



AEROSPACE RECOMMENDED PRACTICE

ARP7131™

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Verification Process for Thermal Runaway Mitigation in Large Electrical Energy
Storage Powertrain Systems in Normal Category Aircraft and Rotorcraft

RATIONALE

A Lithium-Ion battery thermal runaway event cannot be reliably *prevented*, but the effects can be *limited* to improve aviation safety. RTCA DO-311A is currently used as guidance for the design, performance, characterization, and installation of permanently installed rechargeable Lithium aircraft batteries. However, certain electric aircraft propulsion initiatives necessitate more comprehensive design and implementation guidance beyond the valid methodologies addressed within the DO-311A standard. This **recommended practice** complements the standard with practical cell to system considerations that better resolve the context of a layered set of preventative failure mitigations necessary for these much larger and more energy-dense battery powertrain systems.

TABLE OF CONTENTS

1.	SCOPE.....	5
1.1	Outline.....	5
1.2	Purpose.....	6
1.3	Background.....	6
1.4	Terminology.....	7
1.4.1	Hazard Definition.....	7
1.4.2	Battery Definitions.....	7
1.5	Single-Cell TR Concept.....	8
1.6	Recommended Practice/Approach.....	9
2.	REFERENCES.....	11
2.1	Applicable Documents.....	11
2.1.1	SAE Publications.....	11
2.1.2	ASTM Publications.....	12
2.1.3	EASA Publications.....	12
2.1.4	FAA Publications.....	12
2.1.5	ISO Publications.....	12
2.1.6	NASA Publications.....	12
2.1.7	NHTSA Publications.....	13
2.1.8	RTCA Publications.....	13
2.1.9	U.S. Government Publications.....	13
2.1.10	Other Publications.....	13
2.2	Acronyms.....	15
3.	CELL LEVEL TR EVALUATION.....	17
3.1	TR Trigger Methods.....	17
3.1.1	Lithium-Ion Cell Field Failure.....	17
3.1.2	Design for Minimum Risk (DFMR).....	17
3.1.3	Mechanical Trigger Methods.....	18
3.1.4	Electrical Trigger Methods.....	19

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Documents

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3.1.5	Thermal Trigger Methods.....	19
3.1.6	Seeding	20
3.2	Battery and Cell Design Impacts on TR Trigger Method Selection	21
3.2.1	Cell Design Impacts	21
3.2.2	Battery Design Impacts	21
3.3	Test Methods for Characterization of TR	22
3.3.1	TR Response Characterization	22
3.3.2	Accelerating Rate Calorimeter (ARC)	22
3.3.3	Bomb Calorimetry	23
3.3.4	Cone Calorimetry	23
3.3.5	Fractional TR Calorimetry (FTRC)	23
3.3.6	NASA Cell TR Database	24
4.	MODULE LEVEL TR EVALUATION	25
4.1	Link Between Cell Data and Module Data	25
4.2	Data Needed from the Cell Level and to Guide the Module Design Process	25
4.3	Design Methodologies	27
4.3.1	Bussing	27
4.3.2	Fault Accommodation	28
4.3.3	Isolation	28
4.3.4	Cell Hold-Down	29
4.3.5	Module Structure	29
4.3.6	Material Selection	29
4.3.7	Number of Cells for Configuration	30
4.3.8	Other Safety Considerations	30
4.3.9	Designing Robust Modules	30
4.3.10	High-Voltage Creepage and Clearance	30
4.3.11	Temperature Measurements	30
4.3.12	Continued Airworthiness	30
4.3.13	Cell Variability Accommodations	31
4.3.14	Module Configuration	31
4.3.15	Test Module Design for Containment	31
4.3.16	Battery Pack	31
5.	SYSTEM GUIDANCE	33
5.1	Overview	33
5.2	Threats and Hazards	34
5.3	General Design, System Installation, and Operational Considerations	35
5.3.1	General Intersystem Design Features and Layers of Protection	35
5.3.2	System Capabilities and Operational Considerations	35
5.4	Battery Compartments and Adjacent Compartments	38
5.4.1	Isolation and Protection between Battery Compartments	38
5.4.2	Fire Protection of Flight Controls, Engine Mounts, and other Flight Structure	38
5.4.3	Fire Protection of Adjacent Systems and Equipment	38
5.4.4	Isolation of Hazards	38
5.5	Battery Venting Locations and External Considerations	39
5.6	High Voltage	40
5.6.1	High-Voltage Isolation	40
5.6.2	High-Voltage Disconnect	41
5.7	General Crashworthiness Considerations	41
5.8	Emergency Response	41
6.	SYSTEM DEVELOPMENT AND SYSTEM SAFETY ASSESSMENT	42
7.	PREVENTION AND FAULT-TOLERANT SYSTEM CONSIDERATIONS	42
7.1	Overview	42
7.2	Precedent	43
7.2.1	U.S. Department of Defense (DOD)	43
7.2.2	U.S. Department of Transportation (DOT)	43

7.3	Methodology.....	43
7.3.1	Distributed Communications and Control Approaches	44
7.3.2	Prevention Methods	44
8.	ESS VERIFICATION.....	45
8.1	Battery Pack Verification	46
8.1.1	Crash or Drop Testing.....	46
8.1.2	High-Voltage Isolation Stress Testing.....	47
8.1.3	Immersion Testing.....	48
8.2	System and Aircraft Level Verification	48
8.2.1	Test and/or Analysis for TR and CSFL	49
8.2.2	Charge Protection	50
8.2.3	Thermal Management, Operating Temperatures, and Limitations	50
8.2.4	Circuit Protection at the System Level	51
8.2.5	High-Voltage Isolation and Disconnect at the System Level	52
9.	INSTRUCTIONS FOR CONTINUED AIRWORTHINESS	53
9.1	Guidance from AC 20-184A (Draft) can be Utilized for Developing Instructions for Continued Airworthiness on ESSs.....	53
10.	CONCLUSIONS	53
11.	NOTES	53
11.1	Revision Indicator.....	53
APPENDIX A	BATTERY SPECIFICATION COMPARISON TABLE.....	54
APPENDIX B	BATTERY SPECIFICATION COMPARISON TABLE - ELECTRICAL ABUSE.....	55
APPENDIX C	BATTERY SPECIFICATION COMPARISON TABLE - FIRE AND CONTAINMENT	56
APPENDIX D	BATTERY SPECIFICATION COMPARISON TABLE - CRASH SAFETY.....	57
APPENDIX E	ALTERNATE ESS CONFIGURATION DEFINITIONS	58
APPENDIX F	STANDARDS AND GUIDELINES DOCUMENTS	60
APPENDIX G	LIST OF OTHER USEFUL ELECTRIC VEHICLE STANDARDS TO AID IN AIRCRAFT CERTIFICATION.....	61
Figure 1	Representation of cell to module and module to pack that comprise a full ESS	8
Figure 2	Typical cell lithium-ion temperature and ARC temperature versus time results	8
Figure 3	Typical cell lithium-ion temperature plotted against temperature rate	9
Figure 4	Nail penetration example	18
Figure 5	Overcharge example.....	19
Figure 6	External heater example	20
Figure 7	Accelerating rate calorimeter (ARC) example (used by THT Permission, 2023)	23
Figure 8	Fractional TR calorimeter (FTRC) example	24
Figure 9	www.nasa.gov/frtc website (2022)	25
Figure 10	Example of Battery Failure Databank (BFD).....	25
Figure 11	Cell TR	26
Figure 12	Voltage and temperature versus time	26
Figure 13	Mass retention comparison	27
Figure 14	Isolation moats	28
Figure 15	Example battery pack.....	32
Figure 16	Example battery system setup	32
Figure 17	Example battery system mockup for aircraft.....	33
Figure 18	Example of a failed battery in an energy storage and distribution system for a conceptual lift+cruise aircraft.....	37
Figure 19	Image of battery venting and conceptual eVTOL aircraft	40
Figure 20	Diagram of inputs defining the worst-case TR event(s).....	45
Figure 21	Diagram showing relationship of various levels of ESS verification	45

