Battery Safety Council – Forum 3
Minutes

Purpose and Organization of the Battery Safety Council (BSC)

The purpose of the BSC is to provide a means whereby battery failure mechanisms and test protocols that may be well-understood in one technical sector are shared with related sectors using the same battery technology. Goals of this forum include: promoting the highest practical levels of safety for state-of-the-art battery technologies, identifying and addressing data deficient areas in battery safety for collaborative research; and sharing data from research in the area of safety for state-of-the-art battery technologies across the different technical sectors.

The BSC was organized by the National Transportation Safety Board (NTSB) and Underwriters Laboratories, Inc. (UL) as collaboration between industry, government, and technical professionals dedicated to advancing and disseminating battery safety science research and lessons learned to benefit public safety. The BSC Co-Chairs are Dana Schulze (Dana.Schulze@ntsb.gov) and Judy Jeevarajan (judy.jeevarajan@ul.com). In addition to Dana and Judy, the other core team members are Jim Barnes (barnesjim@aol.com), Daphne Fuentevilla (daphne.fuentevilla@navy.mil), Margot Wasz (Margot.L.Wasz@aero.org) and Daniel Doughty (dhdoughty@gmail.com).

BSC membership includes design and test specialists from the manufacturing and user communities engaged in state-of-the-art cell and battery development. Members represent those in the automotive, aviation, transportation, defense, space, commercial electronics, utility, fire-fighters, academia, and national research laboratories industries, and their participation is on a voluntary basis.

Forum 3 Overview

Forum 3 was convened on January 12th and 13th at the PRBA Rechargeable Battery Association Office, Washington, DC.
The topic of focus was “Internal Shorts in Lithium-ion Batteries”.

Lithium batteries (lithium-ion rechargeable and lithium primary) provide the highest energy density of the battery chemistries used today. In addition, lithium-ion also provides the highest cycle life when compared to other high energy density battery chemistries (such as Li-S, Li-air, etc.). However, associated with the high energy density is its high propensity to produce catastrophic events like fire, toxic material venting, shrapnel and thermal runaway if not designed or used in the correct manner. Battery design best practices, external safety devices, and active battery management systems are relied upon to control the risk associated with most significant causes of thermal runaway. However, once formed, internal short circuits cannot be controlled using external controls. Internal shorts are known to have two main causes: manufacturing defects and environmentally-induced damage. Multiple approaches are needed to prevent internal shorting to provide safe and reliable designs including cell design, manufacture quality practices, battery operation, and safety testing. Although many of the causes for internal cell shorts can be mitigated at the beginning of life though manufacturing controls and screens, reports of latent shorting occurring in the middle of the life of a battery continues to cause safety and reliability concerns.

This Forum included the following main sessions: background on internal shorts in lithium-ion cells, manufacturing quality controls for preventing and screening shorts at the beginning of life, detecting and preventing internal shorts during battery field operations and finally, methods for simulating internal shorts to determine design tolerance to this hazard cause.

Introductions

The meeting was started with briefings given by Dana Schulze (Deputy Director, NTSB). Dana talked about the importance of understanding the cause of internal shorts, the screening of these in fresh cells and the detection of shorts that manifest themselves in the field. Dana referred to the Boeing 787 event and the more recent events with hoverboards, laptops and phone batteries. The attendees introduced themselves and a short discussion on the rules of the road were also addressed by Dana Schulze.

