SAFETY & HEALTH LEARNING ALLIANCE

Lithium-Ion Battery Safety

April 11, 2017

1-3:30 p.m. Eastern

Presenters

- **Robert Swaim**, National Resource Specialist, Aerospace Engineering Investigator, National Transportation Safety Board (NTSB)
- **Tamera Tucker**; High-Energy Storage Systems, Safety Program and Certification Authority; U.S. Navy
- **Dr. Larry Valencourt**, U.S. Army (retired)
- **Penni Dalton**, International Space Station Battery Subsystem Manager, NASA Glenn Research Center
- **Dr. Eric Darcy**, Battery Technical Discipline Lead, NASA Johnson Space Center
- **Michael Milbert**, Quality and Safety Analyst, NASA Safety Center

Summary

Facilitator: Mike Lipka, Knowledge Officer, NASA Safety Center

Attendees: 187 (approximately)

Purpose of the Safety and Health Learning Alliance (SHLA): Share experiences and collaborate ideas across various government and defense agencies, related industries, and professional organizations for the mutual goal of achieving high levels of safety and health.

SHLA Goals:
1. Collaborate: Create an open forum for collaboration.
2. Concentrate: Accelerate learning by connecting people to people.
3. Context: Learn from your peers about how and why.
4. Connect: Establish networking opportunities.

The SHLA website includes a video recording of the event and a copy of the presentations. Please submit questions, comments and event recommendations on the website or by emailing NASA-NSC@nasa.gov.

Event Summary

Although the underlying technology has roots dating back to the 1910s, lithium-ion (Li-ion) batteries have been in widespread use only since introduced commercially in the early 1990s. Today, Li-ion battery usage ranges from small tool operation to transportation vehicles to aeronautic and space flight systems.

Li-ion batteries allow for greater battery energy density and a slower energy discharge rate, but there are safety issues with regards to storage, transportation and battery aging that must be addressed.

During this offering of SHLA, guest speakers will provide insight into several mishaps within NASA and the resulting mitigation approaches, as well as insight into Li-ion battery safety lessons learned from the U.S. Army, U.S. Navy and the National Transportation Safety Board.

Presentations

"787 Battery Investigation Summary" — Swaim

- Three 787 planes experienced Li-ion battery failures in that first year
- There was heat and smoke, but no electrolyte fire (batteries showed burned connectors at the front of the case and "protrusion" melting at the back of the case)
- Failure started in one cell and progressively spread through all eight prior to the redesign
- Initial findings included that there had not been an over-charge or over-discharge, no external source of damage, and no external pre-failure
- Physical findings included steel particles in the bottom of the cases, cells with three electrical parallel windings of unequal thickness, mechanical gaps developed rivets in cell terminals and the potential for extensive improvements in monitoring
- Cold temperatures were the only commonality between the three failures
- Test findings
    - Internal Short Circuit (ISC) starting in a single winding melted aluminum current collectors for winding having initial failure
    - Radio frequency emissions found during runaway could be a potential issue for digital electronics
    - Insufficient temperature and voltage monitoring led to strongly recommending measurements of internal cell temperatures, millivolts and microseconds for response
    - Charge current oscillations weren't a factor
- The 787 Main and Auxiliary Power Unit (APU) battery installation changes
    - Containment chamber added for the battery
    - Cells vented out of the battery case and overboard
    - Battery design changed
    - Maintenance changes adopted
- Probable cause was an internal short circuit within a cell of the APU Li-ion battery, which led to thermal runaway that cascaded into adjacent cells

"Lithium Battery Safety" — Tucker

- There was a catastrophic, cascading, cell-to-cell failure of a large, high-energy dense Li-ion battery
    - Also touched on an armory fire, electronic nicotine devices and hoverboards
- Had lacked a full understanding of what could happen with these batteries and the system in general
- Lessons learned
    - Systems engineering and system-level hazard analysis
    - Expanded safety testing, characterization and qualification
    - Independent safety certification (NAVSEA INST 9310.1C)
- Best practices
    - Segregated storage (e.g., new, used, damaged, hazmat, charging)
    - Storage facility design (e.g., fire suppression capabilities, ventilation, fire proof)
    - Emergency responders (informed and trained)
    - Use of protection devices (e.g., venting, thermal, cell-to-cell balancing, Battery Management Systems (BMSs))
    - Charging system design and use
    - Battery and system design (e.g., non-propagating; solid lithium; deluge/containment systems; alerts, scan rates, and BMS component redundancy)