Figure 22	From NHTSA EVS-06-34e: Schematic of some possible short circuit pathways that could be created due to pollution of an ESS; a short circuit could form (from left to right) on module connected electronics components, on pack level electronics components, or between modules and the ESS enclosure	47
Figure 23	Images of immersion testing from NHTSA DOT HS 813 136.....	48
Table 1	Methods to implement TR	17
Table 2	Voltage level range definitions	40
Table 3	Battery safety tests.....	46
Table 4	Installation, system, and aircraft level verification.....	49

1. SCOPE

This SAE Aerospace Recommended Practice (ARP) is an industrial collaboration with regulatory bodies like the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) to determine the worst-case credible thermal runaway (TR) condition (energy released and maximum temperature) for the design of an aviation large propulsion battery system to quantitatively verify TR in lieu of battery level RTCA DO-311A testing with protections disabled. The ARP considers the three stages of TR within a cell and defines the two critical temperatures for a specific cell design. These temperatures are key to understanding the layers of monitoring necessary to determine the severity of a TR event.

Different trigger methods can be used to quantify the heating characteristics and resultant energy profile releases as a function of time. Results show three general phases of the event critical temperature (see 1.5) corresponding with the reaction between the cell's solid electrolyte interphase (SEI) for graphite anodes and the electrolyte, resulting in heat generated by the cell rather than heat supplied from the accelerating rate calorimeter (ARC). The temperature of the cell continues to rise until the separator begins to melt. Critical Temperature 2 occurs after the separator melts and electrodes are shorted together to generate large amounts of heat, raising the cell temperature quickly to 377 °C. These temperatures are key precursors of TR, regarding the length and severity of an event. Understanding this key bit of information is vital to the approach presented herein.

1.1 Outline

A recommended practice or approach has been developed by various transportation industries using large lithium-ion battery storage systems. The approach presented in 1.5 describes characterization at the cell, module, and pack levels of an aviation propulsion lithium-ion battery energy storage system (ESS). Through this approach, the ESS reaction to a TR event can be determined. This approach also provides a quantitative method to determine the engineering margin of the TR mitigation and includes the applicant's concept of operations (CONOPS) to better guide system safety assessment (SSA)/functional hazard assessment (FHA) efforts and assess preventative measures that improve functional safety.

The cell level TR evaluation in Section 3 explains the four major types of trigger method categories: mechanical, electrical, thermal, and seeding. This section describes the advantages and disadvantages of each trigger method. Design for minimum risk is presented as a way to control risk at the cell level in a design. Battery and cell design impacts are also presented from the type of cell (cylindrical, pouch, or prismatic) to the impact of the electrolyte. This section concludes with insights on how to capture data for cell level TR testing to understand how TR can affect the system. The NASA cell database is presented as a repository from over 200 fractional thermal runaway calorimetry (FTRC) experiments conducted on commercial lithium-ion cells.

Cell level conditions are discussed to provide practical methods for causing the early exothermic reactions, resulting in the TR at the cell level. This information serves not only to guide the mechanical design and materials selection, but also to guide the test methodology for triggering TR in the module. Module level testing will be discussed to characterize the propensity towards TR cell-to-cell propagation, dependent upon module design implementation.

Module level TR evaluation is presented in Section 4 and opens with a brief discussion about the link between cell data to module data. The cell level TR data are critically important in defining the module design process and are enumerated. A number of design impacts including bussing, cell spacing, and several other module considerations are discussed in great detail throughout the rest of this section. There is an intrinsic link between the characteristics of the cell TR and module TR. Cell TR risk may not be completely removed, due to the energetic nature of the material involved in high energy/power electrochemical storage devices. However, careful engineering of the module can reduce not only the violence of a cell level TR but also the overall risk to the rest of the system, enabling containment of a TR event. RTCA DO-311A was not specifically created for propulsion ESS level TR verification but continues to be applicable in most cases for module testing in addition to the standards listed in Appendix A and G. Using the presented approach should provide sufficient data to validate a TR propagation test at the module level.

The system section builds off other sections for large aviation propulsion batteries and many additional considerations are presented. The proposed system is based on a compartmentalized approach in which TR propagation is contained within the module. The modules are designed to be vented and installed so that there is no module-to-module propagation, damage to aircraft structure, or risk to passenger egress. This does not imply a module only solution but rather one of various options. This section concentrates on the full ESS and aircraft installation considerations and hazards. It also provides a look at various industry standards for lithium-ion battery-based ESS(s). In this comparison it provides the appropriate level for the standards application.

High-level considerations for the installation of an ESS into small aircraft are provided in Section 5. The threats and hazards during normal, abnormal, and emergency operating conditions that increase the risk of system-level TR are discussed and the means to reduce or remove these threats through design are highlighted. Also discussed are the design considerations that are expected to reduce risk to the aircraft, passengers, maintenance crew, and emergency response personnel if TR in the ESS occurs. Section 6 includes a high-level overview of the safety analysis process that should take place as part of the ESS installation. Active methods to prevent TR in an ESS installation, along with how one should justify their pursuit or lack thereof, are discussed in Section 7. General guidance on verification analysis and tests are outlined in Section 8. The document then closes with a callout to the specific behaviors of an ESS that may drive particular requirements to the instructions for continued airworthiness before wrapping up with conclusions.