1. Background on Internal Shorts in Lithium-ion Cells: Dr. Judy Jeevarajan, Underwriters Laboratories Inc.

Dr. Jeevarajan gave an introduction and background on internal shorts in lithium-ion cells. She discussed the two main causes of internal shorts which are those caused due to manufacturing defects and poor quality and then those caused due to misuse in the field. The former is easy to comprehend but the latter cause is not usually given much attention. Defects created in the manufacturing process scan a wide variety from metallic contaminants, separator defects including crevices and folds, drying out of electrolyte, etc. to non-uniform electrode coatings. Several of these cannot be conclusively determined to be present unless destructive analysis of sample cells are carried out to determine the quality of cell manufacturing processes and a stringent audit of the cell and battery manufacturing facility is carried out. The instances where field failures are caused due to a defect that grows in the field are more commonly simulated especially when a cell or battery is used outside the manufacturer's recommended limits or if the battery is designed incorrectly or insufficiently with respect to safety controls or thermal management as well as with respect to its environmental conditions in the field. Characterization of the cell and battery design in the relevant configuration and environment may help with minimizing the risk associated with these field failures.
The questions raised in this presentation were the following:
Is diligence used to look at manufacturing defects as well as to follow stringent design and test requirements? Is one factor being blown out of proportion compared to the other (whether manufacturing defects or those created due to misuse in the field induce internal shorts)? Are batteries being designed to prevent the formation of shorts in the field? Do we understand the type of defects that can become a catastrophic hazard? Do we need to worry about all types of defects? Do we need to pay attention to cell and battery screening? Is there data in the literature that can prove unequivocally that manufacturing defects lead to catastrophic thermal runaway?

The rest of the forum addressed cell screening for internal shorts before assembly into a battery, screening for the formation of shorts in the field and latent field failures as well as methods to simulate internal shorts in order to understand a cell design's tolerance to an internal short.

2. ***Manufacturing Quality Controls for Preventing and Screening Shorts at Beginning of Life (BOL): (Facilitator: Judy Jeevarajan)***

Dr. Jeevarajan introduced the topic and provided literature data on the effects of defects on cycle life and performance of lithium-ion cells. The cell defects presented were those found in top tier cell manufacturers and ranged from metal contaminants (60 to 200 micron size) in the electrodes and separator, separator compromise (wear-down or tear), anode current collector damage, etc. She discussed the screening tests she had performed in the past to distinguish between fresh cells with defects and fresh cells that had none. Her studies showed that without performing destructive analysis it was difficult to determine with just self discharge studies or capacity and impedance /internal resistance studies, if a cell was of poor quality or had manufacturing defects.
The self-discharge study data indicated that cells could be studied at full SOC, 0% SOC or at an intermediate value and cells that had defects as well as those that did not behaved in a very similar manner after varying periods of storage (3 days or 14 days). An example was provided where a cell that had a hole in the anode current collector showed an out-of-family ac impedance

value when the “as-received” cell was tested but showed in-family ac impedance value after one charge discharge cycle was carried out. These types of defects that go undetected after the formation cycle are a challenge for battery manufacturers. She concluded that the following were imperative to prevent or screen for cells with defects: a good understanding of cell and battery manufacturing processes and quality control, stringent characterization and study with destructive analysis of sample cells from every lot and cell and battery screening with stringent pass/fail criteria.

The next talk was given by Dr. Rob Gitzendanner of the Yardney Division of Eagle Picher. Dr. Gitzendanner discussed the design and process controls that was used to minimize defects and contaminants in their cell manufacturing process. He also talked about the cell screening methods they used that included charge and discharge stand measurements where they continuously measured OCV in charged stand state for 3 days and measured OCV once a day for 14 days during the discharge stand tests. For the space applications, the criteria was extremely stringent with a 6 mV drop limit during the discharge stand test and a 12 mV drop limit for the charge stand test. He pointed out that both methods had pros and cons and a complimentary set of tests would provide a good screening method to remove those with a level of defects that would be of concern. He also discussed the other screening methods used to screen at the battery and assembly level that included measurement of coulombic efficiency along with capacity and internal resistance checks before and after environmental tests. Dr. Gitzendanner concluded that screening the cells in addition to process control during the manufacturing phase is critical in getting cells with the minimum risk of internal shorts.

