The Landscape of Thermal Runaway Propagation Testing

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Outline

• Introduction.
• Goals of failure propagation test.
• Examples of cell failure propagation.
• Discussion of details of 8 battery test standards that describe failure propagation tests.
• Summary
Tests are Developed for Specific Objectives

• Qualification Testing.
  – Does product meet intended goals?
  – Decide if a new product development program is on track.
  – Demonstrate proof of concept.

• In-process testing.
  – Controlling the uniformity of production of products or components.
  – Help solve problems with current product.

• Validation Testing (includes Safety Testing).
  – Determine if, or verify that, the requirements of a specification, regulation, or contract are met.

• Acceptance Testing.
  – Testing of materials & devices received to assure specifications and contract requirements are met.
Failure Propagation Resistance Test

- Most experts admit that a single cell failure, while very low probability, cannot be completely eliminated (at any cost).
- Several of the test standards specifically mention shift of focus from prevention to measurement & reduction of severity:
  - “This requirement focuses not on the likelihood of such an event but rather on understanding the severity of consequences in the intended application should this unlikely event occur.” (NASA)
  - “Understanding the consequences of an event allows an informed risk assessment and identifies potential mitigation via design or operations.” (AIAA)
  - “Since there is a possibility that a cell may fail within a battery system, the battery system shall be designed to prevent a single cell failure from propagating to the extent that there is fire external to the DUT or an explosion.” (UL)
- Battery packs can be designed to prohibit the propagation of thermal runaway of one cell to consume entire battery pack.
Failure Propagation Test Goal

• Failure of one cell should be contained by battery pack.
  • Thermal runaway of one cell should not cause destruction of entire battery pack.
  • Battery pack should contain the event.

• Failure Propagation Test is the only way to evaluate this possible outcome.
  – Packs have successfully passed this test.
  – Goal is “Graceful Failure” to a potentially serious event.
  – This test is particularly important for:
    • Large format applications such as vehicles or stationary grid power applications.
    • Applications where egress of people is a concern.
Failure Propagation

Will single cell failure lead to damage and destruction of the module/pack?

Response determined by intrinsic cell properties

Response determined by engineering design
Recent Li Ion Failure Propagation Video

How does general public handle cell failure propagation?

- No abusive environment or off-normal conditions.
- Dell computer is being charged.
- Home monitoring camera documents computer battery fire (Los Angeles, CA 02Jan17).
- 4 Li-ion cells in computer entered thermal runaway within 8 minutes.
  - For full video, see:
  - https://www.youtube.com/watch?v=CIB4UQ2oSJo
    - Thermal runaway of 4 cells at video time of:
      » ~30 sec.,
      » +1:30 (+ 3 minutes, 5:46:35 on camera timer),
      » 3:35 (+ 7 minutes, 5:50:45 on camera timer), and
      » 3:50 (+ 7.25 minutes, 5:51:00 on camera timer),
- Home video documents the propagation of single cell failure to other cells in a computer battery pack.
Standards That Have Cell Failure Propagation Testing Procedures

2. UL 2580 (2013) "Batteries for Use in Electric Vehicles”, Sect. 43 “Internal Fire Exposure Test”
5. RTCA* DO-311 (2017) “Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems,” Sect. 3.3.3

* RTCA = Radio Technical Commission for Aeronautics
**American Institute of Aeronautics and Astronautics

Rationale

Abuse testing is performed to characterize the response of a Rechargeable Energy Storage System (RESS) to off-normal conditions or environments. The primary purpose of abuse testing is to gather response information to external/internal inputs that are designed to simulate actual use and abuse conditions. This response information is used to expose the hazards, if any, associated with a given RESS under a given set of use and abuse conditions and to help quantify the hazard mitigation efforts that should be taken for a particular RESS design.

The revisions are intended to expand the scope of SAE J2464 to include other types of electric energy storage devices and vehicular applications, make the test results more quantitative as well as incorporate improvements in test procedures and data analysis.