1.2 Purpose

This document encapsulates a 2-year effort done in collaboration with regulators, battery and aircraft manufacturers, and researchers in aviation. The purpose was to present a set of tools for those developing large lithium-ion battery energy storage systems for electric propulsion applications. Test methods for triggering TR and accumulating data to support validation of TR mitigation testing are provided. It also provides a basis for testing and modeling development to reduce testing when appropriate. The use of modeling without testing verification is not advocated herein. The system section of this document was provided to give an insight into aircraft installation issues and full system issues that cannot be demonstrated adequately at lower assembly levels.

1.3 Background

Recent notable advances in rechargeable lithium-based electrochemistries have initiated a new era of electrification in aviation. Continued development of higher-energy cells and improved packaging methods will result in higher constrained energies that can aggravate a TR condition. Safety remains paramount for all manned flight programs, such that each developed battery solution must show resistance to TR and sufficiently contain the effects of a foreseeable propagated TR event. While methods may vary, and the amount of data to interpret can be overwhelming, rigorous systematic testing of new propositions through the scientific method can identify true cause and effect. This failure mode cannot be ignored and must be mitigated to ensure passenger and aircraft functional and structural safety.

RTCA DO-311A, the present aviation safety standard for rechargeable lithium batteries, was developed for net energies categories (1-4) up to and exceeding 200 Wh. While the general principles and many of the guidelines in RTCA DO-311A are relevant for electrified propulsion ESSs, some of the specific recommendations in RTCA DO-311A are based on the battery designs and architectures that were envisioned at the time of its publication. This ARP expands upon those foundational safety principles and the standards listed in Appendix A and G, allowing their application to be broader range of ESS architectures and designs. Improved means are described to verify the performance, mitigation, and resistance to TR events for more complex-propulsion battery systems. These systems are often represented by a multi-box ESS with net energy exceeding 400-times the 311A Category 4 threshold (>200 Wh) and frequently utilize a distributed communications and hierarchical control scheme.

This ARP is intended to be agnostic of the selected battery technology. It provides an improved definition of TR, embraces a layered failure mitigation design strategy that progresses from cell → module → battery → ESS, and includes additional best-practice recommendations that address:

- a. A broader set of characterization methods to more thoroughly quantify the severity of an induced TR event via the effects of different triggering (TR initiation) methods.
- b. The application of design for minimum risk (DFMR) approach presently employed for crewed space mission batteries within the context of design priorities and constraints.
- c. Many of the concerns expressed within the RTCA DO-311A Appendix D, through a defined worst-case credible (DWCC) TR events development approach to quantify the potential means to induce and resolve possible failures for a given ESS design application.
- d. Design guidance for test characterization and suppression of potential TR events complemented by functional prevention considerations to evaluate the specific ESS operational use within the application to leverage interfaces for tailored control opportunities.

This recommended practice results from a 2-year effort with battery developers, aircraft manufacturers, researchers, and regulators to provide a rigorous approach in assessing TR by evaluating the impact from the cell, module, and finally, from the ESS as a whole. Consequently, as we look to the future of electrification within aviation, we must continue to maintain and improve the safety of future enabling innovations.

1.4 Terminology

1.4.1 Hazard Definition

“Worst-Case Credible Thermal Runaway Event(s)” are defined as the TR scenario(s) producing the most severe effects (i.e., heat, pressure, and time duration) at a certain level of abstraction (cell, module, pack, system, or aircraft level) that, once identified, allow the proper selection of mitigations to avoid the total system TR in the case of a single defective cell TR. “Worst-case” means when multiple mutually exclusive possibilities exist (e.g., cell initiation mechanism, location of the initiating cell within a module or pack, system and aircraft operational considerations from the CONOPS, and functional limitations such as battery states [temperature and charge]), the one(s) with the most severe effect should be considered. It also intends all operational and environmental parameters (e.g., state of charge [SOC], ambient temperature, and pressure) should be set at credible values contributing the most to the severity of the outcome. “Credible” means only scenarios and conditions that could realistically occur must be considered. For example, combinations of operational and environmental parameters cannot occur during normal, abnormal, or emergency operation (or are mutually exclusive) and need not be considered. Likewise, multiple unrelated failures or defects need not be considered. Finally, “credible” implies TR prevention and mitigation design features should be assumed to perform as demonstrated by testing or other acceptable means and should not arbitrarily be presumed to be failed or ineffective. This coupled evaluation (cell, module, pack, system, aircraft) also helps to provide data to determine the proper pass/fail criteria for verification methods needed to demonstrate continued safe flight and landing (CSFL). General guidance (such as time, magnitude, and duration of a TR event) on verification analysis and tests is outlined in Section 8.

1.4.2 Battery Definitions

ESS and their constituent parts can vary widely in architecture, installation, and design between different applications. To ensure a common basis for application of this recommended practice, the following definitions are used in accordance with AIR6897:

CELL: Individual electrochemical unit consisting of anode, cathode, separator, and electrolyte contained within a sealed casing.

MODULE: Sub-assembly of cells that are electrically connected in series or parallel, or a combination thereof. It may include a battery management system (BMS) or BMS components. Battery packs may or may not include modules.

PACK: Assembly of cells or modules that are electrically connected in series, in parallel, or a combination thereof, along with the BMS. It represents the fully packaged article that is installed in the aerospace vehicle.

SYSTEM: Top-level configuration for installations that include multiple battery packs or a dedicated battery charger.

In addition to AIR6897, the following definitions are also used:

STRING: Assembly of cells, modules, or packs connected in series. A string or multiple strings in parallel can also be considered a system.

VIRTUAL CELL: Multiple cells electrically connected in parallel.