Mr. David Ginder of SAFT discussed the cell screening methods used by SAFT to eliminate cells with manufacturing defects. He indicated that their commercial cell production was up to 15K cells per week. He discussed their 7-day stand test and that their cell production process was mostly automated. During their cell formation process, the cells were exposed to 60 C for 3 to 4 days and they went into a OCV stand at 72 °C on the third day and their criteria for pass was less than 0.8 mV drop in OCV. The cells that fail went through a formation process again and checked for self discharge. This confirms that the cells underwent a good formation process. Cells that failed after the second formation process were removed from the production line.

Dr. Jeevarajan, on behalf of Dr. Margot Wasz, also presented the methods listed in the Aerospace Corporation’s lithium-ion standard, “Aerospace Corporation TOR (SMC-S-017)”. The information was provided by Dr. Margot Wasz of Aerospace Corporation who was unable to attend the forum due to schedule conflicts.

3. Detecting and Preventing Internal Shorts during Battery Field Operations: (Facilitator: Daphne Fuentevilla)

The first talk given by Dr. Brian Barnett of CamXPower focused on the detection of internal shorts that grow in the field and that careful characterization of the baseline behavior of cells and batteries can provide a way of determining when any cell or battery gets into a state of no-return with respect to a thermal runaway condition. Dr. Barnett discussed the method and instrument used by CamX Power to detect the growth of the internal shorts in the field. He indicated that this method of detection will provide the warning, and if acted upon early enough, can prevent cells from going into a catastrophic thermal runaway condition. More details can be found in Dr. Barnett’s presentation.

Another talk on detection of internal shorts in the field was given by Dr. Srinivasan of the Johns Hopkins Applied Physics Lab. Dr. Srinivasan uses certain features of an ac impedance measurement to determine internal cell temperatures which can be significantly different from those measured on the cell surfaces. Dr. Srinivasan indicated that the ability to measure internal temperature of the cells gives the user adequate time to mitigate any catastrophic events from occurring. He discussed the ac impedance based BMS that JHUAPL has developed under his leadership for the detection of changes in the cell that may lead to an unsafe condition. More details of this technique can be found in Dr. Srinivasan’s presentation.

The third talk was given by Dr. Matthew Wagenhofer of RTI Forensics. Dr. Wagenhofer talked about their forensic work experience in the area of lithium-ion batteries and on the equipment they use for their studies. More details of Dr. Wagenhofer's forensic work can be found in his presentation.

4. Methods for Simulating Internal Shorts to Determine Cell Design Tolerance: (Facilitator: Jim Barnes)

This session included presentations by various organizations on the methods used to physically simulate internal shorts to determine a cell design's tolerance to an internal short.

Dr. Brian Barnett from CamXPower was the first speaker and he talked about their efforts to include metal contaminants inside the cells in order to create a contaminant induced internal short. His tests that included the inclusion of Ni particles showed that if the particle was placed on the cathode, then the particle passed through two layers of separator and deposited itself on the anode resulting in a short circuit. However, if it was placed in the anode, then no shorting was observed even over 500 charge/discharge cycles. He explained that the grown-in internal shorts typically started from an infinitely high resistance and matured to a very low resistance thus heating the cell until the cell was either dead or went into thermal runaway. More details can be found in Dr. Barnett's presentation.

Dr. Joshua Lamb of Sandia National Labs presented next on their pulse laser induced method to simulate an internal short inside a li-ion cell. Dr. Lamb provided details on the laser pulse power and the total energy required to cause a cell failure. More details can be found in Dr. Lamb's presentation.

Dr. Ahmad Pesaran of National Renewable Energy Lab (NREL) spoke about the method they had developed to create an internal short in lithium-ion cells. The method included the creation of a short by using a device that was designed into the cell. The device consisted of a low melting point polymeric material and a copper puck that would cause the short to occur when the polymer melted at temperatures of about 40 °C. More details of this method can be found in Dr. Pesaran's presentation.

