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(R) Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

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.

Revisions are intended to update and improve the test description and methods.

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1. SCOPE

This SAE Recommended Practice is intended as a guide toward standard practice and is subject to change to keep pace with experience and technical advances. It describes a body of tests which may be used as needed for abuse testing of electric or hybrid electric vehicle rechargeable energy storage systems (RESS) to determine the response of such electrical energy storage and control systems to conditions or events which are beyond their normal operating range. This document does not establish pass/fail criteria. However, SAE J2929 does define pass/fail criteria for automotive RESS safety testing.

Abuse test procedures in this document are intended to cover a broad range of vehicle applications as well as a broad range of electrical energy storage devices, including individual RESS cells (batteries or capacitors), modules, and packs.

RESS includes any type of rechargeable electrical energy storage device, such as batteries and capacitors. This document does not apply to RESS that uses mechanical devices to store energy (e.g., electro-mechanical flywheels) or fuel cells.

1.1 Purpose

This document is designed to provide a common framework of tests to evaluate the response of various RESS technologies to abusive conditions. These tests are intended to characterize the RESS response to undesirable abusive conditions also termed “off-normal” conditions or environments that may arise as a result of operator negligence, vehicle accidents, device or system defects, poorly informed or trained users or mechanics, failure of specific RESS control and support hardware, or transportation/handling incidents or accidents.

Tests in this document represent conditions for which the RESS was not designed or intended for use, but can reasonably be expected to be encountered infrequently during field use.

These tests were derived from failure mode and effect analysis, user input, and historical abuse testing. The outcome of testing shall be documented for use by potential users of the tested RESS.

It is not the intent of this procedure to establish acceptance criteria since each application has its own unique safety requirements. Moreover, cell, module, and pack safety contribute to a safety approach that will employ active and passive protection devices such as thermal and electronic controls, state of health monitoring, automatic disconnects, as well as mechanical protection and ancillary support systems.

This document is not intended to certify the RESS for shipping.

Users of these technologies shall make their own determination as to what measures to take to ensure a sound application of said technology. The test data from SAE J2464 may be used as input to battery safety and hazards risk mitigation approach that has been developed (refer to “Analysis of Battery Safety and Hazards Risk Mitigation”).

SAE J2464 tests can be used to characterize the hazard level associated with an RESS without active protective devices. The hazard level response of the RESS without active protective devices to various abuse conditions can be used as basis for determination of safety mechanism and integrity level of safety functions required by functional safety. Higher safety integrity levels may require higher levels of redundancy or diagnostic coverage. Functional safety standards such as the relevant sections of ISO 26262 and IEC 61508 can provide guidance on determination of these hazards.

The scope of this document is to evaluate the response to abusive conditions at the cell, module and pack levels of RESS integration. While the abusive conditions developed in this test are intended to be representative of potential hazardous conditions in the vehicle environment, not all types of vehicle level hazards are within the scope of this document.

The tests described in this document should be supplemented with additional testing (performed at the test sponsor’s or manufacturer’s discretion) based on their need for data and their determination of the most susceptible condition of the technology. The primary purpose of the tests is to gather response information to external/internal inputs. Specific tests and/or measurements in this document may not be appropriate for some RESS technologies and designs if it can be demonstrated by the RESS users (or system integrators) that the test is not applicable or the results will be duplicated by other tests.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

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.

SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology

SAE J1739 Potential Failure Mode and Effects Analysis (FMEA) Inclusing Design FMEA, Supplemental FMEA-MSR, and Process FMEA

SAE J1950 Proving Ground Vehicle Corrosion Testing

SAE J2344 Guidelines for Electric Vehicle Safety

SAE J2929 Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-Based Rechargeable Cells

SAE J2950 Recommended Practices for Shipping Transport and Handling of Automotive-Type Battery System - Lithium Ion

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 Electrochemical Society Publications

Available from the Electrochemical Society, 65 South Main Street, Building D, Pennington, NJ 08534-2839, Tel: 609-737-1902, http://www.ecsdl.org/vsearch/servlet/VerityServlet?KEY=ECSTF8&ONLINE=YES.

Ashtiani, C., "Analysis of Battery Safety and Hazards Risk Mitigation," ECS Transactions 11 (19), 1 (2008).

2.2.2 Sandia National Laboratories Publications

Available from https://www.sandia.gov/news/publications/index.html.

SAND99-0497 Electrochemical Storage System Abuse Test Procedure Manual

SAND2005-3123 FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications

SAND2017-6925 Recommended Practices for Abuse Testing Rechargeable Energy Storage Systems (RESSs)

2.2.3 AIHA Publications

Available from American Industrial Hygiene Association, 2700 Prosperity Ave., Suite 250, Fairfax, VA 22031, Tel: 703-849-8888, www.aiha.org.

Refer to the following link for Emergency Response Planning Guidelines, Level 2 (ERPG-2) description: https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/emergency-response-planning-guidelines-erpgs.html.

2.2.4 EUCAR Publications

Available from EUCAR Office, Avenue des Nerviens 85, 1040 Brussels, Belgium, Tel: +32-2-73-87-352, www.eucar.be.

Josefowitz, W. et al. "Assessment and Testing of Advanced Energy Storage Systems for Propulsion-European Testing Report." Proceedings of the 21st Worldwide Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition. Monaco, EU. April 2-6, 2005. p. 6.

2.2.5 United Nations Publications

Available from UN Economic Commission for Europe, Information Service, Palais des Nations, CH-1211 Geneva 10, Switzerland, Tel: +41-0-22-917-44-44, www.unece.org.

Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, 6th revised edition, 2015. ST/SG/AC.10/11/Rev.6.

2.2.6 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 62660-3 Secondary Lithium-Ion Cells for the Propulsion of Electric Road Vehicles - Part 3: Safety Requirements

IEC TR 62660-4 Secondary Lithium-Ion Cells for the Propulsion of Electric Road Vehicles - Part 4: Candidate Alternative Test Methods for the Internal Short Circuit Test of IEC 62660-3

2.2.7 ISO Publications

Copies of these documents are available online at http://webstore.ansi.org/.

ISO 26262 Road Vehicle - Functional Safety

2.2.8 Other Publications

Mikolajczak, C., Kahn, M., White, K., and Long, R.T., "Lithium-Ion Batteries Hazard and Use Assessment," Fire Protection Research Foundation, July 2011.