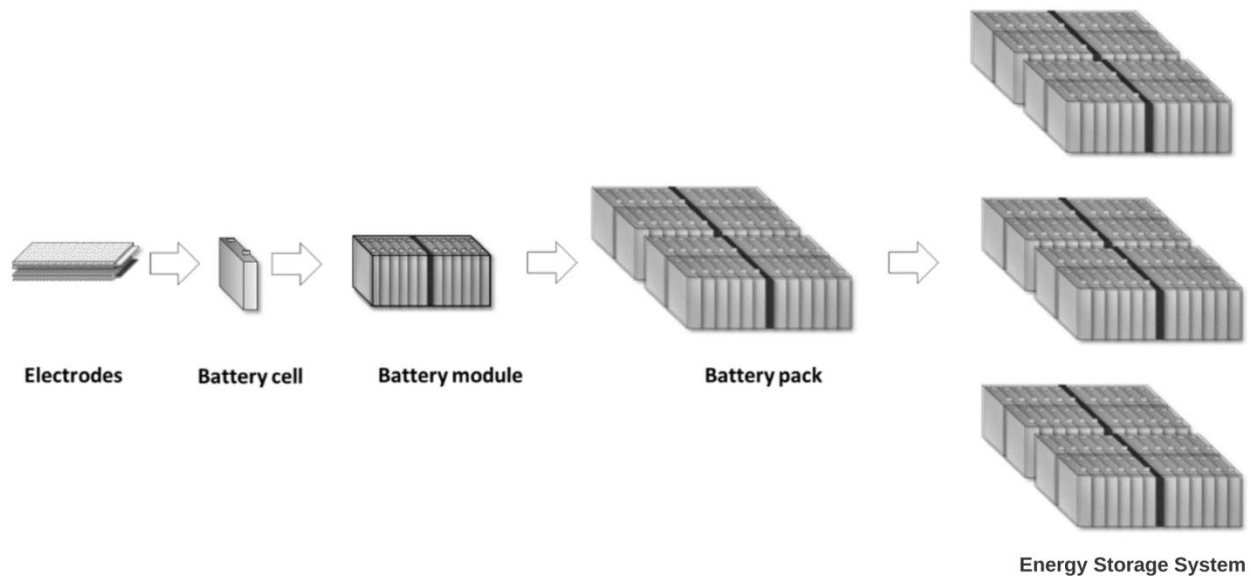


Figure 1 - Representation of cell to module and module to pack that comprise a full ESS

Figure 1 depicts the general distinction between cell, module, pack, and system level. Appendix E illustrates further diagrams of possible configurations between cell, string, module, subpack, and pack assemblies. The arrangement must be quantified when performing safety analyses and determining what testing will be required.

1.5 Single-Cell TR Concept

Abuse tolerance conditions (mechanical, electrical, and thermal) can result in large exothermic (heat-releasing) reactions in lithium-ion cells, quickly reaching temperatures up to 1800 °C. Notwithstanding other TR methodologies and using lithium-ion as an example, the positive electrode (cathode) reacts exothermally with the electrolyte to produce oxygen, which can combust with the carbon/graphite negative electrode (anode). This reaction can cause increases in temperature and pressure of the cell, often referred to as TR. An example of this reaction is shown in Figure 2. The cell temperature is gradually raised from time 0 minutes to time 2400 minutes within an ARC. The cell temperature rises rapidly to 400 °C and drops off rapidly, illustrating the TR.

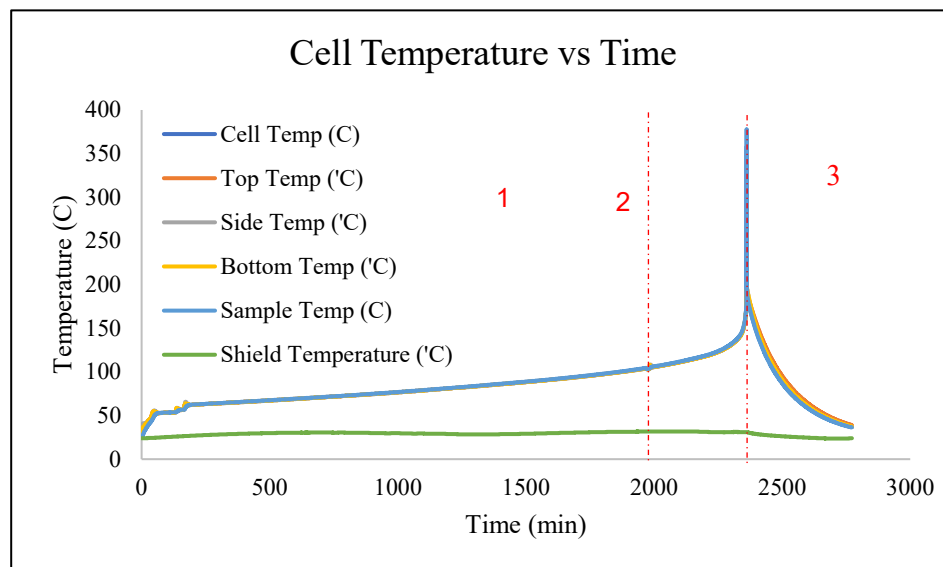


Figure 2 - Typical cell lithium-ion temperature and ARC temperature versus time results

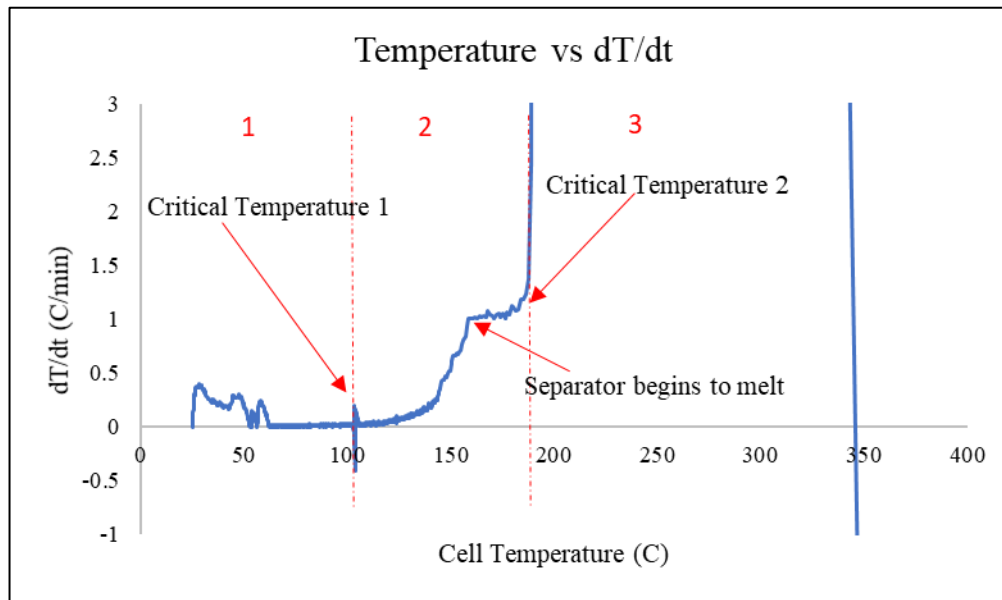


Figure 3 - Typical cell lithium-ion temperature plotted against temperature rate

A differential analysis of the same temperature data is shown in Figure 3 (refer to Zhao et al., 2020). Results identify three general phases of the event and two critical temperatures. Critical Temperature 1 corresponds with the reaction between the solid electrolyte interphase and the electrolyte, resulting in heat generated by the cell rather than heat from the ARC. The temperature of the cell continues to rise until the separator begins to melt. Critical Temperature 2 occurs after the separator melts and electrodes are shorted together to generate large amounts of heat, raising the cell temperature to 377 °C, as seen in Figure 2.