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Sect. 4.4.5 Passive Propagation Resistance

- The Device Under Test (DUT) is charged to 100% SOC.
- All external circuits, cooling systems, or other devices are turned off or disconnected.
- The DUT is heated until the cells stabilize at 55°C or the maximum operating temperature, whichever is greater.
- One cell within the DUT is uniformly heated in-situ to a temperature of 400°C (or until the cell enters thermal runaway) in less than 5 minutes. Heater is turned off.
- Other methods to initiate thermal runaway in one cell are allowed.
  - The method used to create a thermal runaway in one cell will be described and documented in the report.
- DUT is observed for 1 hour.
- Test is repeated at different locations of trigger cell.
- Hazard Severity Level is documented.
- No pass/fail criteria.
UL 2580 (2013) "Batteries for Use in Electric Vehicles"

Sect. 43 “Internal Fire Exposure Test”

UL 2580

STANDARD FOR SAFETY
Batteries for Use In Electric Vehicles

UL 2580

• Sect. 43 “Internal Fire Exposure Test”
  • The electric energy storage assembly shall be designed to prevent a single cell failure within the assembly from cascading into a fire and explosion of the assembly.
    • The battery system is “fully charged”.
    • Heating an internal cell that is centrally located within the DUT until thermal runaway or otherwise forcing the failure of the cell through any means necessary (i.e. overvoltage, nail penetration, etc. that results in a thermal runaway condition).
    • Thermal runaway of the cell should be reached within 10 minutes.
      » Once the thermal runaway is initiated the mechanism used to create the thermal runaway is shut off or removed.
  • There shall be no explosion of the DUT that results in projectiles falling outside of the circular inner perimeter.

UL 9540A

STANDARD FOR SAFETY

UL 9540A

• The propensity of the cell to exhibit thermal runaway shall be demonstrated by heating the cell with an externally applied flexible film heater & onset of thermal runaway shall be documented.

• Repeat test at module and unit level.
  – Measure heat and gas generation rates;

• Pass Criteria:
  – Surface temperature measurements along instrumented wall surfaces does not exceed 60°C (108°F) temperature rise above ambient;
  – The surface temperature of modules within the BESS units adjacent to the initiating BESS unit does not exceed the temperature at which thermally initiated cell venting occurs;
  – There is no flaming outside the BESS unit;
  – Explosion hazards are not observed, including deflagration, detonation.

Note: BESS = Battery Energy Storage System
UL 1973 (2018)
“Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications”

Sect. 37. Single Cell Failure Design Tolerance

UL 1973

STANDARD FOR SAFETY
Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications

Second Edition, Dated February 17, 2018
UL1973


• Since there is a possibility that a cell may fail within a battery system, the battery system shall be designed to prevent a single cell failure from propagating to the extent that there is fire external to the DUT or an explosion.

• Any number of methods can be used to produce a single cell thermal runaway failure.
  – Thermal runaway in cells can be achieved through the use of heaters, nail penetration, overcharge, etc.
  – Once the thermal runaway is initiated, the mechanism used to create thermal runaway is shut off or stopped and the DUT is subjected to a 24-h observation period.

• The details of the method used when analyzing the cell’s reaction that can impact the results are to be documented.

• The sample shall be at the maximum specified use temperature and state of charge.

• Temperatures on the failed cell and surrounding cells are to be monitored and reported for information purposes.

• There shall be no fire propagating from the DUT or explosion of the DUT.
IEC 62619 (2017) Safety requirements for Secondary Lithium Cells and Batteries, for use in Industrial Applications

Sect. 7.3 “Considerations for internal short-circuit – Design evaluation”
IEC 62619 (2017)

Sect.7.3 “Considerations for internal short-circuit – Design evaluation”

– The purpose of the test is to determine that an internal short-circuit within a cell will not result in fire of the entire battery system or fire propagating outside the battery system.
  • This shall be demonstrated either (A) at the cell level according to 7.3.2 internal short-circuit test or (B) at the battery system level according to 7.3.3 propagation test.
  • I believe that this is an error in the standard – these tests are not equivalent. Forced internal short circuit (cell failure) cannot substitute for a failure propagation test, which presumes that a cell failure has occurred.

– 7.3.2 Internal Short Circuit: nickel particle may be inserted into cell followed by pressing pressure not to exceed 400 N
– 7.3.3 Propagation Test. This test evaluates the ability of a battery system to withstand a single cell thermal runaway event so that a thermal runaway event does not result in the battery system fire.
  – The battery system is fully charged and then left until the cells stabilize at 25°C.
  – One cell in the battery system is heated until the cell enters thermal runaway.
    » The method used to create a thermal runaway in one cell is to be described and documented in the test report.
  – After thermal runaway in the cell is initiated, the heater is turned off and battery system is observed for 1 hour.
  – No external fire from the battery system or no battery case rupture.
SANDIA REPORT

Sect. 3.4. “Failure Propagation Test”
• Sect. 3.4. “Failure Propagation Test”
  • No preferred initiation technique as long as they result in a typical and reproducible thermal runaway condition for a given cell type.
  • It is recommended that the cell failure be initiated at 100% state-of-charge (SOC) and 25 °C.
  • Trigger cell should be in the most vulnerable initiation location, which will vary with battery design and should be guided by thermal modeling, previous test experience, or other data.
  • Because of the variability that can exist with cell thermal runaway, multiple tests are highly recommended at several initiation locations and SOCs to determine reliable design margin.
  • Locations within a battery module or pack should be considered to (1) maximize the number of cells involved in the test and (2) represent any potential design vulnerabilities based on use condition or misuse.
RTCA* DO-311A (2009)
“Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems,” Sect. 3.3.3 Explosion Containment

* RTCA = Radio Technical Commission for Aeronautics, sets Safety Standards for commercial aircraft, adopted by FAA in USA. RTCA’s objectives include but are not limited to:
1. ensuring the safety and reliability of airborne systems;
2. developing minimum operational performance requirements;
3. developing guidelines for use by a regulatory authority.
Sect. 3.3.3, Explosion Containment

- Goal: No single failure in either battery system or aircraft equipment can cause safety hazard to passengers or crew.
- Test is conducted "to determine the effectiveness of battery case to contain ignition of vapors and/or electrolyte in the battery that might occur if a cell were to short" in batteries permanently mounted in the aircraft.
  - Lithium Content in Single & Multi-Cell batteries >1 gram.
  - Thermal runaway achieved on cell closest to the center of the assembly by causing the overcharge of a single cell.
    - Includes spark source.
    - If overcharging does not create a thermal runaway, use an alternate method to create a thermal runaway.
- All debris shall be contained within the battery casing.
- Venting of gas & liquids is permitted.
- Venting of solid material and flames, as well as rupture of test unit is prohibited.
- Peak pressure must be equal or below 80% of the design strength of the battery casing.

Sect. 5.1.5 “Thermal Runaway Propagation”
• Sect. 5.1.5, “Thermal Runaway Propagation”
  – For battery designs greater than a 80-Wh energy employing high specific energy cells (Li ion) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.
  – Thermal runaway can be induced by:
    • Overcharge, Short circuit, Internal cell short circuit, or Excessively high temperature.
  – The evaluation shall include all necessary analysis and test to:
    • Quantify the severity (consequence) of the event in the intended application and environment as well as,
    • Identify design modifications to the battery or the system that could appreciably reduce that severity.
Sect. 4.4.1.3 “Battery Level Tests - Battery Level Thermal Runaway Propagation Test

This standard is under public review.

*American Institute of Aeronautics and Astronautics
ANSI/AIAA S-136

• Batteries shall be tested to determine the effects of a worst-case single-cell thermal runaway and the cell-to-cell failure propagation in the intended application and environment.
  – This requirement focuses not on the likelihood of such an event but rather on understanding the severity of consequences.
  – Worst-case thermal runaway events shall include methods and location of thermal runaway initiation and environmental conditions as determined by test or analysis.
  – Thermal analysis may be used in determining the method and location of thermal runaway initiation and it shall be validated by test. The analysis and test should closely mimic the actual battery configuration and the relevant environment.
  – Thermal runaway may be triggered by the application of heat using a heating tape, laser source, heating element or an overcharge to high voltages for these tests.
Common Aspect of the Nine Failure Propagation Tests

• 7 of 9 apply to confined spaces, or locations with uncertain egress.
  – Automotive – SAE J2464 & UL 2580
  – Battery Energy Storage Systems in buildings – UL 9540A
  – Light Electric Rail – UL 1973
  – Aircraft – RTCA DO-311

• The other 2 tests are not application-specific.
## Comparison of Failure Propagation Standards