3. DEFINITIONS

3.1 ACTIVE PROTECTION DEVICE

Components integral to the cell or battery that require external controls to take actions to mitigate abusive and/or out-of-range conditions as defined by the manufacturer.

3.2 AMBIENT TEMPERATURE

The ambient temperature for any test defined in this document shall be within the range of 25 °C ± 5 °C.

3.3 BATTERY

A general term that inclusively refers to electrochemical cells, modules, packs, and energy storage systems.

NOTE: More specific terminology should be used to describe the level of functionality where appropriate.

See RESS.

3.4 CAPACITOR

An electrostatic device capable of accumulating and holding a charge of electrons that consists of two opposing electrodes separated by a dielectric material.

See RESS. See SUPERCAPACITOR.

3.5 CAPACITY

The total coulometric charge that can be withdrawn from a fully charged electrochemical cell under specified conditions.

3.6 CELL

A basic electrochemical functional unit that at minimum consists of a positive electrode, a negative electrode, and an electrolyte.

See RESS CELL.

3.7 COMBUSTIBLE AND FLAMMABLE LIQUIDS

Refer to NFPA 30.

3.7.1 COMBUSTIBLE LIQUID

Any liquid that has a closed-cup flash point at or above 100 °F (37.8 °C).

3.7.2 FLAMMABLE LIQUID

Any liquid that has a flash point below 100 °F (37.8 °C) and a Reid vapor pressure that does not exceed an absolute pressure of 40 psi (276 kPa) at 100 °F (37.8 °C).

3.8 DEVICE UNDER TEST (DUT)

A general term used to describe the device being tested. This term includes all levels of integration of the test article and can refer to a single unit (cell), a multiple unit assembly (module or pack), or a complete system.

3.9 EFFLUENT

Liquid or gas released when a RESS cell leaks or vents.

3.10 ELECTROCHEMICAL CELL

An electrochemical device that is capable of producing electrical energy from chemical reactions or storing electrical energy through chemical reactions.

3.11 EMERGENCY RESPONSE PLANNING GUIDELINES, LEVEL 2 (ERPG-2)

ERPG-2 levels are defined as the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. This guideline is taken from the American Industrial Hygiene Association (www.aiha.org).

3.12 ENERGETIC FAILURE

Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage. The kinetic energy of flying debris from the RESS may be sufficient to cause damage as well. Also may be described as "explosion."

3.13 FIRE OR FLAME

Ignition and sustained combustion of flammable gas or liquid (approximately more than 1 second). Sparks are not flames.

3.14 FLAMMABLE GAS

The OSHA Hazard Communication Standard (29 CFR 1910 is available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=10099) definition for flammable gas is "a gas that, at ambient temperatures and pressures, forms a flammable mixture with air at a concentration of less than 13% by volume; or forms a range of flammable mixtures with air wider than 12% by volume." Thus, a gas can be categorized as flammable if the gas burns in air at a concentration of less than 13% by volume or the difference between the lower flammability limit (LFL) and the upper flammability limit (UFL) is greater than 12% by volume.

3.15 FLAMMABLE SOLID

The OSHA Hazard Communication Standard (29 CFR 1910 is available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=standards&p_id=10099) definition of a flammable solid is "a solid, other than a blasting agent or explosive as defined in 29 CFR 1910.109(a), that is liable to cause fire through friction, absorption of moisture, spontaneous chemical change, or retained heat from manufacturing or processing, or which can be ignited readily and when ignited burns so vigorously and persistently as to create a serious hazard. A chemical shall be considered a flammable solid if, when tested by the method described in 16 CFR 1500.44, it ignites and burns with a self-sustained flame at a rate greater than one tenth of an inch per second along its major axis."

3.16 FLASH POINT

Flash point is defined in OSHA's 29 CFR 1910.106 as the minimum temperature at which a liquid gives off vapor within a test vessel in sufficient concentration to form an ignitable mixture with air near the surface of the liquid.

3.17 FULLY CHARGED

100% state of charge. The charge state of a RESS after completion of maximum charge procedure specified by the RESS manufacturer (such as reaching the voltage, current, and/or temperature limits). For purposes of this document, a RESS is considered fully charged after the completion of the charge cycle provided that the state of charge shall not fall below 95% before initiating the test sequence.

3.18 FULLY DISCHARGED

0% state of charge. The state of a RESS after reaching the minimum voltage at zero load as specified by the RESS manufacturer.

3.19 INTEGRATOR

For the purposes of this manual, the integrator is the vehicle manufacturer or vendor who installs the RESS for use in an electrified vehicle.

3.20 LEAK or LEAKAGE

Loss of hermeticity of the RESS cell container leading to slow escape of gas or liquid without actuation of a designed vent.

3.21 LFL

Lower flammability limit. Refer to http://www.ilpi.com/msds/ref/flammablelimits.html.

3.22 OVERCHARGE

Continued charging of a fully charged battery.

NOTE: Overcharge is also the act of charging beyond a certain limit specified by the manufacturer.

3.23 PERCENT OF OVERCHARGE

The amount of overcharge in Ah divided by the RESS capacity multiplied by 100.

3.24 OSHA

Occupational Safety and Health Administration, part of U.S. Department of Labor. Refer to http://www.osha.gov/.

3.25 OVER CURRENT PROTECTION DEVICE

A fuse, circuit breaker, intelligent contactor, or other device placed in an electrical circuit to provide current overload protection.

3.26 OVERDISCHARGE

The continuation of discharging after reaching the cutoff voltage.

3.27 PACK

See BATTERY PACK (RESS PACK).

3.28 MAXIMUM PACK VOLTAGE

Open circuit voltage of a pack when fully charged.

3.29 PASSIVE PROTECTION DEVICE

Safety device that is intended for protection from or mitigation of abusive, out-of range conditions experienced by the RESS that does not require active controls or electrical energy supply (e.g., shutdown separator).

3.30 RELEASE

A release means any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment.

3.31 REVERSAL

Forced discharge of a cell or battery to the point that the cell's electrical terminals change polarity.

3.32 RECHARGEABLE ENERGY STORAGE SYSTEM (RESS)

Any energy storage system that has the capability to be charged and discharged. (Example: batteries, capacitors, and electro-mechanical flywheels.)