1.6 Recommended Practice/Approach

The following process defines a general approach that can be followed to help generate data to evaluate battery safety from lower levels up to the system and aircraft level.

- Characterize cell properties, failure modes, and effects. If virtual cells or submodules (smaller representative modules) are to be evaluated, conduct testing to show non-propagation and demonstrate a TR can be contained to allow for a safe landing. Evaluation for this is outlined in the corresponding cell (see Section 3) guidance.
- Characterize module failure modes and effects. Conduct testing to show: 1. “non-propagation” and demonstrate a TR can be 2. “contained” to allow for a safe landing, including mitigation of 3. “module-to-module propagation.” Evaluation for this is outlined in the corresponding module-level (see Section 4) guidance.
- Perform battery pack safety tests and other tests such as crashworthiness or immersion testing as required by the regulatory authorities (see 8.1).
- Define the intended CONOPS for the ESS specific to the application; i.e., describe the comprehensive handling, storage, use and operation, maintenance, shipping, and disposal considerations for the ESS that quantify the conditions relevant for the safety analyses (see 5.3.2).
- Identify the highest level of communications and control authority for the ESS as this will define the boundary conditions for fault awareness and subsequent mitigation opportunities within the safety assessment processes.

- f. Characterize system failure modes and effects within the context of the defined application CONOPS, and determine which hazards are potentially hazardous and catastrophic. This should be the result of an SSA, though general considerations are listed in 5.2. Fault injection testing (FIT) at the system level may be required to validate assumptions. The results from the safety analysis may also inform additional test/analysis conditions at lower-level evaluation (see Sections 2 and 3). This ensures that all DWCC failures are evaluated at the appropriate level(s) and fed back up into system-level verification efforts. For each given failure mode:
 - 1. Consider the relevant layers of protection that address this failure mode. If there are no layers of protection for the failure mode, then the system should be tested as-is with the relevant requirement.
 - 2. Consider at what level the protective measure must be tested to validate that the protection works properly. This may include the ESS level, pack level, subpack level, etc.
 - 3. Perform an analysis to define the worst-case credible failure(s) relevant to the system level. Note that for complex geometries or systems there may be multiple DWCC failures. Multiple modules or packs may be affected during different failure modes. All distinct lifecycle phases and operating and emergency conditions should be considered when generating these failure cases. This could include evaluating multiple combinations of aircraft and battery states.
 - 4. Consider the failure modes of the protection system itself in accordance with the SSA. Validate any assumptions regarding the operation of the protection system.
 - 5. Evaluate the high-risk items from the safety assessments and determine if preventative measures are available to further reduce risk in complement with the DFMR mitigations described in 3.1.2 (see Section 7).
- g. Verify through test and analysis that worst-case credible failure(s) and resulting failure effects are mitigated at the installation and system levels (see 8.2).
 - 1. Ensure adequate containment of TR at the battery module/subpack/pack level (see Section 4).
 - 2. Test the worst-case credible failure(s) at the installation level. Perform TR tests of the battery module/subpack/pack in a test article that is representative of the installation to validate the effects on adjacent structure and systems/components. Utilize the results to validate assumptions in the SSA and inform any relevant structural analysis.
 - 3. Test the worst-case credible failure(s) at the system level. Ensure that the system detects the failure (and alerts the crew), automatic responses function as intended, and the remaining operable system can provide essential loads for the time period required for CSFL. Utilize the results to validate assumptions in the SSA and electrical loads analysis (ELA).
- h. Perform additional system tests as required to verify that other system protection features function as intended (a few examples are described in 8.2).
- i. Utilize the results from the above testing and analysis to demonstrate compliance with the applicable safety, system, structural, and aircraft level requirements.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR6127	Managing Higher Voltages in Aerospace Electrical Systems
AIR6343	Design and Development of Rechargeable Lithium Battery Systems for Aerospace Applications
AIR6897	Battery Management Systems for Rechargeable Lithium Batteries Used in Aerospace Standards
AIR8678	Architecture Examples for Electrified Propulsion Aircraft
ARP4754	Guidelines for Development of Civil Aircraft and Systems
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
ARP8676	Nomenclature and Definitions for Electrified Propulsion Aircraft
AS6968	Connection Set of Conductive Charging for Light Electric Aircraft
SAE J1715/2	Battery Terminology
SAE J1766	Recommended Practice for Electric, Fuel Cell and Hybrid Electric Vehicle Crash Integrity Testing
SAE J1797	Recommended Practice for Packaging of Electric Vehicle Battery Modules
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules
SAE J2289	Electric-Drive Battery Pack System: Functional Guidelines
SAE J2344	Guidelines for Electric Vehicle Safety
SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
SAE J2929	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
SAE J3040	Electric Vehicle (E-Vehicle) Crash Test Lab Safety Guidelines
SAE J3220	Lithium-Ion Cell Performance Testing

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org

ASTM F3316/F3316M-19 Standard Specification for Electrical Systems for Aircraft with Electric or Hybrid-Electric Propulsion

2.1.3 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, www.easa.europa.eu.

SC VTOL_2 Special Condition for VTOL and Means of Compliance

2.1.4 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 20-135 Powerplant Installation and Propulsion System Component Fire Protection Test Methods, Standards and Criteria

AC 20-184 Guidance on Testing and Installation of Rechargeable Lithium Battery and Battery Systems on Aircraft

AC 23-17 Systems and Equipment Guide for Certification of Part 23 Airplanes and Airships

AC 27-1 Certification of Normal Category Rotorcraft

2.1.5 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 26262 Road Vehicles - Functional Safety

2.1.6 NASA Publications

Available from NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, Tel: 757-864-9658, Fax: 757-864-6500, <http://ntrs.nasa.gov/>.

NASA (2021). Battery Failure Databank, Rev. 1. Retrieved from NREL.gov.