<table>
<thead>
<tr>
<th>Test</th>
<th>Temperature</th>
<th>SOC</th>
<th>How to Trigger TR</th>
<th>Location of Trigger Cell</th>
<th>Replicate Tests?</th>
<th>Pass/ Fail?</th>
<th>Pass Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE J2464</td>
<td>55°C</td>
<td>100%</td>
<td>Heat cell to 400°C</td>
<td>Multiple</td>
<td>Yes</td>
<td>No</td>
<td>There shall be no fire or explosion of the DUT.</td>
</tr>
<tr>
<td>UL 2580</td>
<td>Ambient</td>
<td>fully charged</td>
<td>Heating</td>
<td>centrally located</td>
<td>Yes</td>
<td>Yes</td>
<td>Surface temperature measurements along instrumented wall surfaces does not exceed 60°C (108°F) temperature rise above ambient; The surface temperature of modules within the BESS units adjacent to the initiating BESS unit does not exceed the temperature at which thermally initiated cell venting occurs, as determined in Task 2A; There is no flaming outside the BESS unit; and Explosion hazards are not observed, including deflagration, detonation.</td>
</tr>
<tr>
<td>UL 9540A</td>
<td>25°C</td>
<td>100%</td>
<td>Heating</td>
<td>The position of the cells forced into thermal runaway shall be selected to present the greatest thermal exposure to adjacent cells not forced into thermal runaway.</td>
<td>Yes</td>
<td>Yes</td>
<td>There shall be no fire propagating from the DUT or explosion of the DUT.</td>
</tr>
<tr>
<td>UL 1973</td>
<td>Maximum use temperature</td>
<td>100%</td>
<td>Heaters, nail penetration, overcharge</td>
<td>Requires an analysis of the DUT design to determine the cell location considered to have the greatest potential to lead to a significant external hazard.</td>
<td>Yes</td>
<td>Yes</td>
<td>There shall be no fire propagating from the DUT or explosion of the DUT.</td>
</tr>
<tr>
<td>IEC 62619</td>
<td>25°C</td>
<td>fully charged</td>
<td>resistive heating</td>
<td>The target cell has at least two other cells nearby.</td>
<td>No</td>
<td>Yes</td>
<td>No external fire from the battery system or no battery case rupture.</td>
</tr>
<tr>
<td>SAND2017-6925</td>
<td>25°C</td>
<td>100%</td>
<td>Other initiation techniques are allowed as long as they result in a typical and reproducible thermal runaway condition for a given cell type.</td>
<td>Locations that represent any potential design vulnerabilities based on use condition or misuse</td>
<td>Yes</td>
<td>No</td>
<td>All debris shall be contained within the battery casing. Venting of gas &amp; liquids is permitted. Venting of solid material and flames, as well as rupture of test unit is prohibited. Also, peak pressure must be equal or below 80% of the design strength of the battery casing.</td>
</tr>
<tr>
<td>RTCA DO-311</td>
<td>Ambient</td>
<td>100%</td>
<td>Overcharge</td>
<td>Closest to the center.</td>
<td>No</td>
<td>Yes</td>
<td>Note: The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.</td>
</tr>
<tr>
<td>NASA JSC 20793</td>
<td>Ambient</td>
<td>100%</td>
<td>Overcharge, Short circuit, Internal cell short circuit, or excessively high temperature</td>
<td>Most vulnerable locations (i.e., more likely propagation of failure) are cells with fewest nearest neighbors.</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>ANSI/AIAA S-136</td>
<td>Operational Temperature</td>
<td>100%</td>
<td>Heating tape, laser source, heating element or an overcharge to high voltages</td>
<td>Edges</td>
<td>3 for Human Rated Missions, 1 for Non-Human Rated</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
Impact of Avoiding Thermal Runaway Propagation

• Lower risk of injury or damage from high energy and large format battery packs.

• If battery pack design is tolerant of single cell failure, perhaps we can reduce levels of acceptance testing, such as:
  – Incoming inspection.
  – Leak testing.

• Less attention to efforts aimed at reducing the probability of a cell failure, such as:
  – Less frequent manufacture inspection.
  – Audits of production line.
  – More accepting of cell design modifications.

• Possible relaxation installation requirements of stationary energy storage in buildings.
Summary and Conclusions

• Evaluation of failure propagation testing is essential for safety of many battery-powered applications.
• Thermal runaway failure propagation tests are becoming more common.
  – 8 are published & 1 under review.
  – Some areas of agreement on test methods:
    • Choice of method to initiate thermal runaway in trigger cell.
    • Pass/fail criteria.
  – More work needed on location of trigger cell and number of repetitions for statistical validity.
  – Impact of verified battery pack designs that avoid thermal runaway propagation needs more study.