3.33 RESS CELL

See ELECTROCHEMICAL CELL.

3.34 RESS MODULE (BATTERY MODULE)

Multiple electrochemical cells connected in series or parallel.

NOTE: Battery modules may or may not include sensors such as voltage and temperature sensors, safety components, and a cooling structure so that each module can be controlled and managed independently.

3.35 RESS PACK (RESS BATTERY)

A battery assembly that consists of one or more modules.

NOTE: A pack may include sensors, interlocks, contactors, battery management controller, safety devices, thermal management, and structural components.

3.36 RUPTURE

Loss of mechanical integrity of the cell housing, resulting in release of contents. The kinetic energy of released material is not sufficient to cause physical damage external to the battery system. Cell venting is not rupture.

3.37 STATE OF CHARGE (SOC)

A commonly used working definition is:

$$SoC(t) = SoC(0) + \int_0^t \frac{i(t)}{C} dt \qquad \text{(Eq. 1)}$$

Here, the instantaneous current is i(t) (if the system is negatively polarized, the current is negative) and the capacity of the cell is given as C, where C is a reference state defined under specific temperature and discharge rates. SoC(t=0) is considered as fully charged.

NOTE: SoC is the representation of the level of charge of a battery relative to its referenced capacity through time. SoC is often expressed as a percentage based a reference point as determined by the manufacturer (for example, 0% = empty charge; 100% = full charge).

3.38 SUPERCAPACITOR (Also Called ULTRACAPACITOR, HYBRID CAPACITOR, or ASYMMETRIC-CAPACITOR)

An electrochemical device which is used to store large amounts of electrical charge in comparison to typical dielectric capacitors.

NOTE: Per IEC 62391-1, there are three categories: double layer capacitors, pseudo capacitors, and hybrid capacitors. Super capacitor may also be referred as ultracapacitor.

3.39 TEST ARTICLE

See DEVICE UNDER TEST.

3.40 THERMAL RUNAWAY

An uncontrolled increase of battery temperature caused by exothermic reactions inside the battery.

3.41 THERMAL STABILITY LIMIT

Maximum temperature at which RESS is stable indefinitely.

3.42 UFL

Upper flammability limit. Refer to http://www.ilpi.com/msds/ref/flammablelimits.html.

3.43 VENTING

An event whereby gas is expelled in a controlled or uncontrolled manner from a battery.

NOTE: For a controlled manner, venting can occur from a designated part such as a pressure relief valve or rupture disc.

4. TECHNICAL REQUIREMENTS

4.1 General Test Guidelines

Before starting abuse tests, a test plan will be developed by the testing organization and the plan may be reviewed by the RESS manufacturer and test sponsor. Specifications for each abuse test should be set to determine relevant abuse responses to the expected range of normal and off-normal conditions. The tests should be designed to generate response data that can quantitatively determine the cell and system response of the device under test as well as serve as a guide for future designs. Due consideration shall be given to the post-test conditions that may create additional hazards. Test plan shall consider storage, handling (e.g., control temperatures) and disposal of the DUT prior to and after testing. Refer to SAE J2950 for more information.

Subjecting the RESS to conditions outside their intended operating range necessarily involves some risk of unintended failures. The responsible testing organization shall consult the RESS manufacturer for information regarding the possible consequences of such failures, including the potential release of hazardous substances, so that appropriate precautions can be taken to ensure the safety of testing personnel.

The test facility needs to assure that it can accommodate the size of the RESS being tested as well as to assure the safety of personnel and facility structures. The test facility should be evaluated by the respective experts for structural integrity under conditions of high overpressure and extended fire, as well as evaluation of ventilation system and containment of potentially toxic materials. Consideration needs to be given to the total energy content and the potential high voltage (where applicable) of the RESS, the size of the test room, and the materials of construction. Secondary containment (such as oven or other test chamber) of the RESS is recommended if possible. Fire suppression systems may be incorporated into the facility but should not be used to mitigate the main abuse response of the RESS.

4.1.1 Number, Condition, and Size of Batteries to be Tested

Initial testing will use a new RESS and additional testing of aged or cycled RESS should be performed at the test sponsor's or manufacturer's discretion based on their determination of the most susceptible condition of the technology. Incorporating RESS manufacturer's knowledge and existing information on how their devices perform under abusive conditions in the formulation of the test plan will improve the quality of the data and validity of the test results. The manufacturer will disclose in the test plan any hazardous substances that may be released during abuse tests.

These tests are intended to characterize the RESS response to undesirable "off-normal" conditions or environments that may arise as a result of operator negligence, vehicle accidents, device or system defects, poorly informed or trained users or mechanics, failure of specific RESS control and support hardware, or weather/transportation/handling incidents or accidents. Tests in this document represent conditions for which the RESS was not designed or intended for use, but can reasonably be expected to be encountered infrequently during field use. Some of the tests are not applicable to all candidate RESS technologies. Many of these tests may result in intentional destruction of the device under test.

The required number of RESS units to be subjected to testing will depend on actual performance. It is acceptable to use a new RESS for each test. However, in many cases, it may be economically or technically desirable to subject a single device to multiple tests, either to reduce the number of test articles required or to study the interaction of multiple events (e.g., mechanical shocks followed by penetration, immersion, or high temperatures.)

Unless otherwise stated, passive protection devices that are integral to the RESS shall remain operational throughout the test. All active protective devices shall be disabled prior to the test. It is encouraged that additional operational tests be performed with active protection devices enabled to verify they function as designed.

Tests are grouped into four categories: hazardous substance monitoring, mechanical, thermal, and electrical abuse. Some tests have been arbitrarily classified as they contain more than one of these elements.