NASA JSC-20793D supports the DFMR discussion covered in 3.1.2.

EP-WI-038 Specification for Side Wall Rupture Characterization of Commercial Lithium-Ion Cell Lots, NASA Work Instruction

NPR 8705.2B (2008, May 6). Human-Rating Requirements for Space Systems. Retrieved from NASA Procedures and Guidelines: https://nodis3.gsfc.nasa.gov/displayAll.cfm?Internal_ID=N_PR_8705_002B_&page_name=all

2.1.7 NHTSA Publications

Available from National Highway Traffic Safety Administration, 1200 New Jersey Avenue, SE, Washington DC 20590, Tel: 1-888-327-4236, <https://www.nhtsa.gov/>.

06-34e RESS Isolation Stress Test

DOT HS 812 418 Lithium-ion Battery Safety Issues for Electric and Plug-in Hybrid Vehicles

DOT HS 812 782 System-Level RESS Safety and Protection Test Procedure Development, Validation, and Assessment-Final Report

2.1.8 RTCA Publications

Available from RTCA, Inc., 1150 18th Street, NW, Suite 910, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

DO-160/EUROCAE ED-14 Environmental Conditions and Test Procedures for Airborne Equipment

DO-178/EUROCAE ED-12 Software Considerations in Airborne Systems and Equipment Certification, Rev. C

DO-254 EUROCAE ED-80 Design Assurance Guidance for Airborne Electronic Hardware

DO-311 Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems

2.1.9 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

NAVSEAINST 9310.1C

NAVSEAINST S9310

NAVSEAINST SG270

2.1.10 Other Publications

Belt, J. and Sorensen, A. (2023). Thermal and Electrochemical Analysis of Thermal Runaway Propagation of Samsung Cylindrical Cells in Lithium-ion Battery Modules. *Journal of the Electrochemical Society*, 170.

Billman, J. and Walker, W.Q. (2020). *Battery Failure Databank*, NASA Aerospace Battery Workshop.

Chandrasekaran, R., Payan, A., Collins, K., and Mavris, D. (2019). *A Survey of Wire Strike Prevention and Protection Technologies for Helicopters*. Technical Report, U.S. Department of Transportation, Federal Aviation Administration. Retrieved from <http://actlibrary.tc.faa.gov>.

Daniel, W.W. and Cross, C.L. (2018). Biostatistics: a foundation for analysis in the health sciences. Retrieved from Wiley. <https://select-statistics.co.uk/calculators/sample-size-calculator-population-proportion/>.

Donal, P., et al. (2019). Modeling and experiments to identify high-risk failure scenarios for testing the safety of lithium ion cells. *Journal of Power Sources*, 417, 29-41.

Feng, M.O. (2018). Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. *Energy Storage Materials*, 246-267.

Feng, X., et al. (2015). Characterization of penetration induced thermal runaway propagation process within a large format lithium-ion battery module. *Journal of Power Sources*, 261-273.

Feng, X., et al. (2019). Investigating the thermal runaway mechanisms of lithium-ion batteries based on thermal analysis database. *Journal of Applied Energy*, 53-64.

Feng, X., Lu, L., Ouyang, J., Li., J., and He X. (2016). A 3D thermal runaway propagation model for a large format lithium-ion battery module. *Energy*, 115, 194-208.

Finegan, D. (2017). Characterizing thermal runaway within lithium-ion cells by inducing and monitoring internal short circuit. *Energy and Environmental Science*, 1377.

Finegan, D. (2017). Characterizing thermal runaway in lithium-ion cells. *Journal of Energy Environmental Science*, 1377-1388.

Finegan, D., et al. (2019). Modelling and experiments to identify high-risk failure scenarios for testing the safety of lithium-ion cells. *Journal of Power Sources*, 417, 29-41.

Finegan, D., et al. (2023). The battery failure databank: Insights from an open-access database of thermal runaway behaviors of li-ion cells and a resource for benchmarking risks. DOI: [10.2139/ssrn.4618782](https://doi.org/10.2139/ssrn.4618782).

Galushkin, N.E., et al. (2018). Mechanism of thermal runaway in lithium-ion cells, *Journal of the Electrochemical Society*, 165.

Hatchard, T., MacNeil, D., Stevens, D., Christensen, L., and Dahn, J. (2001). Thermal Modeling of Cylindrical and Prismatic Lithium-ion Cells. *Journal of the Electrochemical Society*, 148(7), A755-761.

Hu, H., et al. (2020). Numerical study on the inhibition control of lithium-ion battery thermal runaway. *Journal of American Chemical Society Omega*, 18254-18261.

Kim, G.H., Peraran, A., and Spotnitz, R. (2007). A Three-dimensional Thermal Abuse Model for Lithium-ion Cells. *Journal of Power Sources*, 170, 476-489.

Kochhar, S. and Friedell, M. (1990). *User control in cooperative computer-aided design*. UIST '90: Proceedings of the 3rd annual ACM SIGGRAPH symposium on user interface software and technology, 143-151. Available at <https://doi.org/10.1145/97924.9794>.

Lei, Z., et al. (2019). Thermal runaway characteristics on NCM lithium-ion batteries triggered by local heating under different heat dissipation conditions. *Journal of Applied Thermal Engineering*, 113-847.

Liao, Z., et al. (2019). A survey of methods for monitoring and detecting thermal runaway of lithium-ion batteries. *Journal of Power Sources*, 226-879.

Lidbeck, A. and Syed, K. (2017). *Experimental Characterization of Lithium-Ion Battery Cells for Thermal Management in Heavy Duty Hybrid Applications*. Chalmers University of Technology, Gothenburg, Sweden, Master's Thesis.

Mandal, B.K. (2006). Thermal runaway inhibitors for lithium battery electrolytes. *Journal of Power Sources*, 1341-1345.

McCoy, C., Offer, D., Barnet, B., and Sriramulu, S. (2012). *Safety Technologies for Lithium-ion Cells*. Power Sources Conference, Las Vegas, NV, USA.

Santhanagopalan, S., Ramadass, P., and Zhang, Jr. (2009). Analysis of internal short-circuit in a lithium-ion cell. *Journal of Power Sources*.

Walker, W., et al. (2019). Decoupling of heat generated from ejected and non-ejected contents of 18650-format lithium-ion cells using statistical methods. *Journal of Power Sources*, 415, 207-218.

Wu, T., et al. (2018). Comparison analysis on the thermal runaway of lithium-ion battery using extended volume accelerating rate calorimeter. *Journal of Hazardous Materials*, 733-741.