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

- Over 700,000 BB-2590U batteries in more than 70 different systems (workhorse of the Army)
- Army assigns a government person to witness Quality Assurance tests on site at the manufacturer
- PP-8498U chargers are universal chargers that can charge multiple battery types and chemistries (were charging the BB-2590U batteries in the discussed scenario)
- Three known incidents between 2010 and 2015
- After first incident the firmware was updated, and after the second a Ground Precautionary Action (GPA) was issued, requiring charger updates
- In the third incident, six chargers were charging four batteries each when an incident occurred, causing the sprinkler systems to go off (resulted in millions of dollars in damages due to the soot damage caused by the sprinklers, and led to an investigation)
- Charger B was shown to have the right, updated firmware, however Charger A did not
    - The older firmware would continue trying to charge a battery even if it wouldn't take the charge and would keep hitting it until it failed
- Another GPA was issued reinforcing that upgrades to chargers were required and batteries must be properly maintained
- Factors at play included that the original firmware was flawed, batteries were not maintained and discarded properly, and there was a communication breakdown that led to the operator not receiving the update

"International Space Station Lithium-Ion Battery Safety Considerations" — Dalton

- International Space Station (ISS) battery is the largest Li-ion battery to be flown on a manned mission
- Was a direct replacement for existing nickel-hydrogen (Ni-H_2) batteries on orbit
- Safety was a prime concern and designed-in from the beginning of the project (including a minimum of two-fault tolerance)
- Tested six different cell designs and vendors; two were subjected to safety and abuse tests and taken through qualification before GS Yuasa 134A-hr cells (aerospace design) were selected
- Battery-level safety features
    - Two independent controls against thermal runaway
    - Voltage and temperature monitoring of all cells
    - Circuit protection/fault isolation at the individual cell level for both high- and low-voltage and high temperature
    - Physical separation between cell pairs and 10 packs
    - Controlled direction of cell vents
    - Micrometeoroid and Orbital Debris shielding
    - Dead face device to remove power from output connector during ground or Extravehicular Activity (EVA)
    - Non-propagation of failures
- Li-ion Orbital Replacement Unit (ORU) safety features
    - Cell terminal/bus bar (specified torque and conformal coat)
    - Cell external short and thermal management
    - Over charge/ over discharge and temperature controls

    - Cell internal short circuits (manufacturing process controls, cell screening, cell and ORU physical design)
- Status
    - Six Li-ion batteries launched December 2016 and installed and started-up on ISS January 2017
    - Approximately 1,200 cells delivered and *no* failures

"Achieving Safe, High Performing Battery Designs" — Darcy

- Even though the Li-ion battery industry is mature, there are still concerns about internal short incidents
- Incidents are often due to latent defects not detectable at the manufacturer
- Internal short incidents are estimated at 1 to 0.1 parts per million probability in consumer applications (if cells from experienced, reputable manufacturers)
- Rigorous screening alone can't retire the risk
- ISC device: minimizes heat required to drive trigger cell into thermal runaway with 57 degrees Celsius wax
- Device led to five better design guidelines
    - Reduce risk of cell can side wall ruptures
    - Provide adequate cell spacing and heat rejection
    - Individually fuse parallel cells
    - Protect the adjacent cells from the hot thermal runaway cell ejecta
    - Prevent flames and sparks from exiting the battery enclosure
- X-57 battery design failed to demonstrate Passive thermal runaway Propagation Resistance (PPR) testing
    - During single cell PPR testing the 320-cell module catastrophically failed (design failed to follow the first two guidelines)
    - Battery redesign and retest requires trigger cells with ISC device
- Led to safer, higher-performing spacesuit battery design (compliant with five guidelines)
- Cell-level benefits
    - ISC device enables unique insight into cell thermal runaway mechanism that replicates field failure responses and conditions
    - It also enables critical battery safety verification
    - Achieving PPR battery designs reduces catastrophic hazards to critical hazards
- Device is maturing (Technical Readiness Level 9)

NASA Mishaps — Milbert

- NASA Office of Safety and Mission Assurance revealed at least four explosions and several close calls over the past decade due to Li-ion batteries
- Li-ion batteries used extensively throughout NASA for flight hardware and Ground Support Equipment systems
- Recent mishap at the Jet Propulsion Laboratory while charging RoboSimian droid battery
    - Replaced a Li-ion battery for a space one and left it to charge
    - During charging process the battery exploded and the droid caught fire
    - Failure analysis in the works and includes Destructive Physical Analysis and Computed Tomography scan for determining proximate cause
- Incident at Armstrong Flight Research Center during the Hybrid-Electric Integrated System (HEIST) test bed battery box fit test
    - Ground testing of Li-ion batteries for HEIST program
    - Arc flash incident occurred