4.1.2 Types of Abuse Tests Addressed in This Document

Table 1 - Recommended abuse tolerance tests, including the number of RESS cells, modules, and packs for each test

Section 4.2	Hazardous Substance Monitoring	Recommended number of cells	Recommended number of modules or packs
4.2.1.1	Electrolyte vapor	1	
4.2.1.2	RESS cell forced vent	3	
4.2.1.3	RESS cell forced vent with thermal runaway	3	
4.2.1.4	Pack level hazardous substance monitoring		3
Section 4.3	**Mechanical Abuse Tests**		
4.3.1	Shock		3
4.3.2	Drop		3
4.3.3	Penetration	5	3
4.3.4	Roll-over		3
4.3.5	Immersion		3
4.3.6	Crush	4-6*	2-3*
4.3.7	Simulated Internal Short Circuit Test	5	
Section 4.4	**Thermal Abuse Tests**		
4.4.1	High Temperature Hazard Test		3
4.4.2	Thermal Stability	3	
4.4.3	Cycling without Thermal Management		3
4.4.4	Thermal Shock Cycling	3	3
4.4.5	Single Cell Failure Propagation Resistance Test		3
Section 4.5	**Electrical Abuse Tests**		
4.5.1	Short Circuit	5	3
4.5.2	Overcharge	5	3
4.5.3	Overdischarge (Forced Discharge)	5	3
4.5.4	Separator Shutdown Integrity	3	

* Two tests per crush axis at the cell level. Pouch cells will have crush test only on flat side axis, perpendicular to cell electrodes. One test per crush axis at the pack level.

4.1.3 Test Conditions and Measurement Accuracies

All test articles shall be tested in conditions and states of charge which reflect the range of normal and off-normal conditions. This includes a fully charged state (100% SOC), at normal operating temperature with any cooling media in place and thermal control systems running unless specifically stated otherwise. The cell fixtures or holders for all abuse tests should be configured to simulate the mechanical and thermal environment they would experience in a module or pack.

The test configuration for modules or packs should include any provisions and hardware for vent gas collection, vent gas manifolding, and/or vent gas removal as intended by the RESS manufacturer for vehicle applications. Testing without system controls and mitigation devices is also recommended to determine the limits of abuse response for the cells and modules. All test articles will be observed for a time period of at least 1 hour or until such time that said test article is judged safe to handle after each test unless specifically stated otherwise.

Except where specifically stated otherwise (e.g., elevated temperature abuse tests or when manufacturer's recommended operating temperature is different from ambient temperature), the ambient temperature for any test defined in this document shall be within the range of 25 °C ± 5 °C, and the RESS environment shall be stabilized at this temperature prior to the start of testing.

Measured data shall be acquired at rates and with accuracies adequate to assure that the usefulness of the test data is not compromised. In the absence of more specific requirements by the test sponsor, the measurement accuracies in Table 2 shall be considered acceptable. Because of the wide variety of test dynamics, it is not possible to specify absolute data rates. However, the required data for a particular test shall be acquired at a rate such that errors due to test dynamics will not exceed the required measurement accuracies. For example, if the required accuracy for a given test is 10 °C, the temperature shall be measured sufficiently often that measurement delays will not contribute more than 10 °C error to the resulting data during the important parts of the test.

Table 2 - Measurement accuracies

Parameter	Accuracy
Temperature (the larger of)	±2 °C or ±5% of reading
Voltage, current, resistance	±1% of reading
Mass and force	±1% of reading
Time	±0.1% of reading
Displacement rate	±10% of reading
Vibration, deformation	±4% of reading
Hazardous substance concentration	±10% of reading

4.1.4 Hazardous Substance Monitoring

This test measures amounts of hazardous substances (airborne volatiles and particulates) released when the RESS container vents or is compromised during an abusive event. A release means any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment.

The testing for hazardous substances should be performed on cells as well as cell electrolyte. Testing will be done using a graded approach in which it is initially determined if hazardous substances are present or could be generated as a result of abuse above ERPG-2 levels. Manufacturers will identify any hazardous materials that may be released by their products during abusive testing using standard analytical techniques. The release of hazardous substances shall be measured and referenced to the ERPG-2 levels.

Hazardous substance monitoring methods shall be selected to accurately measure anticipated release products; manufacturer's input or initial screening tests shall be required to determine this. The manufacturer will provide mathematical formulas that describe time-dependent gaseous concentrations that will be used by the testing organization in order to determine if any gas component exceeds ERPG-2 levels or falls into the concentration range between upper and lower flammability limits when mixed with air. The time resolution of such sampling is not specified because of the wide variability in test dynamics and release amounts/rates expected.

For substances not considered hazardous by ERPG-2, the EPA reportable release limits are used as a reference for comparison purposes only.

4.1.5 Flammability Determination

Flammability should be measured whenever the hazard severity level is to be determined during any test which may result in the release of potentially flammable materials. Flammability determination and spark ignition sources are not required for tests that are performed for other purposes, such as failure mode (tear down) or gas species analysis according to 4.1.4.

The determination of flammability requires the presence of an ignition source in combination with fuel and oxidizer in concentrations that will support combustion. A fire or flame will not be observed if any of these elements are absent. Credible abuse environments would likely include a spark source. For this reason, it is recommended that when determining the hazard severity level during any test described in this document (see Table 3), a continuous spark source (at least 2 sparks/s with sufficient energy to ignite natural gas) be used during tests that are likely to result in venting of the RESS. The flammability of any expelled materials will be determined using external ignition sources in at least two separate locations around the RESS to evaluate flammability of different fuel to air ratios. Location of spark sources will be documented.

4.1.6 Identification of Severity

RESS response to abusive tests will be determined. Severity level described in Table 3 will be reported for each test and this information can be used in the battery safety and hazards risk mitigation approach.

Table 3 - Hazard severity levels and descriptions (adapted from EUCAR and SAND2005-3123)

Hazard Severity Level	Description	Classification Criteria and Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No damage or hazard; reversible loss of function. Replacement or re-setting of protection device is sufficient to restore normal functionality.
2	Defect/Damage	No hazard but damage to RESS; irreversible loss of function. Replacement or repair would be needed to restore normal functionality. No venting or leaking of electrolyte.
3	Minor Leakage/ Venting	Visual or audible or some other evidence of cell venting or leaking of electrolyte or vapor; or leak without significant pooling of free electrolyte; or venting without significant smoke or loss of particulate material; or total RESS mass loss typically <5%.
4	Major Leakage/ Venting	Visual evidence of leaking or venting; or leaking with significant pooling or observed free electrolyte; or venting with significant smoke, solvent vapor, and/or loss of particulate material; or visual obstruction of the RESS by vent gases and/or smoke; or total RESS mass loss typically ≥5% and <30%.
5	Rupture	Loss of mechanical integrity of the RESS container, resulting in release of contents. The kinetic energy of released material is not sufficient to cause physical damage external to the RESS. No projectiles outside battery enclosure. Total RESS mass loss typically ≥30%.
6	Fire or Flame	Ignition and sustained combustion of flammable gas or liquid (≥1 second sustained fire). Sparks or incandescent material are not considered a fire or a flame.
7	Energetic Failure	Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage, depending on the size of the RESS.