Xu, J., Lan, C., Qiao, Y., and Ma, Y. (2017). Prevent thermal runaway of lithium-ion batteries with mini-channel cooling. *Applied Thermal Engineering*, 110, 883-890.

Yayathi, S., et al. (2016). Energy distributions exhibited during thermal runaway of commercial lithium-ion batteries used for human spaceflight applications. *Journal of Power Sources*, 197-206.

Zhao, C., et al. (2020). Thermal runaway hazards investigation on 18650 lithium-ion battery using extended volume accelerating rate calorimeter. *Journal of Energy Storage*, 101-232.

2.2 Acronyms

AES	avionics and electrical systems
ARC	accelerating rate calorimeter
ARP	Aerospace Recommended Practice
BIT	built-in tests
BMS	battery management system
CCA	common cause analysis
C.G.	center of gravity
CMA	common mode analysis
CONOPS	concept of operations
CSFL	continued safe flight and landing
CTOL	conventional take-off and landing
DFMR	design for minimum risk
DLS	diamond light source
DOT	Department of Transportation
DWCC	defined worst-case credible
EASA	European Aviation Safety Agency
ECS	environmental control system
ELA	electrical loads analysis
ESRF	European Synchrotron Radiation Facility
ESS	energy storage system
ESSs	energy storage systems
EWIS	electrical wiring interconnect system
FAA	Federal Aviation Administration

FCS	flight control systems
FHA	functional hazard assessment
FIT	fault injection testing
FTA	fault tree analysis
FTRC	fractional thermal runaway calorimetry
FMEA	failure mode and effects analysis
Hipot	high-potential dielectric withstand
HV	high voltage
ISCD	internal short circuit device
LFP	lithium iron phosphate
LCO	lithium cobalt oxide or lithium cobaltite
NHTSA	National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
PPR	passive propagation resistance
PRA	particular risk analysis
PSSA	preliminary system safety assessment
QR	quick response
SEI	solid electrolyte interphase
S-FTRC	small format fractional thermal runaway calorimetry
SIL	system integration laboratory
SOC	state of charge
SSA	system safety assessment
TR	thermal runaway
VTOL	vertical take-off and landing
ZSA	zonal safety analysis

3. CELL LEVEL TR EVALUATION

3.1 TR Trigger Methods

3.1.1 Lithium-Ion Cell Field Failure

Despite 30 years of high-volume commercial production with improving design and manufacturing quality controls, latent, defect-induced cell internal shorts still escape detection at the point of manufacturing and can lead to spontaneous catastrophic battery field failures. All other root causes (overcharging, external short, overtemperature, or mechanical over-stress) can, however, be prevented with redundant design features and prudent operations. The defect-induced internal short failure is a rare 6-sigma event that cannot reliably be screened out at beginning of life due to its latency. Most field failures have happened at high states of charge during charging, but many have occurred when at rest or in storage with states of charge as low as 30%. The latency hazard was first demonstrated by implanting precisely sized and located Ni particles in cylindrical cells, showing that they will pass acceptance screening and later, with further cycling, yield a TR response (refer to McCoy et al., 2012). There are four main types of cell internal short circuits:

- Active to active material short.
- Collector to collector short.
- Two types of active-to-collector shorts are possible (negative active to cathode current collector and positive active to anode current collector).

Research has found that negative active material shorts to cathode current collectors result in the most energetic and hazardous TR failures (refer to Santhanagopalan et al., 2009).

3.1.2 Design for Minimum Risk (DFMR)

Redundant design features aren't always practical to apply to prevent occurrence of a cell-defect induced TR event in batteries given design priorities and system constraints. To control this risk, DFMR (refer to NPR 8705.2B, 2008) can be applied to a design for a minimum risk approach, which combines best design, manufacturing, testing, analysis, and operational practices to assess the margins against this failure to be sufficient to enable safe, robust, and high-quality battery designs. The optimal practices for preventing defective cells from being assembled into batteries are combined with design features in batteries that can be demonstrated to be capable of passive propagation resistance (PPR) from a single-cell TR event. This design resistance behavior must be demonstrated through a PPR test campaign where cells in various positions, directions, installation effects, and at worst-case credible operational conditions are intentionally triggered into TR in a manner that is representative of the defect-induced cell TR response. What follows is a description of the various trigger methods along with an explanation of the possible limitations of each method.

Table 1 - Methods to implement TR

Methods	Implementation	Comments
Mechanical: Crushing	Cell or subscale battery	Repeatability is difficult, may compromise cell enclosure.
Mechanical: Pinching	Cell or subscale battery	Repeatability is difficult, may compromise cell enclosure.
Mechanical: Penetration	Cell or subscale battery	Repeatability is difficult, may compromise cell enclosure.
Electrical: Overcharge	Cell, module, system	BMS would limit this failure.
Electrical: Short	Cell, module, system	
Electrical: High-Rate Cycling	Cell, module, system	BMS would limit this failure.
Thermal	Cell	Bias temperature of adjacent cells.
Seeding	Cell	Lack of availability and cost.

3.1.3 Mechanical Trigger Methods

Crushing, pinching, or penetration (refer to SAE J2464) methods are widely used to induce a hard short in an electrode stack or wind (jellyroll). These methods are relatively easy to implement on subscale battery assemblies without intricate enclosures. These methods can be implemented on nearly any cell design but result in severe modifications to the cell enclosure and cause or require perforation in many cases. (For safety reasons, these mechanically destructive methods - as with any triggering methods described in this document - obviously require a means of remotely activated testing/monitoring to be performed by personnel.) The main advantage for a mechanical battery propagation test is the temperature bias risk on the adjacent cell is eliminated, and therefore may be the best method for high-start temperature conditions. The disadvantages are as follows:

- a. It is difficult to consistently get the same type of internal short without careful implementation that uses consistent nail features and ensures repeatable penetration depth and speed, along with exercising great care to use the same cell alignment and clocking orientation.
- b. It is challenging to implement in a battery propagation protection (PP) test, particularly for interior cell locations within a pack, without compromising blast plates, cell ejecta dissipation paths, and flame-arresting features.
- c. Perforation of the enclosure relieves internal cell pressure prematurely and is not relevant to most field failure conditions.
- d. Piercing the cell by nail or screw penetration can inadvertently hold the electrode stack or jellyroll inside the cell enclosure longer than would otherwise happen in a field failure. This can bias the amount of heat transferred through can walls during TR.