The next talk was given by Dr. Rajesh Nagappala of GM. He discussed the tests they had performed with different sizes of iron particles as well as the tests they carried out to detect the presence of the iron contaminants in the cells. He discussed the self discharge and cycle life tests that were carried out under compression, the voltage degradation for beginning of life and end of life cycled cells. Dr. Nagappala also discussed that when the metal particles were located in the anode, they did not observe internal cell shorting. However, if they were initially located in the cathode, and if they were of sufficient size and mass, they typically caused internal shorts and larger particles usually resulted in cell failures.

Dr. Frank Cao of SAFT gave a presentation on their method of inducing internal shorts. SAFT used an embedded heater in their cells to simulate an internal short. More details of their technique can be found in Dr. Cao's presentation.

Dr. Elham Sahraei of George Mason University/MIT, discussed her pinch/crush test method for simulating short circuits. Her interest was in mainly simulating crash effects on separators in lithium-ion cells and the types of damage observed with the various types of separators and the resulting failures of the lithium-ion cells. More details of Dr. Sahraei's method can be found in her presentation.

Dr. Clint Winchester of NSWC (Carderock), presented a paper that was coauthored with Dr. Hsin Wang of Oakridge National Lab on the mechanically induced internal short circuit method. The technique involved the use of two 2-inch diameter spheres. He indicated that this method worked very well for pouch type lithium-ion cells but may not work as well for the metal can cells. More details can be found in his presentation.

The last presentation was made by Dr. Judy Jeevarajan on the work she had carried out during her career at NASA on simulating internal shorts in cells. Dr. Jeevarajan spoke of her crush test method that she introduced in 1998 to determine a cell design's tolerance to internal shorts and how a more stringent screening method of vibration was used on those battery chemistries/cell designs that were intolerant to an internal short. From 2008 to 2010, she had collaborated with Underwriters Laboratories (UL) to standardize the crush test method as UL was also using a similar crush test method with a custom built automated test equipment. The goal of the method was to create a deformation that was just enough to cause the electrodes to touch each other (due to separator breakdown) without penetrating the cell container. More details can be found in Dr. Jeevarajan's presentation.

The intent of this session was to introduce the various methods that were available to create or induce an internal short circuit in lithium-ion cells. It was clear that several good methods were available and proven to work. It was also clear that depending on the capability and resources available to the various organizations or agencies, different methods were adopted to carry out this type of testing.

High-level Observations and Comments

The discussions and presentations prompted a number of questions and observations. The presentations were very informative and indicated that this area of work had different levels of maturity.

1. The cause of internal shorts was wide and varied and included those formed due to manufacturing defects, latent field failures, those created in the field due to misuse, etc.
2. The screening methods used to detect cells that had defects before they were placed into batteries or into a battery system varied significantly. But it was agreed upon that stringent screening of cells and batteries for critical characteristics including destructive analysis of cells from every new lot was imperative in understanding the quality of the cells.
3. Methods to detect latent field failures or internal short formation due to misuse were attaining a certain level of maturity and although many techniques were not available, the ones presented were of great interest to the attendees.
4. Methods to simulate internal shorts in cells were wide and varied. The method used seemed to depend on the capability of the organization to simulate an internal short in cells. For instance, organizations with the ability to introduce a defect or contaminant internal to the cell chose to use that method while those without that capability chose to use methods such as crushing or using a laser pulse.
5. In general, it was understood that internal shorts were a significant concern because one could not mitigate this hazard using a protective device but needed to mitigate or minimize the risk by using good manufacturing practices, stringent screening and field detection techniques.

Topics for Future Meetings:

1. Thermal Runaway Propagation: Methods to induce thermal runaway in lithium-ion cells and batteries and methods to mitigate the propagation of thermal runaway.
2. Stranded Energy: When a battery has undergone a catastrophic event but is only partially affected, how does one go about understanding how much energy is left behind and how one can safely transport and dispose the battery.

<u>Actions for the BSC:</u>

1. Plans are underway in organizing Forum 4 to be held in mid-June and the location is still under discussion.