4.1.7 Measured Data

The following is a list of measurements and data that will be collected as required and specified in the abuse tests described in this document. The data shall be collected before, during, and after the test for the specified post-test observation period (1 hour).

a. FLAMMABILITY. The flammability of any solids, liquids, and gases released during the mechanical abuse tests will be analyzed according to 4.1.5.

b. ACCELERATION. Acceleration exerted to the DUT case to be measured with a minimum of 2 kHz bandwidth.

c. DEFORMATION. RESS deformation to be determined by measurements before and after the test.

d. TEMPERATURE. The temperature of the RESS to be recorded at several external and internal (where applicable) locations as a function of time.

e. VOLTAGE and RESISTANCE. Voltage and resistance of the RESS case with respect to the positive and negative terminals before and after the test.

   WARNING: Check for voltage difference between terminals and case before resistance measurement. Do not perform a low-impedance type resistance measurement (e.g., ohm-meter) if a voltage is present. Resistance can be measured using AC impedance techniques with blocking capacitors.

f. PHOTOGRAPHS. Still photographs of the test setup and the RESS, before and after the test, including the post-test observation period.

g. VIDEO. Video monitoring for the duration of the test, including the observation after the test.

h. MASS. Mass of the DUT will be measured before and after the test to determine if venting and loss of contents has occurred.

4.1.8 Test Plans and Reporting

Recommended test plans and reporting format is given in Appendix A. Test reporting documents with other formats are acceptable, provided they include the content listed in Appendix A.

4.2 Hazardous Substance Monitoring Tests (Cell Level and Above)

This test evaluates hazardous substances (airborne volatiles and particulates) released when the RESS container vents or is compromised during an abusive event.

4.2.1 Test Description

Tests require quantitative hazardous substance identification and monitoring to be conducted in a closed volume of appropriate size to accommodate the test article and provide adequate space for the vented gases. The concentration of the released hazardous substances shall be scaled to the full RESS pack for quantitative comparison.

Electrolyte and representative parts of the RESS cell will be exposed to abuse tests and analyzed for their airborne volatiles and particulates. Four types of tests are to be conducted:

1. Electrolyte vapor analysis.

2. Cell forced vent without thermal runaway.

3. Cell forced vent with thermal runaway.

4. Pack level hazardous substance monitoring will be performed in conjunction with one other pack level abuse tests during which combustion of the cells and pack materials is expected.

When cells are used, they will be charged to 100% SOC and inserted into a closed chamber.

4.2.1.1 Test #1

A sufficient amount of electrolyte to saturate the gas volume (i.e., liquid must always be present during the test) is placed in a closed chamber at the upper operation temperature of the cell or 50 °C, whichever is higher, and >90% humidity. After 60 min at temperature, the vapors are sampled.

4.2.1.2 Test #2

Cells will be exposed to one of the following abusive conditions without entering thermal runaway:

a. Thermal stability at elevated temperature (4.4.2),

b. Overcharge (4.5.3), or

c. Nail penetration (4.3.3).

If venting occurs, vented airborne volatiles and particulates will be analyzed.

4.2.1.3 Test #3

The method to force a cell into thermal runaway shall be left to the discretion of the tester. In the report, the method chosen to force the cell into thermal runaway will be described in detail and the choice justified, since the method used may significantly influence the nature of the vented airborne volatiles and particulates. One method is to apply heat from an external source and heating the chamber at 5 °C/min to 400 °C. Another method may involve overcharging the cells. Vented airborne volatiles and particulates will be analyzed.

4.2.1.4 Test #4

Pack level hazardous substance monitoring will be performed in conjunction with one other pack level abuse tests during which combustion of the cells and pack materials is expected. Localized sampling of combustion products will be performed to determine the possible presence of hazardous gas species released from the combined combustion of the pack materials. Total containment of the pack is not required during this test.

4.2.2 Measured Data

a. The data shall be collected before, during, and after the test for the specified post-test observation period (1 hour). All solids, liquids, and gases released during the abuse tests will be identified by using accepted analytical techniques. This includes the airborne samples collected during testing and the swiped samples from the chamber walls. Examples of acceptable analytical techniques are EPA Methods TO-15 and TO-17. (Refer to http://www.epa.gov/ttnamti1/files/ambient/airtox/to-15r.pdf or http://www.epa.gov/ttnamti1/files/ambient/airtox/to-17r.pdf.)

b. Cell mass before and after test. (MASS.)

c. Still photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS.)

d. Concentrations of gas scaled to the full pack and scaled to an appropriate volume will be compared to LFL and UFL (where they are known) to estimate the potential flammability.

e. Pack level test only: The flammability of any solids, liquids and gases released during the mechanical abuse tests will be analyzed according to 4.1.5. When determining the hazard severity level, procedures described in 4.1.5 shall be used.

4.3 Mechanical Abuse Tests

The mounting and support of the RESS shall be as similar as possible to the manufacturer's recommended installation requirements for mechanical shock and vibration tests. If the support structure has any resonance below 50 Hz, the input will be determined by the average of the acceleration at each of the major support points.

4.3.1 Shock Tests (Cell Level or Above)

4.3.1.1 Test Description

Subject the DUT to shock events at one or more defined shock levels. The shock test described in Section 38.3 of the UN "Manual of Tests and Criteria" for Transport of Dangerous Goods is to be applied to cells regardless of cell chemistry. The shock levels and durations described in Table 4 are to be applied to the pack. Each shock level is specified in terms of a velocity change and a corresponding maximum duration. (Shock duration is defined as the time between 10% and 90% of peak value.) The DUT should be observed for a minimum of 1 hour after the test.

Table 4 - Shock levels and durations

	Acceleration	Duration	Pulse Form	Total Number of Shocks
Pack	25 g	15 ms	Half sine	18 = 3 repeats on three axes in both positive and negative directions

4.3.1.2 Measured Data

The following data shall be collected as part of this test:

a. Acceleration exerted to the DUT case to be measured with a minimum of 2 kHz bandwidth. (ACCELERATION.)

b. DUT deformation to be determined by measurements before and after the test. (DEFORMATION.)

c. The temperature of the DUT to be recorded at several external and internal (where applicable) locations as a function of time. (TEMPERATURE.)

d. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE.)

e. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

f. Mass of the DUT will be measured before and after the test to determine if venting and loss of contents has occurred. (MASS for cells only.)

g. For pack-level testing in systems which include a high-voltage isolation and/or high-voltage interlock system, changes in the reported high voltage isolation state or high voltage interlock state from initial values will be noted at the end of the test exposure.

h. Steps (c) and (d) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.2 Drop Test (Pack Level Only)

4.3.2.1 Test Description

Drop the DUT (free drop) from a height of 1 m, or a height dictated by actual field use procedures, whichever is larger, onto a hard flat surface in the most vulnerable orientation. A horizontal impact into a hard flat surface with an equivalent velocity and deceleration on impact is acceptable. The DUT should be observed for a minimum of 1 hour after the test.

4.3.2.2 Measured Data

The following data shall be collected as part of this test:

a. Deceleration exerted on the DUT case to be measured with a minimum of 2 kHz bandwidth. (ACCELERATION.)

b. DUT deformation to be determined by measurements before and after the test. (ACCELERATION.)

c. The temperature of the DUT to be recorded at several external and internal (where applicable) locations as a function of time. (TEMPERATURE.)

d. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE.)

e. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

f. For pack-level testing in systems which include a high-voltage isolation and/or high-voltage interlock system, changes in the reported high voltage isolation state or high voltage interlock state from initial values will be noted at the end of the test exposure.

g. Steps (c) and (d) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.3 Penetration Test (Cell Level or Above)

4.3.3.1 Test Description

Penetration tests represent only one type of possible cell damage from an external object that compromises the integrity of the cell. Penetrate the DUT with a mild steel (conductive) rod. The diameter of the rod, its end type, as well as the depth and rate of its penetration can be found in Table 5. The orientation of the penetration shall be perpendicular to the cell electrodes.

The DUT should be observed for a minimum of 1 h after the test with the rod remaining in place. If parallel cells are used in the module, the cell level test should be configured with the same number of cells in parallel to the cell that is to be penetrated. When determining the hazard severity level, procedures described in 4.1.5 shall be used.

Table 5 - Penetration characteristics

Size of Test Object	Diameter of Rod	Rod End Type	Rate of Penetration	Minimum Depth of Penetration
Cell	3 mm	Tapered to a sharp point	8 cm/s or greater	Through cell
Module/pack	20 mm	Tapered to a sharp point	8 cm/s or greater	Through three cells or 100 mm, whichever is greater

4.3.3.2 Measured Data

The following data shall be collected as part of this test:

a. DUT deformation to be determined by measurements before and after the test. (DEFORMATION.)

b. The temperature of the DUT to be recorded at several external and internal (where applicable) locations as a function of time. (TEMPERATURE.)

c. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE.)

d. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

e. Rate of Penetration will be measured during the test.

f. Steps (b) and (c) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.4 Rollover Test (Module and Pack Level)

4.3.4.1 Test Description

Rotate the DUT one complete revolution in 1 minute in a continuous slow roll fashion, and observe whether any material leaks from the DUT. Then rotate the DUT in 90 degree increments for one full revolution. Observe the DUT for 1 hour at each position and for a minimum of 1 hour after the test.

4.3.4.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.)

b. Voltage and resistance of the DUT to be recorded as a function of time. (VOLTAGE and RESISTANCE.)

c. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

d. Steps (a) and (b) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.5 Immersion Test (Module or Pack Level)

4.3.5.1 Test Description

With the DUT in its normal operating orientation and temperature, immerse the DUT in ambient temperature salt water (5% by weight NaCl in H_2O) for a minimum of 2 hours or until any visible reactions have stopped. The water depth must be enough to completely submerge the DUT. The DUT may be placed into a tank filled with water or may be placed in an empty tank and water pumped into the tank to fully submerge the DUT.

4.3.5.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.)

b. Voltage and resistance of the DUT to be recorded as a function of time. (VOLTAGE and RESISTANCE.)

c. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

d. Gas analysis to measure potential gases produced by electrolysis of salt water (e.g., hydrogen or chlorine gas).

e. Steps (a) and (b) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.6 Crush Test (Cell, Module, or Pack Level)

4.3.6.1 Test Description

The DUT shall be crushed between a fixed surface and a crush fixture that results in sufficient localized deformation to cause shorting. For modules and packs, the crush fixture shall consist of a textured platen with semi-cylindrical crush surfaces of a diameter comparable to the smallest dimension of the DUT. To the greatest extent possible, the crush platen orientation shall be perpendicular to the cell electrode surfaces.

If cell level crush tests have been performed per UN T6, UL 1973, or IEC CD 62619 (2017), additional tests are not required.

The number and spacing of the semi-cylindrical crush surfaces should be sufficient to span the main area of the DUT where shorting can occur. Figure 1 illustrates an example of the approximate shape of a platen with three semi-cylindrical crush surfaces of 75 mm radius separated by 30 mm. For individual cells, crush will be performed using a crush fixture of sufficient length to cause deformation over a major portion of the crush surface. For prismatic and pouch cells, the crush fixture surface should contact the cell parallel to the crush surface. For cylindrical cells, a single cylindrical crush bar to be used should be of diameter comparable to the diameter of the cell with the long axis of the crush bar perpendicular to the long axis of the cell and parallel to the cell surface. See Figure 2 for a photograph of an example of a cylindrical cell crush fixture for cells.

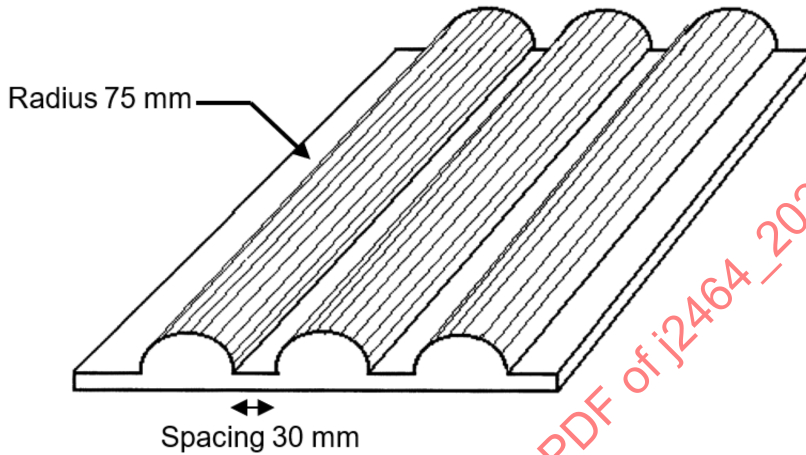

Figure 1 - Example of a crush test platen for modules and packs

Figure 2 - Photograph of an example of a cylindrical crush test fixture for cells

The DUT shall have all integrated control and interconnect circuitry (if provided; may not be applicable at the cell level) in place and operating. A DUT is to be crushed in at least two of the three axes (using a different RESS for each crush), with the semi-cylindrical crush surfaces of the platen at the most vulnerable location to include the main cell area. The long axis of the crush surfaces should be oriented perpendicular to the cell major dimension so that the cells are deformed and not merely spread apart. For each DUT, crush to 85% of the initial dimension and hold for 5 minutes. After the hold period, continue the crush to 50% of the initial dimension and hold for 5 minutes. The crush force should be limited to a maximum of 1000 times the weight of the DUT. The crush speed should be sufficiently slow to allow determination of the source of any shorting and the rate of internal heat propagation leading to possible thermal runaway (between 0.5 cm/min and 1 cm/min for packs and between 0.5 mm/min and 1 mm/min for cells). If the test is performed outside, the wind speed should be <3 mph. When determining the hazard severity level, procedures described in 4.1.5 shall be used.

4.3.6.2 Measured Data

a. Acceleration force exerted to the DUT case to be measured with a minimum of 2 kHz bandwidth. (ACCELERATION.)

b. DUT rate of deformation to be determined by measurements during the test. (DEFORMATION.)

c. The temperature of the DUT to be recorded at several external and internal (where applicable) locations as a function of time. (TEMPERATURE.) In addition, air temperature immediately above the DUT shall be monitored as an aid to detect the presence of flames.

d. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE.)

e. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

f. Mass of the DUT will be measured before and after the test to determine if venting and loss of contents has occurred. (MASS for cells only.)

g. The flammability of any solids, liquids and gases released during the mechanical abuse tests of cells will be analyzed according to 4.1.5. When determining the hazard severity level, procedures described in 4.1.5 be used.

h. For pack-level testing in systems which include a high-voltage isolation and/or high-voltage interlock system, changes in the reported high voltage isolation state or high voltage interlock state from initial values will be noted at the end of the test exposure.

i. Steps (c) and (d) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.3.7 Simulated Internal Short Circuit Test (for Cells Only)

This section is “for information only” to provide the reader with information on internal short circuit test procedures that are being developed by various organizations. This document does not express an opinion on the usefulness or validity of these tests.

Internal short circuit tests are being developed that use (a) unmodified production cells, and (b) cells with an implanted internal short circuit device.

Examples of internal short circuit tests that are being developed are listed below. These examples do not represent a complete list of all types of internal short circuit tests that are in development.

4.3.7.1 Internal Short Circuit Tests on Unmodified Production Cells

1. UL and NASA “Blunt Nail Crush.” Crush the cell with a blunt nail until detection of 100 mV open-circuit voltage (OCV) drop. Blunt nail is defined as having an angle of 45 degrees and a radius of 0.9 mm. (Refer to ANS/CAN/UL 1973, “Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications,” Appendix F, F3.2, “External indentation without casing/surface penetration.”)

2. Motorola and ORNL “Pinch Test with Two Large Spheres,” which provides a larger area for the internal short circuit to develop. (Refer to Maleki, H. and Howard, J.N., J. Power Sources, 2008.)

These tests may be useful in measuring progress in development of cells with better abuse tolerance. However, they may not be representative of all types of internal short circuit that occur in the field, since internal shorting in these tests will occur over several layers of anode and cathode, unlike the internal short circuit that results from a dendrite or conductive inclusion.

Note that a nail penetration test is not representative of an internal short circuit that occurs in the field.

4.3.7.2 Internal Short Circuit Tests on Modified Cells

These tests involve insertion of foreign material inside a cell to trigger an internal short circuit.

1. Japanese Industrial Standard (JIS) describes the insertion of "L-shaped" Ni metal object into cell between electrodes of a fully charged cell. Force is applied to the cell to create internal short circuit. (Refer to JIS C 08714 (2007) "Safety Tests for Portable Li-Ion Secondary Cells and Batteries for Use in Portable Electronic Applications.")

   JIS C 08714 procedure has been adopted by IEC 62133-2 Ed. 1.0, Feb. 2017, "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Lithium Systems."

2. NREL/NASA describes internal short circuit test method to evaluate cells specially prepared by the cell manufacture. A portion of an electrode coating is removed and replaced with this device, which has a low melting wax as an insulator. The application of mild heat melts the wax, creating an internal short circuit. (Refer to U.S. Patent # 9,142,829.)

These types of tests are a closer simulation of an internal short circuit that occurs in the field, since internal shorting will occur between specific layers of anode and cathode. However, care must be taken to assure that these modified cells are representative of production cells.

4.4 Thermal Abuse Tests

4.4.1 High Temperature Hazard Test (Module Level and Above)

4.4.1.1 Test Description

The objective of this test is to intentionally destroy a DUT at temperatures that might be experienced in a fuel fire and evaluate the risk of explosion hazard. A further objective of this test is to reproduce the temperature experienced in a fuel fire (590 °C nominal) in a manner that allows collection of data and gas samples that cannot be achieved in an actual fuel fire test.

The thermal chamber temperature should be achieved within 5 minutes and shall be held for a period of 20 minutes or until another condition occurs which would prevent the completion of the tests. This test can be performed by placing the DUT inside a "radiant heating" fixture described below. The DUT will be at 100% SOC. The DUT will not be insulated or protected unless this is the standard configuration for the test article. If the DUT ignites, it may be extinguished with a method appropriate for the technology after the completion of the test.