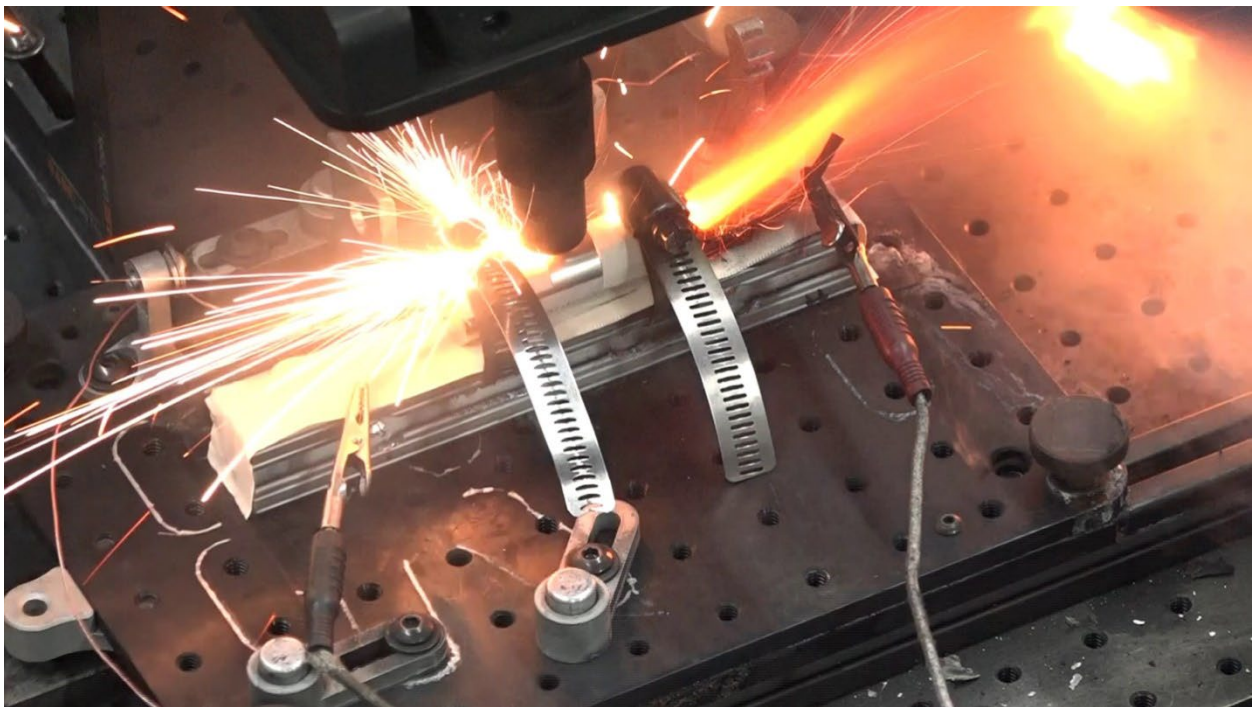


Figure 4 - Nail penetration example
(Reprinted from NASA.)

3.1.4 Electrical Trigger Methods

Methods of electrical triggers involve overcharge, short circuit, or high-rate cycling. These methods can also be implemented in nearly all cell designs with little or no modifications. The disadvantages are as follows:

- a. Electrically isolating the trigger cell from the rest of the pack is required, particularly for adjacent cells.
- b. Overcharge drives TR to much higher states of charge than at credible worst-case relevant conditions. This could result in a severe over- or under-test result depending on the cell response. For example, electrode stack or jellyroll ejection is a common response and yields an under-test result relative to heat transferred through the cell wall and onto adjacent cells. Conversely, it can result in an over-test relative to amount of heat and pressure associated with the TR ejecta on the ejecta dissipation path.
- c. The type of internal short circuit that will trigger the response cannot be controlled, and therefore that increases the variability of the TR response.



Figure 5 - Overcharge example

3.1.5 Thermal Trigger Methods

Thermal triggers involve heating the cell or part of the cell to the point of melting the separator (130 °C) between the anode and cathode. This trigger is typically achieved with a custom heater applied to the cell enclosure but can also be touchless with laser radiation. Variants of these methods can be implemented on any cell design. Typically, this involves using a custom heater design to the cell enclosure. The disadvantages are as follows:

- a. Typically, this type of test can only get an active-to-active material internal short circuit.
- b. The cell heater may have to displace the battery design features that provide PPR in order to make room.
- c. Heater energy may bias the temperature of the adjacent cells at the onset of TR, resulting in an over-test and preventing tests at high start temperatures.
- d. Laser or heater methods typically weaken the cell enclosure and induce side wall rupture in cylindrical cell designs.



Figure 6 - External heater example
(Reprinted from NASA.)

3.1.6 Seeding

Various seeding methods have been created to cause a minimally biased TR event. Some of these examples are discussed here:

3.1.6.1 Ni Particle

An Ni particle, developed by TIAX, is a tiny, precisely L-shaped nickel particle implanted in unwound jellyroll to strategically induce an anode active material to cathode current collector short after numerous charge/discharge cycles. This strategy laid the foundation for the Battery Association of Japan's Forced Internal Short Test (BAJ-FIST) used in a few countries and was adopted by the IEC 62133-2 standard in 2017.

3.1.6.2 Tungsten Wire Heater

A tungsten wire heater, developed by SAFT, is a thin (0.25-mm diameter wire) heater patch (1 x 1 cm) isolated with separator material and wound into the jellyroll outer wrap on an electrode surface adjacent to the separator. This heater yields an active material-to-active material short. Heater power wires are routed through potted holes in the cell header. The method is suitable for large-capacity (>25 A·h) cells if reliable TR response is the goal. This seeding method also requires a more invasive process to occur during the cells' manufacturing.

3.1.6.3 Wax Internal Short Circuit Device (ISCD)

A wax internal short circuit device (ISCD), developed by the National Renewable Energy Laboratory (NREL) and NASA, is a low-profile, Al and Cu foil device isolated by a thin spin-coated wax that melts around 57 °C (refer to Finegan, 2017). The device is implanted in dry jellyrolls while on an interrupted winder or by manual unwinding and rewinding. It is optimally designed for each cell type and internal short type desired. All four types of seeding devices have been implanted and triggered on a few cell designs, leading to a similar conclusion that the aluminum-to-graphite short produces the most energetic TR response. The device has matured since its invention in 2010 to be more reliable and consistent; such that numerous NASA battery projects have performed their PPR test campaigns with ISCD trigger cells. Furthermore, the technology has been licensed to KULR Technology (www.kulrtechnology.com), now a commercial source for the seeding device and trigger cells. Disadvantages of the ISCD trigger cells include: