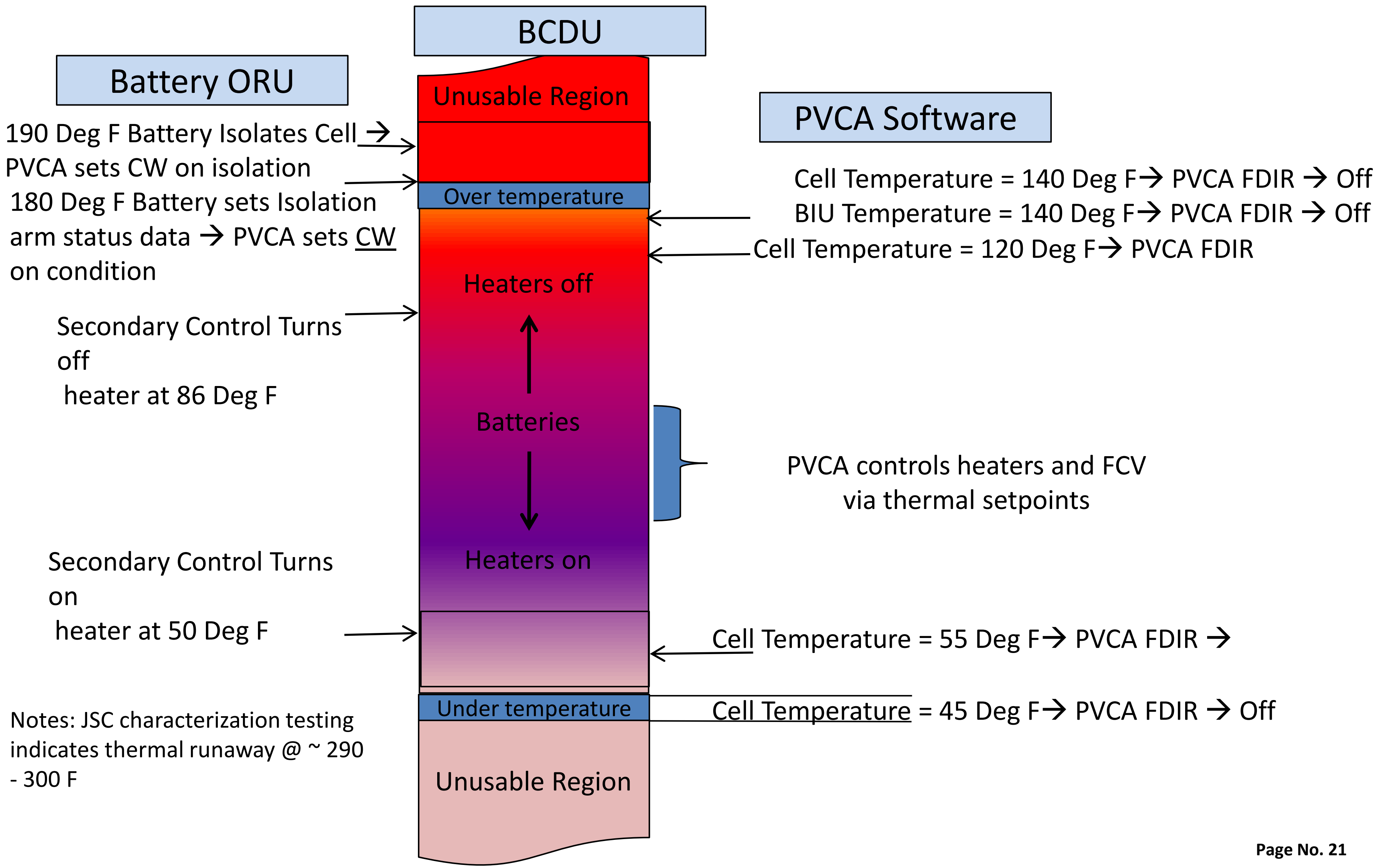


PVCA controls charge current via profile

Cell Voltage = 3.0 V→ PVCA FDIR

No Cell voltage should ever be less than 2.0 V_{DC}

Safety Feature - Overtemperature Control



Notes: JSC characterization testing indicates thermal runaway @ ~ 290 - 300 F

Achieving Safe, High Performing Battery Designs

by
Eric Darcy, Ph.D
Battery Technical Discipline Lead
NASA-JSC

Li-ion Battery Safety Event
11 April 2017

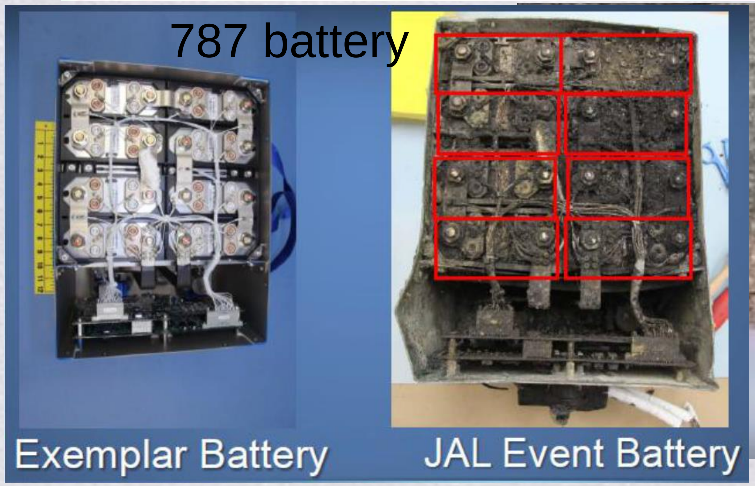
Why are Li-ion cell internal shorts still a concern?

- Despite extensive QC/QA, standardized industry safety testing, and over 26 years of manufacturing learning, major recalls have taken place and incidents still occur.
  - Search “battery fire recall statistics” at CPSC website (http://www.cpsc.gov/en/Search/?query=&filters=recalls) finds:
    - 28 recalls in last 12 months (May 2015-May 2016).
    - The recall rate has slightly increased over the last 10 yrs.[1]
- Many safety incidents that take place in the field due to latent defects not detectable at the manufacturer
- These internal short incidents are estimated at 1 to 0.1 ppm probability (well beyond 6 σ) in consumer applications using cells from experienced and reputable manufacturers[2]
  - Risk increases to 10 to 1000 ppm for certain lots of cells even from reputable manufacture
    - Boeing 787
    - Samsung Galaxy Note 7
- This risk can’t be retired by rigorous screening alone
- Worldwide Li-ion battery market is valued at $20 billion and failures can cost billions

Galaxy Note 7

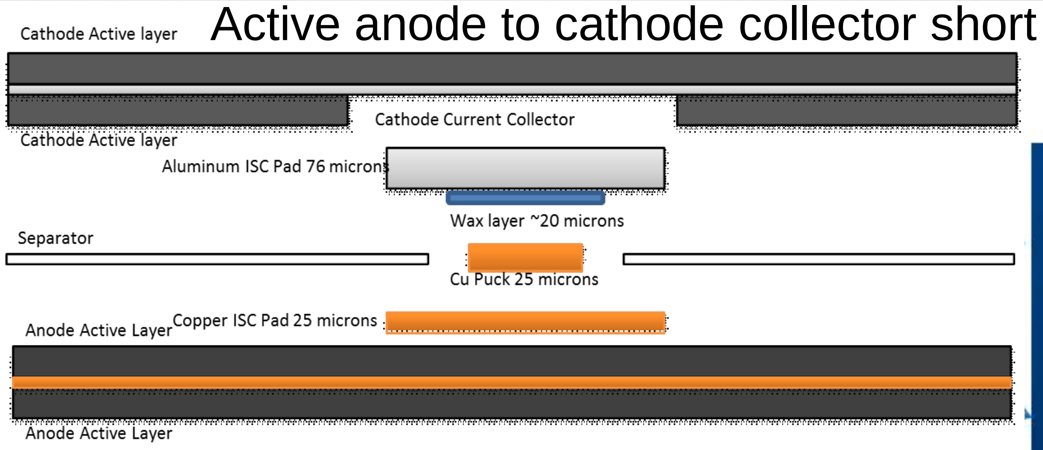
Sony Laptop

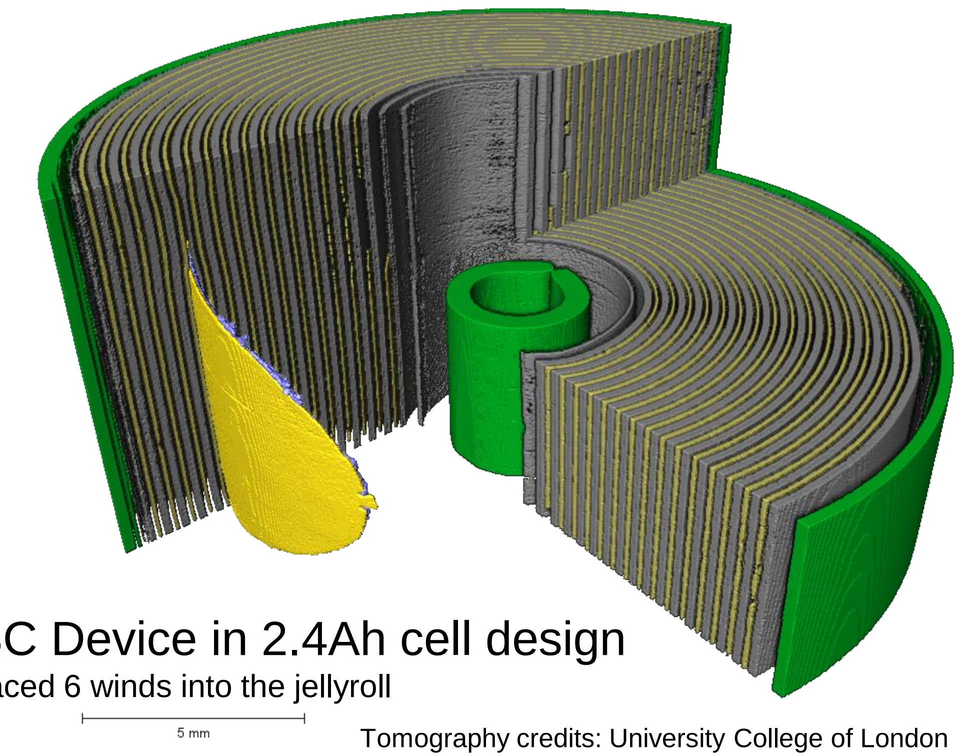
787 battery



1. D. Doughty, Li-ion Cell and Battery Safety, NASA-JSC Li-ion Battery Course 2017
2. B. Barnett, TIAX, NASA Aerospace Battery Workshop, Nov 2008

NREL/NASA ISC Device Design

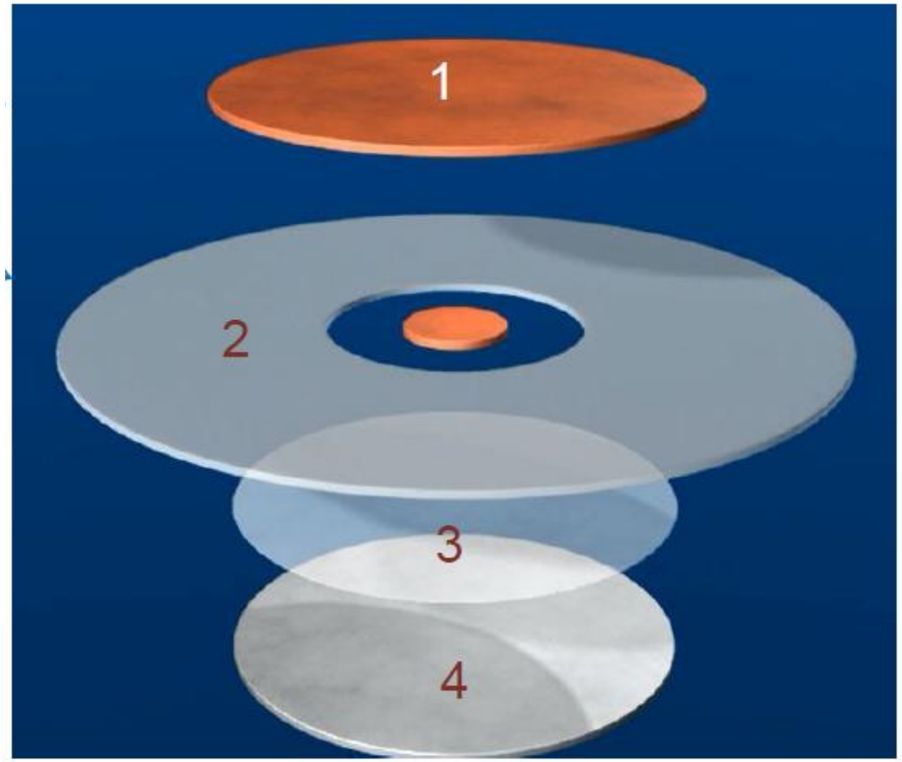




ISC Device in 2.4Ah cell design

Placed 6 winds into the jellyroll

Tomography credits: University College of London



Graphic credits: NREL

Top to Bottom:
1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

2010 Inventors:
- Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
- Eric Darcy at NASA

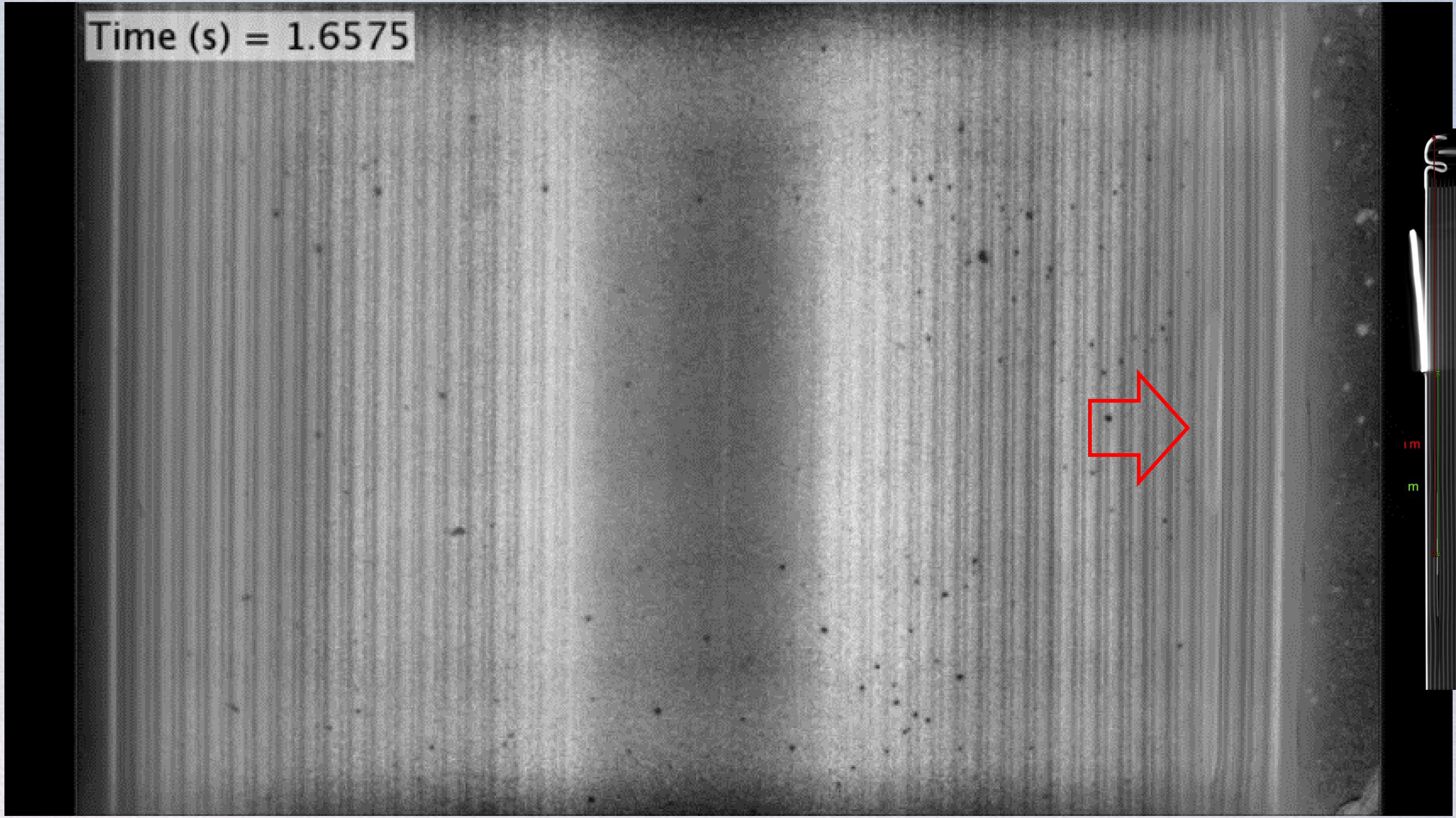
US Patent # 9,142,829 issued in 2015

Wax formulation used melts ~57°C

Thin (10-20 μm) wax layer is spin coated on Al foil pad

2016 Award Winner

LG 3.4Ah Cell with ISC Device Video



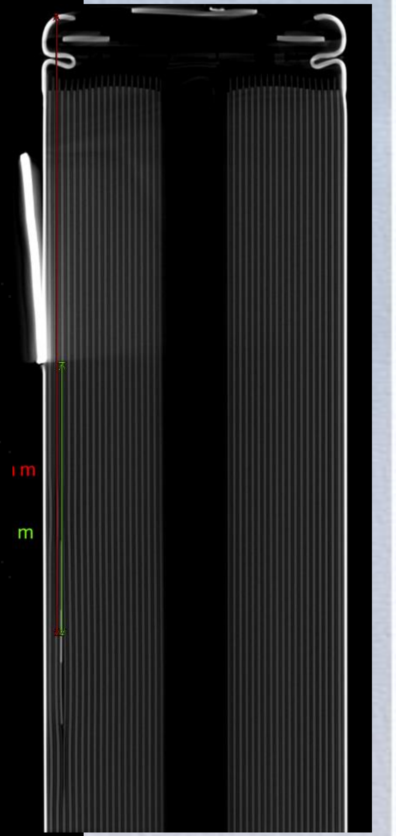
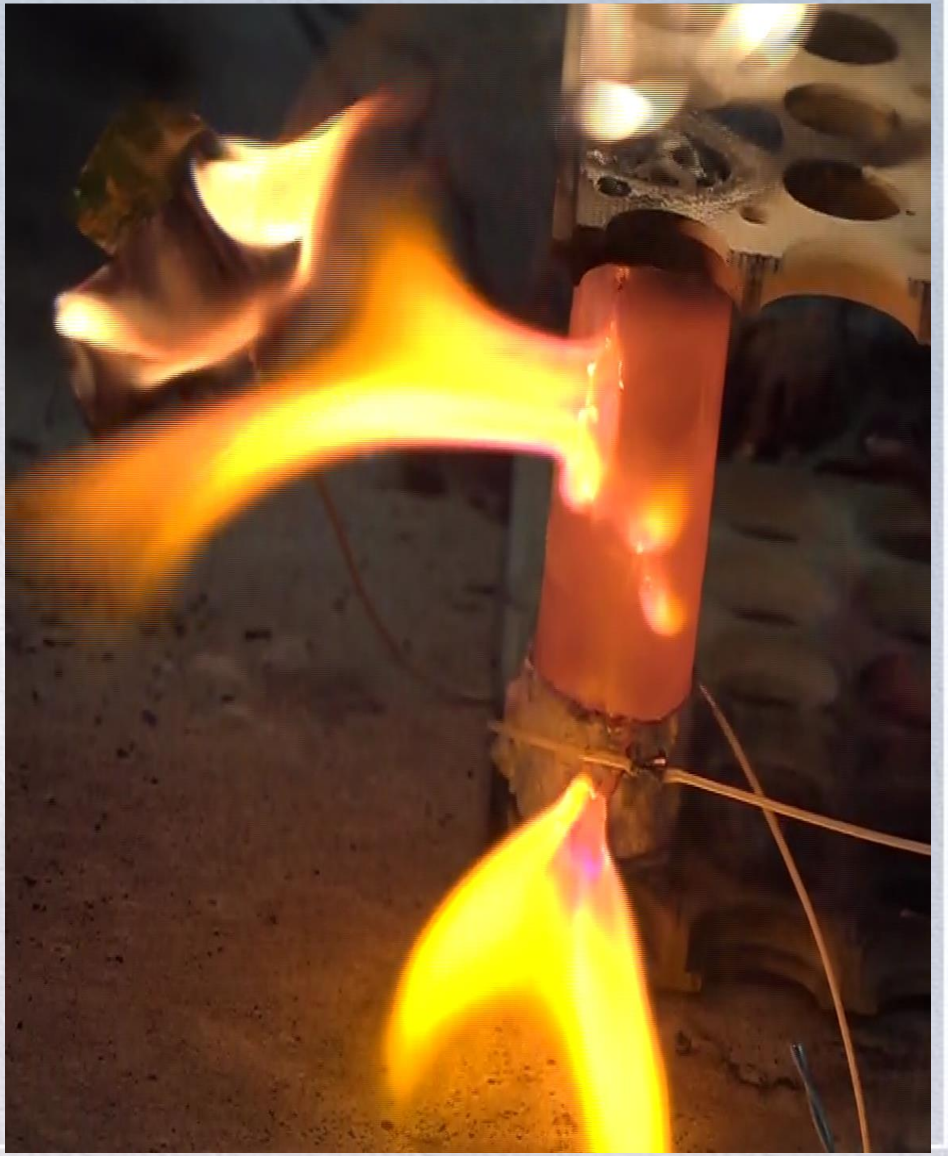


Image and video courtesy of D. Finegan, University College of London

Extremely high speed X-ray videos of cell with ISC device taken at the Diamond Synchrotron Facility near Oxford, UK

Thanks to the ISC Device, we now have 5 Battery Design Guidelines for Reducing Hazard Severity from a Single Cell TR

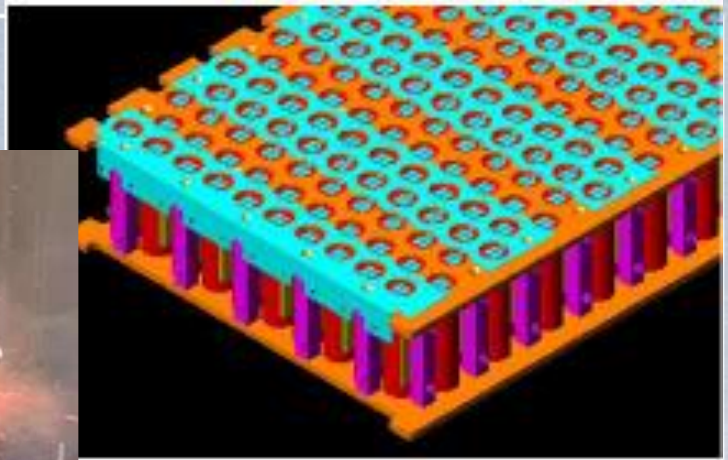
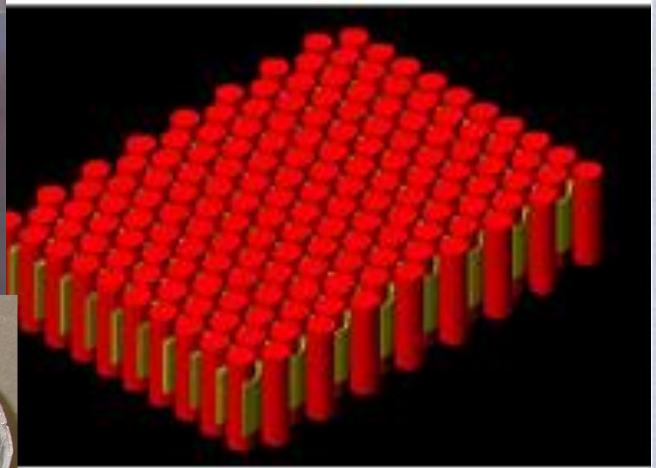
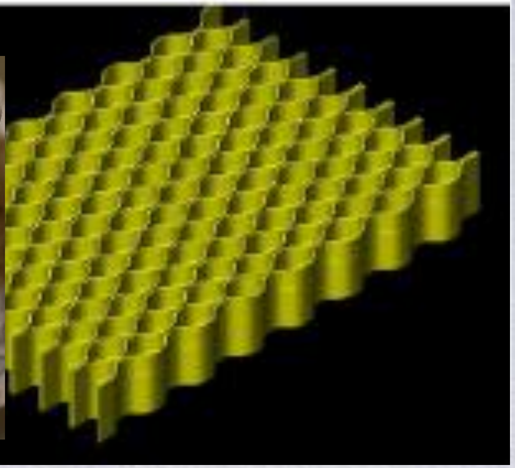
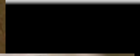
- Reduce risk of cell can side wall ruptures
  - Without structural support most high energy density (>660 Wh/L) designs are very likely to experience side wall ruptures during TR
  - Battery should minimize constrictions on cell TR pressure relief
- Provide adequate cell spacing and heat rejection
  - Direct contact between cells nearly assures propagation
  - Spacing required is inversely proportional to effectiveness of heat dissipation path
- Individually fuse parallel cells
  - TR cell becomes an external short to adjacent parallel cells and heats them up
- Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - TR ejecta is electrically conductive and can cause circulating currents
- Prevent flames and sparks from exiting the battery enclosure
  - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens



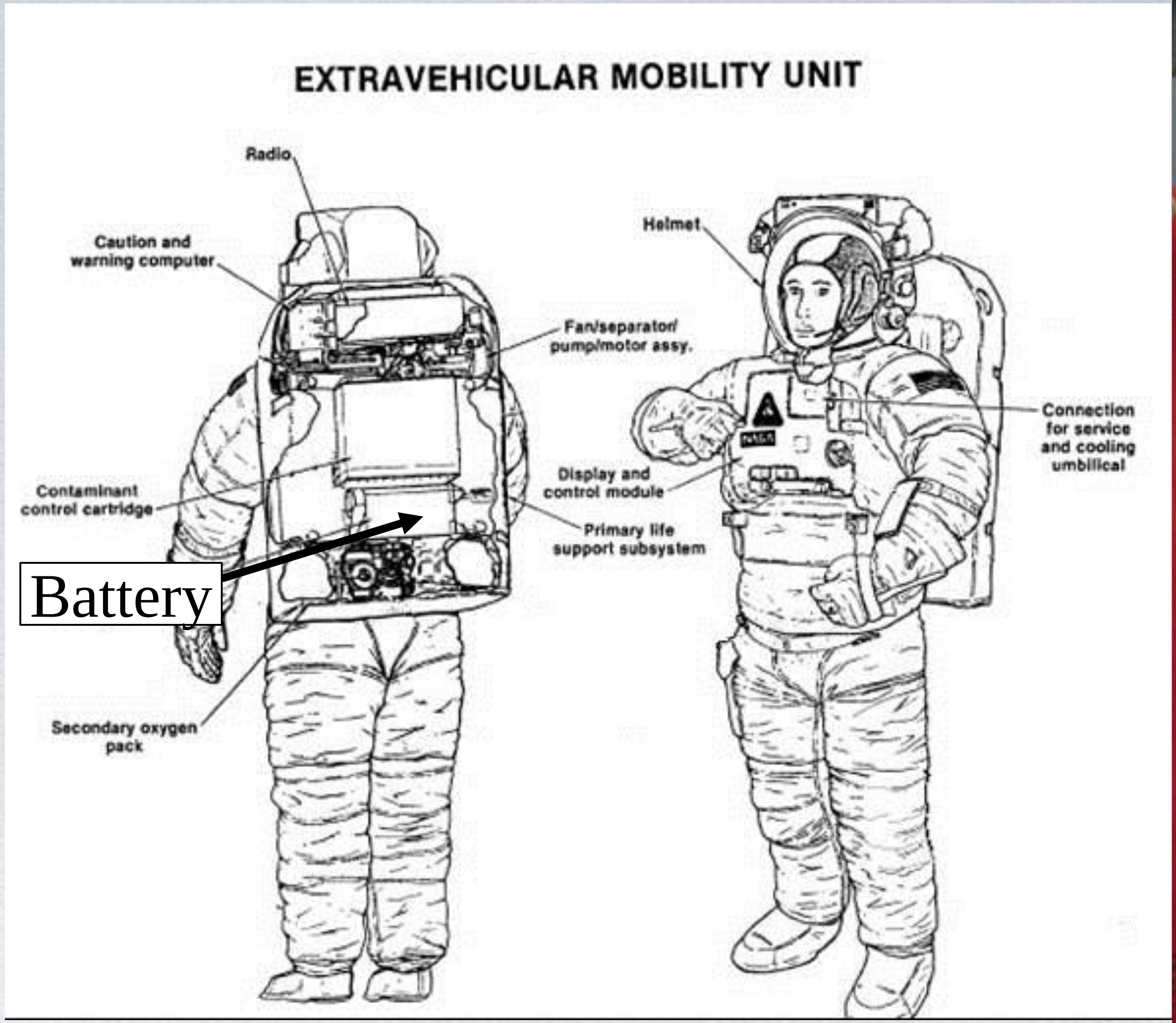
X-57 Battery Design Fails PPR Testing

- 320-cell module catastrophically fails during single cell PPR testing
  - Multiple cells propagated TR nearly simultaneously
  - DPA revealed numerous cell can side wall ruptures
- Design not following guidelines 1 and 2
  - Doesn’t protect against sidewall rupture
    - Nomex paper (yellow) is weaved in between cell can walls
    - Cell secured at their ends with G10 capture plates maybe held too tightly
  - Doesn’t provide sufficient heat dissipation between cells
    - Cell heat is dissipated through Ni bussing
    - Ni is a poor thermal conductor
- Battery redesign and retest will require trigger cells with ISC device



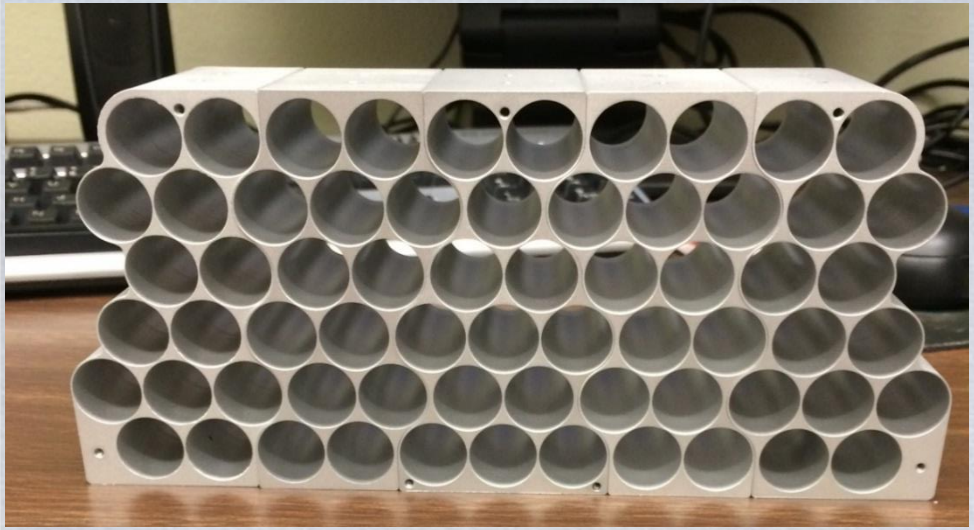






Current Li-ion Spacesuit Battery



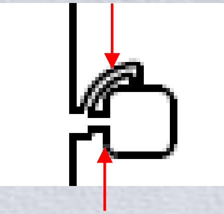
Used on over 29 spacewalks for far

Safer, Higher Performing Spacesuit Battery Design

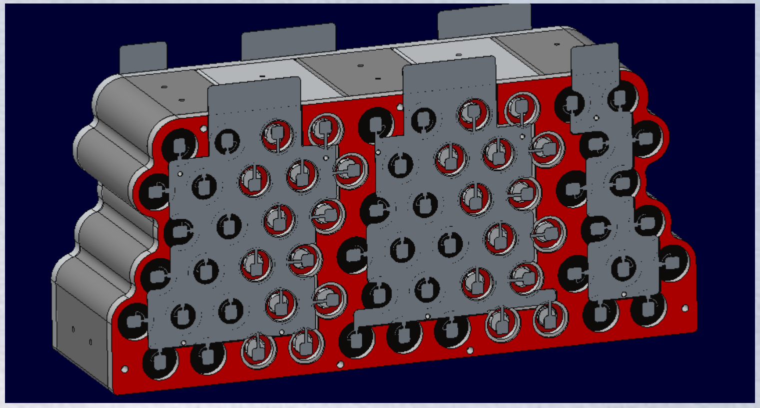


Features
- 65 High Specific Energy Cell Design 3.4Ah (13P-5S)
- 37Ah and 686 Wh at BOL (in 16-20.5V window)
- Cell design likely to side wall rupture, but supported

Fusible link



Assembly tab
Removed after welding



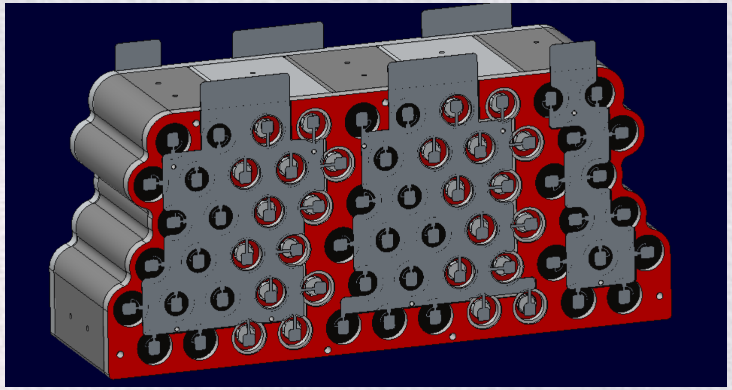
Aluminum interstitial heat sink protects adjacent cells from side wall ruptures during TR and dissipates heat very effectively
- No corner cell locations

Full scale battery

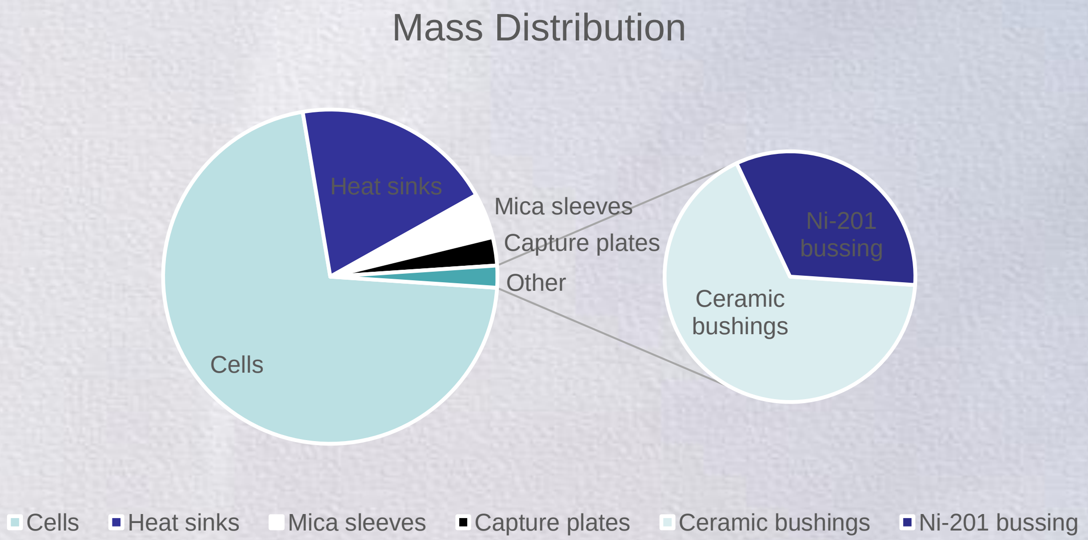
<u>Compliance with the 5 rules</u>
- **Minimize side wall ruptures**
  - Al interstitial heat sink
- **No direct cell-cell contact**
  - 0.5mm cell spacing, mica paper sleeves on each cell
- **Individually fusing cell in parallel**
  - 12A fusible link
- **Protecting adjacent cells from TR ejecta**
  - Ceramic bushing lining cell vent opening in G10 capture plate
- **Include flame arresting vent ports**
  - Tortious path with flame arresting screens
  - Battery vent ports lined with steel screens

Cell Brick Assembly > 180 Wh/kg

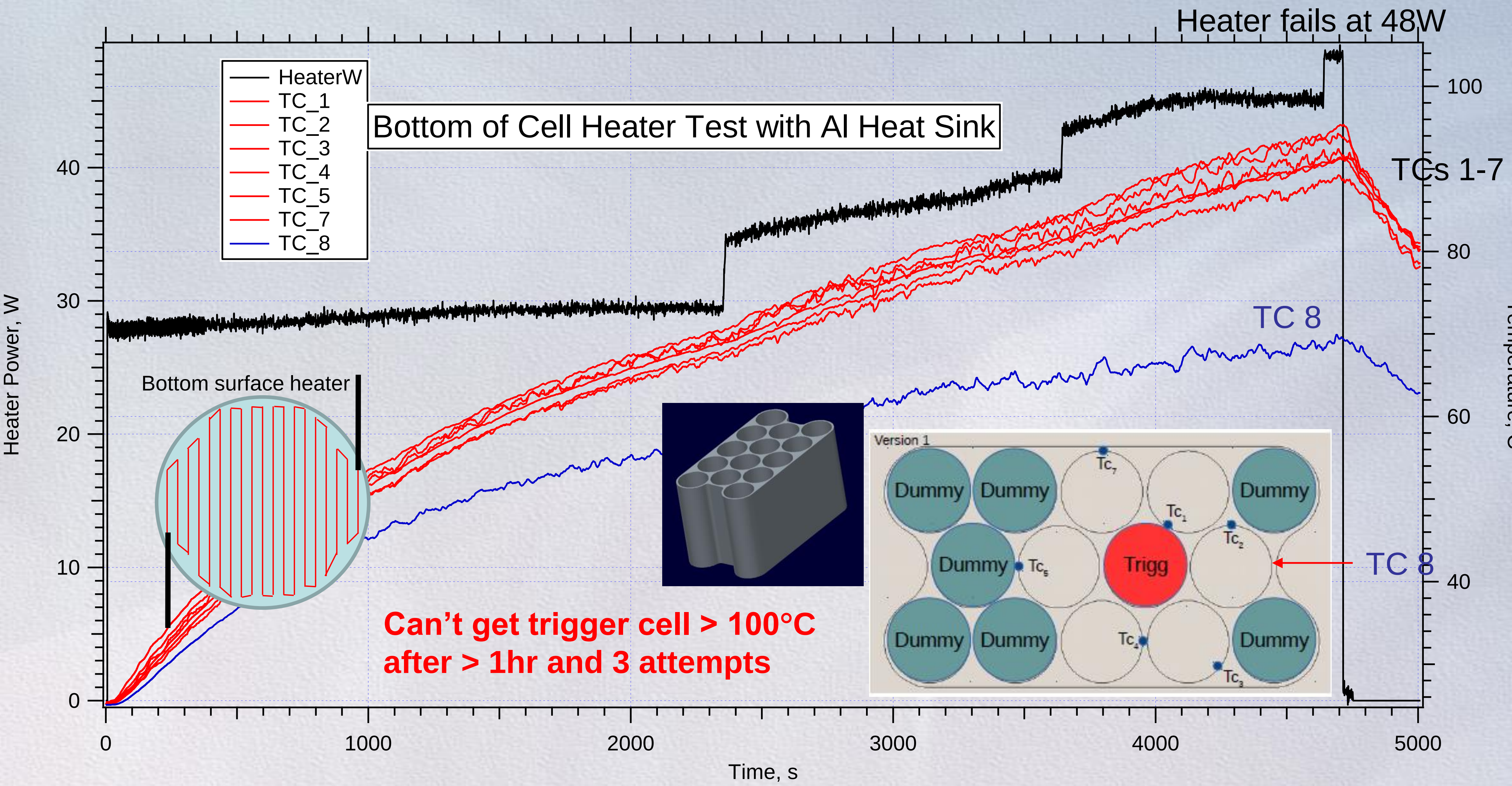
Mass Categories	g	%
LG MJ1 Cells	3012.75	71.3%
Heat sinks	824.95	19.5%
Mica sleeves	182.31	4.3%
Capture plates	115.81	2.7%
Ceramic bushings	60.15	1.4%
Ni-201 bussing	29.71	0.7%
Total	4225.7	



- With 12.41 Wh/cell, cell brick assembly achieves 191 Wh/kg
  - Assuming 12.41Wh per cell
- Design has 1.4 parasitic mass factor
  - Cell mass x 1.4 = Brick mass



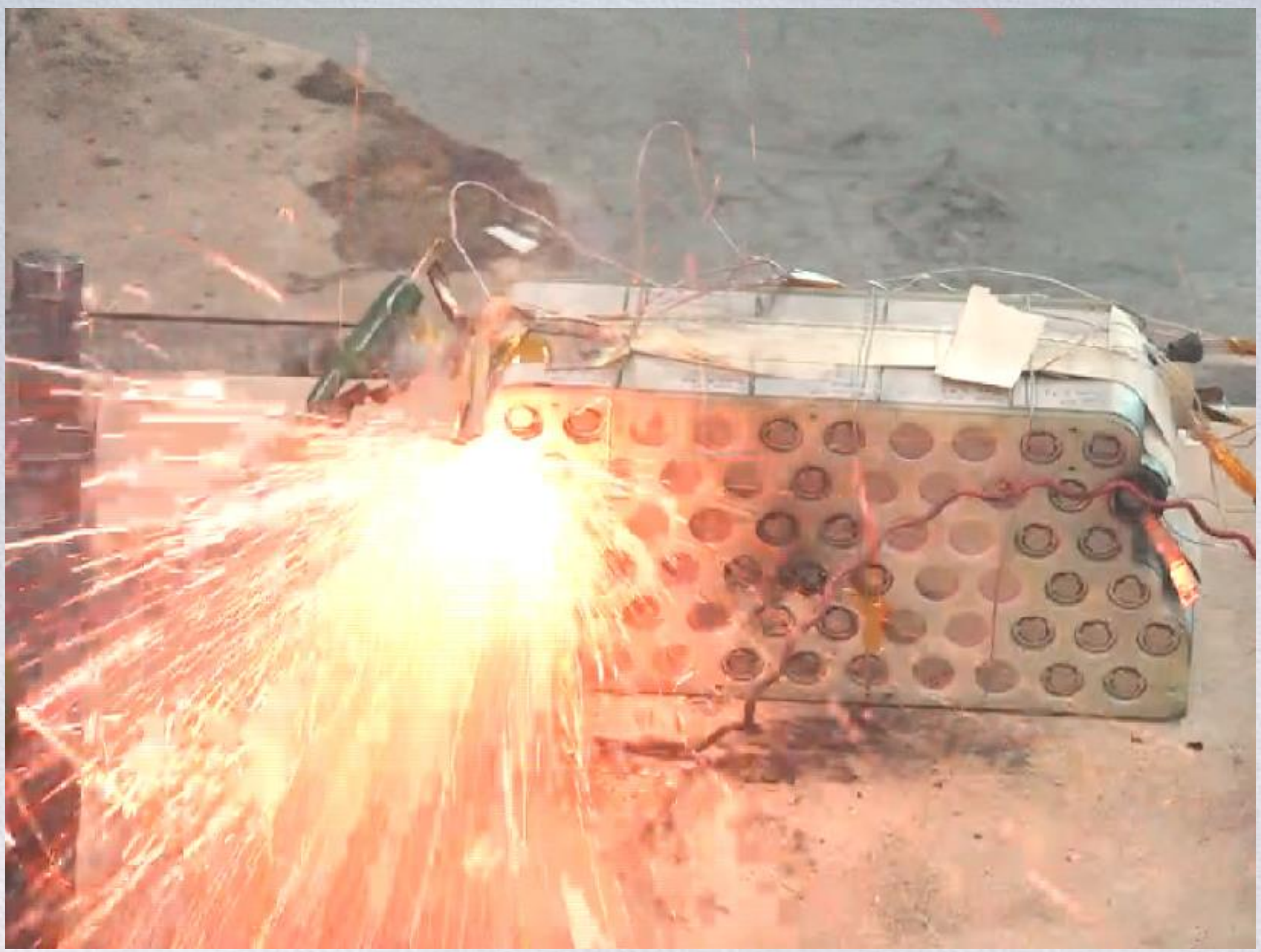
Attempt to Drive TR with Bottom Heater While in Al HS

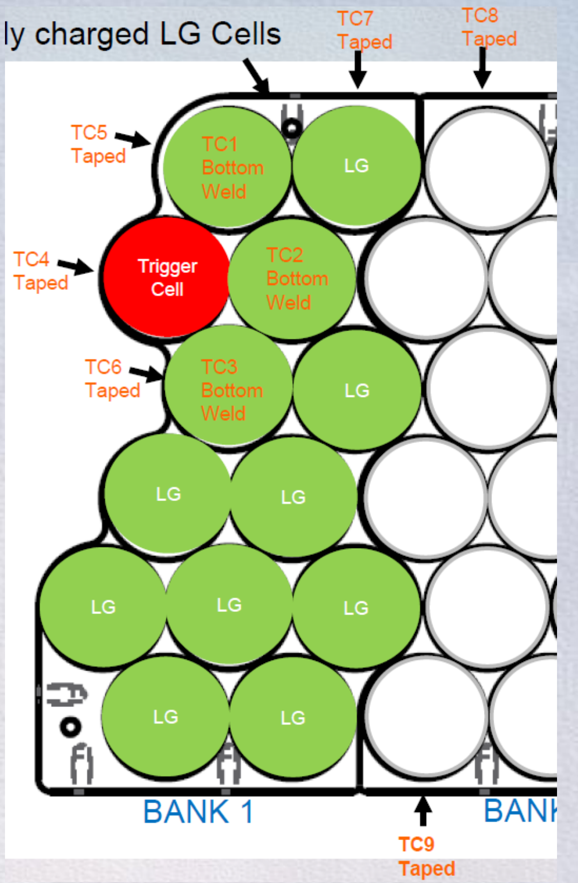


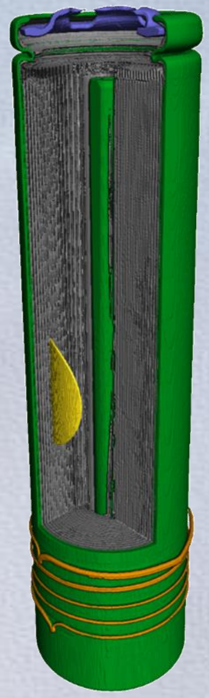
Can't get trigger cell > 100°C after > 1hr and 3 attempts

Spacesuit Battery Brick: Thermal Runaway Test

This safety verification test was only possible with cells implanted with ISC device!
Without device, battery would have to be overdesigned by several pounds





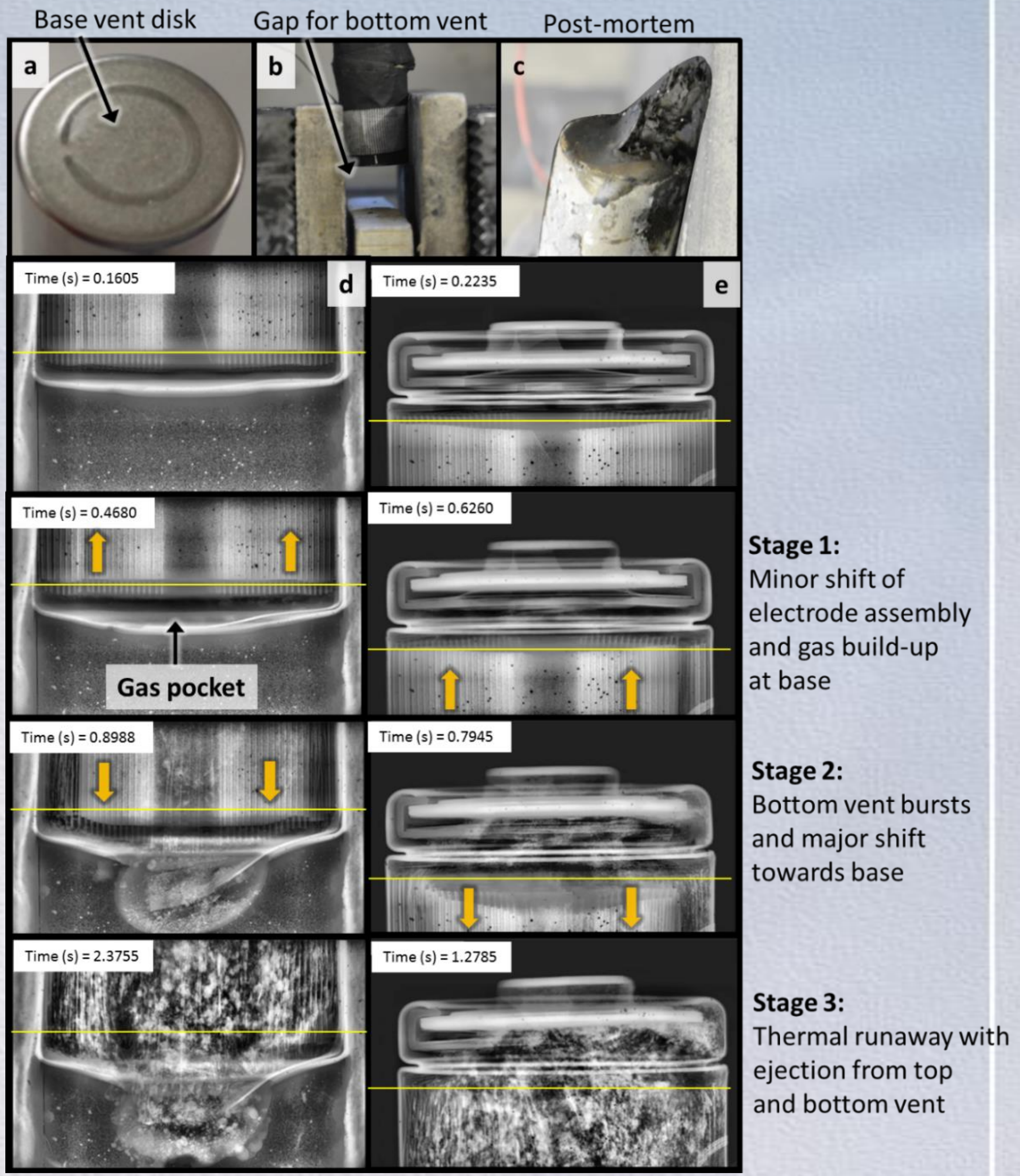


Trigger cell is 2.4Ah cell with Type 2 ISC device
Result - No TR propagation to other cells

Cell Level Benefits

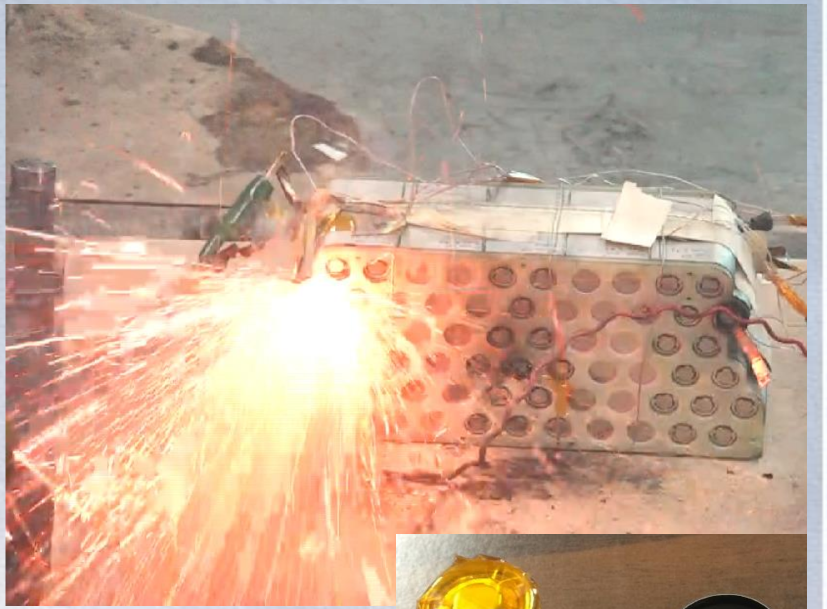
- ISC device enable unique insight into cell thermal runaway mechanism that replicates field failure responses and conditions
  - It's consistent and reliable, safe to implant, and can be activated on demand
  - Can be used to test all 4 types of shorts, at any state of charge, and without compromising cell enclosure
    - We've confirmed that the anode-to-Al short is most hazardous
    - Predisposition of cells to experience side wall ruptures can be assessed fairly with device
  - Can be used to test numerous cell safety features and find out their limitations and greatly improving safety
    - non flammable electrolytes, advanced separators, internal fusible links, bottom vents, thicker can walls, etc
    - The insights from high speed X-ray videos are shedding new light on cell failure and are guiding the development of safer commercial cell designs
    - LG is currently buying them from NREL for their internal R&D while negotiating terms for licensing

Images courtesy of D. Finegan, UCL



Battery Level Benefits

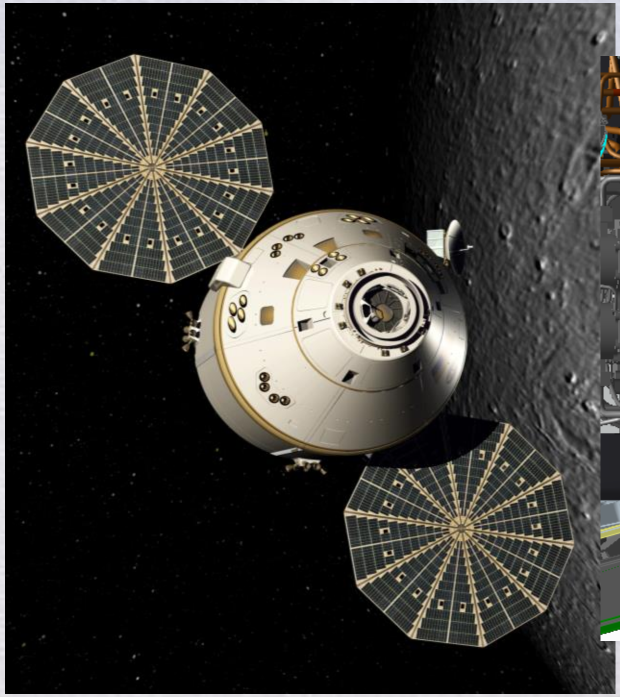
- ISC device enables critical battery safety verification
  - Recent NASA studies show that maximizing heat dissipation between cells is best way to achieve high performance and best protect adjacent cells from TR propagation
  - With the aluminum interstitial heat sink between the cells, normal trigger cells can't be driven into TR without excessive temperature bias of adjacent cells
  - ISC device in trigger cells enabled the verification of the spacesuit battery to be passively TR propagation resistant (PPR)
    - New spacesuit battery brick design achieves > 190 Wh/kg (vs 120 Wh/kg for current spacesuit battery design)
  - ISC device in trigger cells enable verification that the steel sleeves on each cell effectively mitigates side wall rupture hazard – critical for Orion CM battery
    - Replaces the catastrophic hazard of the previous large cell battery design
- Achieving PPR battery designs reduces catastrophic hazards to critical hazards (check engine light)
  - This design and vetting methodology also benefits terrestrial battery applications

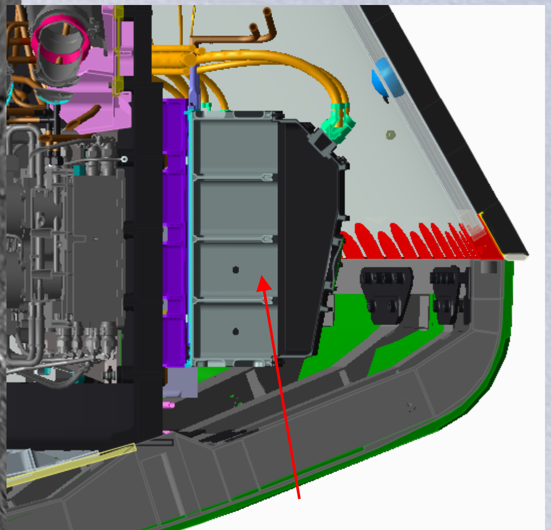


ISC Device is Maturing Very Well

- Maturity (TRL 9)
  - Cells with device sought by numerous researchers (including University College of London) and battery developers (ex, Navy, SpaceX, X-57)
  - Device has been successfully implanted in more than 5 commercial cells (cylindrical and pouch) designs to date
  - Device has enabled the safety verification of the spacesuit, small experiment, and Orion batteries, and with many more to come
  - Licensing agreements are currently in negotiations with >3 parties (cell manufacturers, battery heat sink developer, and consumer electronic company)

X-57 Electric Airplane





Orion CM Battery

SAFETY & HEALTH LEARNING ALLIANCE

NASA Lithium Ion Battery Mishap: RoboSimian Droid Lithium Ion Battery (LIB) Caught Fire

- NASA's office of Safety and Mission Assurance has revealed the Agency has had at least four explosions, and several close calls over the past decade due to lithium-ion batteries (LIBs).
  - These cells pose unique risks to safe use, storage, and handling
  - It was determined that Fire and Building Codes, and Safety Data Sheets are not current with LIB hazard classifications
- LIB's are extensively used throughout NASA for a viable source of DC power for flight hardware and ground support equipment (GSE) systems, so understanding their risks and hazards are essential.
- A recent explosion/fire involving a LIB occurred at Jet Propulsion Lab during battery charging onboard a DARPA RoboSimian droid, in June of 2016.
  - Team of scientists replaced a lithium-ion battery for a spare one and left the vicinity to allow the spare battery to charge. During the charging process, the battery exploded and the droid caught on fire.
  - RoboSimian includes 96 cells: Two banks of 48 cells arranged in parallel (24s2p) operating at ~ 100V and could provide up to 20 amp-hours (Ah) of capacity
  - Failure analysis is under completion and includes Destructive Physical Analysis (DPA) and Computed Tomography (CT) scan for determination of proximate cause .
- Video: https://www.youtube.com/watch?v=UxJBRK2EXFc
  - Ref: AB Video Studio - Science and Technology via You Tube

SAFETY & HEALTH LEARNING ALLIANCE

NASA Lithium Ion Battery Mishap – Armstrong Flight Research Center (AFRC) Hybrid-Electric Integrated System (HEIST) Testbed Battery Box Fit Test

- Ground testing of lithium-ion (LiFePO4) batteries (LIB) for HEIST program in Bldg. 4853 (Shuttle Hangar)
    - Future X-57 type aircraft testing using LIB Battery Boxes for ground support
- One Engineer received minor injury (1st degree burns), due to arc flash incident
    - 53.8VDC was shorted across the positive & negative terminals of Battery Box with no PPE donned (exceeding OSHA exposed energized source criterion for shock at 50V, but not NFPA 70E: Greater than 100.0 volts)
- These LIBs were not COTS, therefore GIDEP Alert is not applicable
- No Mishap Warning Action Report (MWAR) created, but Centers are aware of this mishap with formation/participation on AFRC's LIB Tiger Team
- AFRC formed this Agency-Wide Tiger Team to address battery hazards and risks reduction for DC (i.e. LIB) powered vehicle programs by requiring LIB safety controls for ground applications
- It was determined that minimal standards apply to DC Battery safety, in terms of arc flash:
    - OSHA has no requirements for DC Arc Flash but references NFPA-70E as a "recognized industry practice"
    - NFPA-70E expanded on DC Battery system's hazard requirements to include arc flash in the 2012 edition
    - IEEE has minimal guidance on DC arc flash hazards with no proven test/calculation methods
    - NOTE: NFPA70E is included under the NASA General Safety Program Requirements document (NPR 8715.3, section 3.6).

SAFETY & HEALTH LEARNING ALLIANCE

NASA Lithium Ion Battery Tiger Team Electrical Safety Considerations

- The following considerations regarding LIB hazard controls and measures include:
  - Designed Protective Controls -
    - Electronic battery management systems, internal protective devices, shock protection, DC ground fault protection…
  - Shock and Arc Flash Protection/Analysis, refer to NFPA 70E:
    - Article 310.5 (C) for Electrical Arc Flash Hazard Analysis and Risk Assessment
      - Reference: Informative Annex D 5.2 - DC Incident Energy Calculations
        - Consider reviewing Chapter 12 of: https://brainfiller.com/product/complete-guide-to-arc-flash-hazard-calculation-studies/
          Disclaimer: This is not an endorsement, but we have found this material to be helpful.
    - Article 310.5 (D) for Safeguards
    - Article 320.3 (A) (5) Labeling
  - Processing Measures -
    - Procurement of UL approved LIBs
    - Work performed on LIBs via approved procedures
  - Training –
    - In process
  - PPE – refer to NFPA 70E:
    - Ref: Table 130.7(C)(15)(B) Arc-Flash Hazard PPE Categories for DC Systems
    - Ref: Table 130.7(C)(16) Personal Protective Equipment (PPE)
  - Awareness – Today's SHLA event
  - Emergency Response -
    - In work with our Fire Protection Working Group
  - Additional Considerations -
    - Handling, Storage, Transportation, and Disposal

SAFETY & HEALTH LEARNING ALLIANCE

Recommended Reading materials:

- Below are web-links to technical articles co-authored by our Commodity Risk Assessment Engineer, Bhanu P. Sood, prior to joining the NASA Goddard Space Flight Center:
  - Williard, Nick, Bhanu Sood, Michael Osterman, and Michael Pecht. "Disassembly methodology for conducting failure analysis on lithium–ion batteries." Journal of Materials Science: Materials in Electronics 22, no. 10 (2011): 1616.
    Ref: http://link.springer.com/article/10.1007%2Fs10854-011-0452-4
  - Williard, Nicholas, Christopher Hendricks, Bhanu Sood, Jae Sik Chung, and Michael Pecht. "Evaluation of Batteries for Safe Air Transport." Energies 9, no. 5 (2016): 340.
    Ref: www.mdpi.com/1996-1073/9/5/340/pdf
  - Sood, Bhanu, Michael Osterman, and Michael Pecht. "Health monitoring of lithium-ion batteries." In Product Compliance Engineering (ISPCE), 2013 IEEE Symposium on, pp. 1-6. IEEE, 2013.
    Ref: www.asminternational.org/documents/10192/18102672/edfa1602p04.pdf/...