- The batteries were *not* Commercial Off-the-Shelf, so a Government-Industry Data Exchange Program alert doesn't apply
- In lieu of a Mishap Warning-Action Response Armstrong formed a Li-ion battery tiger team to address battery hazards and risk reduction
  - Team is looking into
    - Designed protective controls
    - Shock and arc flash protection/analysis
    - Processing measures
    - Training
    - Personal Protective Equipment (PPE)
    - Awareness activities
    - Emergency response
    - Handling, storage, transportation and disposal

Questions and Answers

***Audience Question (for Swaim*)**

During the testing for internal short circuit and thermal runaway, were any arc flash events captured?

Response

Arc flashes weren't something they were able to catch on camera. They ignited the cells and were able to get some incredible bursts, but as far as an electrical-type arc flash, nothing was captured.

Audience Question (for Swaim)

Has the 787 overboard mitigation been proven if cell-to-cell propagation does occur inside the battery compartment?

Response

Yes, Boeing extensively tested the battery's stainless steel box. As soon as the first cell vents, there is enough pressure in the box that it blows the disk. They have had full batteries runaway.

Audience Question (for Swaim)

Did cold temperature have anything to do with the 787 fires?

Response

Yes, for the rivet issue. The separator melted only at cold temperatures.

Audience Question (for Tucker)

What type of batteries were used in the catastrophic failure that was just talked about? Li-ion polymer (LiPo)? Li-ion PO4?

Response

Due to the nature of the programs, details cannot be shared. In general terms, a very large Li-ion battery.

Audience Question (for Tucker)

Is there any PPE for fire crews to protect them from off-gassing fumes? For example, is there a known filter that can be used on a respirator to protect firefighters from breathing LiPo off-gassing?

Response

Wasn't sure. Noted that emergency responders may already have that information based on training, possibly normal gear.

Additional Response from Valencourt
Self-Contained Breathing Apparatuses (SCBAs) are recommended in these kinds of fires.
Additional Response from Swaim
Acids are so intense and venting can be extremely hot, so SCBAs are recommended.
Additional Response from Gerry Schumann, NASA Institutional Safety Program Executive
Fire response is done with Scott Air packs.

Audience Question (for Valencourt)
Was 400 milliampere per hour enough to start these fires?
Response
Yes.

Audience Question (for Valencourt)
Did you augment fire protection or detection systems where storage is? Or charging stations?
Response
No, no special augmentation was used.

Audience Question (for Dalton)
What material are the radiant heat barriers made from?
Response
That's Boeing proprietary information.

Audience Question (for Dalton)
What is the logic for taking a battery that has a too low voltage out? Is it a recharging issue?
Response
Yes, it's a recharging issue.

Audience Question (for Dalton)
Does the charge controller try to keep them fully charged or does it try to make sure the cells get cycled?
Response
It's an automated system. It charges when the solar arrays are in the light, and when it's in the eclipse, it automatically switches to discharge.

Audience Question (for Dalton)
What state of charge do you use during storage?
Response
They are stored at about 10 percent.

Audience Question (for Dalton)
How many layers of protection do you have against thermal runaway?
Response
Two-fault tolerant (minimum), with the exception of internal shorts where that can't be done.

Audience Question (for Milbert)
This is an Li-ion phosphate battery, so its behavior should be much safer than previous lithium chemistries we've been discussing, correct?

Response
Hasn't seen that stated before, but has seen organic and inorganic compared, and organic (to include Lithium Iron Phosphate (LiFePO4) batteries) are considered safer.
Note: Organic electrolytes typically have a max toxicity of level 2, while inorganic electrolytes typically have a max toxicity of level 4 and have explosive levels that are in the TNT equivalency range. (Reference: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120002724.pdf)

Audience Question (for Milbert)
Regarding fire extinguishers, I have a Class D extinguisher for use on LiPo fires. What is the consensus of the effectiveness of this type of extinguisher?
Response
NASA's Fire Protection Working Group (FPWG) and 3M are working on an answer. Class D typically is for flammable metals (to include Lithium). These types of fire extinguishers are often believed to be the catch-all and capable of putting out an Li-ion battery fire, but there really isn't an easy answer. 3M is working on a proposal for a new suppression agent to extinguish Li-ion battery fires.
Additional Response from Schumann
The FPWG is working on developing direction for LiPo fires.

Audience Question
Where could I expect to find these around my house and what should I do if I find one that is smoking or getting hot?
Response (from Milbert)
Li-ion batteris are not typically just floating in devices around the house, they are more typically used as rechargeable batteries in power tools, laptops and cell phones. Best advice is to check the manufacturer's specs and instruction sheets for warning information concerning Li-ion battery usage and handling. Also, adhere to the information provided on equipment warning labels. Ensure your products are UL listed — even though UL is reconsidering its test methods and standards, it's the best certification to rely on. With that being said, if you feel your cell phone getting warm in your pocket, remove it from the area and place it under some cooling source (e.g., under an A/C vent) and close out all open apps to decrease its energy consumption (plus it allows your phone to last longer without a recharge).

Speaker Bios

Swaim

- Has worked around the world as an aviation accident investigator with the NTSB since 1988 in positions including systems engineering investigator to accredited representative of the United States
- Led on-scene and laboratory groups during mishap investigations into fuel tank explosions, in-flight fires and collisions, wiring and instrument investigations, flight control failures; safety recommendations developed from these investigations include sweeping changes to regulations, changes in design and operational revisions
- Worked in engineering positions at Lockheed, Kaman Aerospace and Hughes Helicopters before joining the government
- Has a bachelor's from University of Maryland

Tucker

- Began career at Puget Sound Naval Shipyard in 2003 and qualified as a nuclear shift test engineer, supporting and directing integrated reactor plant maintenance and testing on submarines and aircraft carriers
- Began supporting Naval Special Warfare as the ship design manager for Shallow Water Combat Submersible and SEAL Delivery Vehicles prior to her current role
- Worked in the U.S. Naval Sea Systems Command Headquarters in the Deep Submergence Qualify Assurance group, supporting and directing Scope of Certification Audits for Dry Deck Shelters, Lockout Chambers and Lockout Trunks
- Bachelor of Science in mechanical engineering from the University of Idaho

Valencourt

- Valencourt provides System Safety engineering analysis and risk assessment for the U.S. soldier of small unit power systems including batteries, fuel cells, power distribution systems, small generators and renewable energy sources
- Was the chief of Risk Management for the U.S. Army Research Laboratory with four facilities
- Worked in private chemical industry as a research and development manager and research engineer before working for the government
- Is a U.S. Air Force veteran (ground radio/microwave maintenance and repair)
- Has a doctorate in chemical engineering with a mathematics minor from the University of Minnesota
- Has a Bachelor of Science in chemical engineering from the University of Delaware

Dalton

- Has 35 years of experience working with battery design, development, test and application
- Leads the technical design, development, deployment and operation of the replacement Li-Ion batteries for the Electric Power System (EPS) of the ISS, the largest Li-ion batteries to be flown on a manned mission
- Led the successful Nickel Hydrogen battery design, development, deployment and operation for the EPS of the ISS
- Is a member of the NASA Engineering and Science Center Power Technical Discipline Team, serving on teams for independent assessment of thermal runaway hazards
- Worked at the Naval Surface Warfare Center at Hughes Aircraft and Gates Energy Storage Company prior to coming to NASA
- Has a Master of Science in chemistry from Indiana University
- Has a Bachelor of Science in Chemistry from the University of California, Santa Barbara

Darcy

- Has a 30-year career at NASA in the areas of battery design, verification and safety assessments for the rigors of manned spacecraft applications
- Has a main objective of developing safe, while high-performing, battery systems with a deep focus on understanding, preventing and mitigating latent defects that could lead to catastrophic cell internal short circuits
- Led NASA's design and test efforts for providing a path for developing safe, high-performing Li-ion spacecraft batteries using small commercial cells
- Has a doctorate in chemical engineering from the University of Houston
- Has a master's in chemical engineering from Texas A&M University

- Has a Bachelor of Arts in chemistry from Pomona College

Milbert

- Has technical experience and expertise including working in avionics engineering on the Shuttle Data Processing Systems at Kennedy Space Center
- Was active in the avionics and electrical engineering for Level 3/2 flight articles in the Payloads Processing Directorate
- Was responsible for electrical flight processing for the ISS, along with the development, operation and maintenance of associated electrical ground systems
- Was the team lead that invented an Electrical Safety device patented as a NASA New Technology
- Is a Professional Engineer
- Has a Bachelor of Science in electrical engineering from Florida International University