The suggested "radiant heating" test fixture is a thin cylindrical metallic fixture whose inside is coated such that it will radiate approximately like a black body. The exterior surface is heated with radiant energy from arrays of quartz lamps (or other heat sources). The test temperature is controlled by thermocouples mounted on the interior surface of the fixture, with the device under test placed in the center of the fixture such that it does not contact the fixture walls. A sketch of such a test fixture is shown in Figure 3.

If such a fixture is not available, this test can be conducted using some other means (e.g., a tube furnace and conveyer mechanism) that would expose the DUT to non-contact heat from a radiating surface at 590 °C ± 5%. The thermal environment of the DUT should increase from ambient to 590 °C within 5 minutes.

Note that pack level hazardous substance monitoring (see 4.2.4) is recommended during this test.

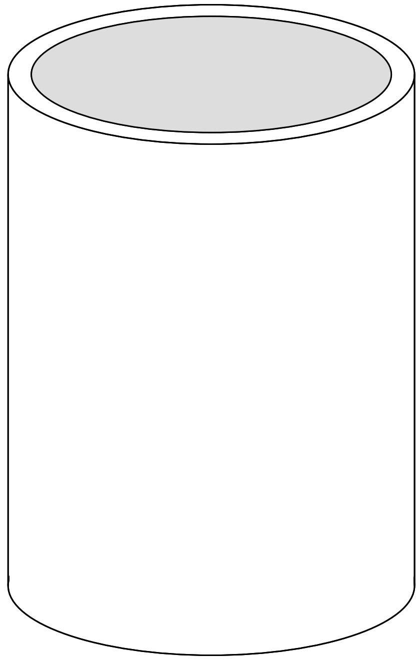

Figure 3 - Radiant heating fixture test fixture

4.4.1.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.)

b. Voltage and resistance of the DUT to be recorded as a function of time. (VOLTAGE and RESISTANCE.)

c. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

d. Note ignition of flammable gases.

e. Evidence of projectiles produced by the DUT.

f. Steps (a) and (b) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.4.2 Thermal Stability Test (Cell Level)

The objective of this test is to measure the thermal stability limit of a cell (maximum temperature at which DUT is stable indefinitely).

4.4.2.1 Test Description

The cell shall be in a fully charged state and at normal operating temperature at the beginning of the test. If the temperature at which a major exothermic reaction occurs is known (i.e., onset of thermal runaway), the test may begin at 25 °C lower than this temperature. Testing at other states of charge may be performed if the cell manufacturer has information that thermal stability is degraded at other SOCs. Thermal ramp rate shall be a minimum of 5 °C/min. Place the cell in a device or chamber capable of heating the cell to 300 °C above its maximum operating temperature. The cell fixtures or holders should be configured to simulate the mechanical and thermal environment they would experience in a module or pack. The DUT shall be uninsulated and exposed to static air conditions in the chamber. Increase the temperature in 5 °C increments, and hold at each temperature step for 30 minutes or until any self heating is detected. Cell temperature will be measured at a cell terminal. If self heating (>1.0 °C/min) is detected, i.e., the cell temperature exceeds the ambient test temperature, the temperature of the chamber shall remain constant until the DUT temperature stabilizes (i.e., DUT temperature remains constant, ±2 °C for 30 minutes) or until (a) the DUT temperature reaches 300 °C above the operating temperature of the cell, or (b) a catastrophic event occurs (e.g., venting or major damage to the cell).

4.4.2.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.) Oven/chamber temperature profile with respect to time as well as temperature(s) at which venting, smoke generation, or other major events will also be recorded. Cell self-heating rate as a function of cell temperature, including temperature at which self-heating is first observed.

b. Maximum temperature at which DUT is stable indefinitely and temperature at which self-heating rate of DUT exceeds 10 °C/min. Cell condition (i.e., age, state of charge, temperature, etc.) will be reported with all data.

c. Voltage and resistance of the DUT to be recorded as a function of time. (VOLTAGE and RESISTANCE.)

d. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

e. When determining the hazard severity level, procedures described in 4.1.5 shall be used. (FLAMMABILITY.)

f. Cell mass before and after test. (MASS.)

4.4.3 Cycling without Thermal Management (Module and Pack Level)

4.4.3.1 Test Description

With the DUT at nominal operating temperature, fully charged, contained in a closed volume of static air, and active thermal controls (primary and secondary) disabled, charge the DUT using the manufacturers defined charge algorithm followed by a discharge at a rate comparable to the intended application. Twenty full charge/discharge cycles should be performed as described with no rest period between charge and discharge. When determining the hazard severity level, procedures described in 4.1.5 shall be used.

4.4.3.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.)

b. Voltage and resistance of the DUT to be recorded as a function of time. (VOLTAGE and RESISTANCE.)

c. Video monitoring for the duration of the test, including the observation after the test as well as photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS and VIDEO.)

d. The flammability of any solids, liquids and gases released during the mechanical abuse tests will be analyzed according to 4.1.5. When determining the hazard severity level, procedures described in 4.1.5 shall be used. (FLAMMABILITY.)

e. Steps (a) and (b) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.4.4 Thermal Shock Cycling (Cell Level or Above)

4.4.4.1 Test Description

With the DUT at the maximum operating state of charge, contained in a closed volume, and active thermal controls (primary and secondary) disabled, thermally cycle the DUT with ambient air cycling between 70 to -40 °C. The time for the chamber ambient temperature to reach each temperature extreme shall be 15 minutes or less; this test may be performed either through the use of a fast-response chamber, or by moving test articles between two chambers at the two test temperatures. The DUT shall remain at each extreme for a minimum of 1 hour at the cell level, 6 hours at the module level, or as required to reach a uniform temperature (±5 °C) at the pack level. A total of five cycles shall be performed. After thermal cycling, inspect the DUT for any damage, paying special attention to any seals that may exist. Also, determine whether control circuitry, if any, is operational. Perform three C/3 discharge cycles at 25 °C ambient air temperature before and after test (using the manufacturers recharge algorithm) to determine immediate effects of the thermal cycling.

4.4.4.2 Measured Data

The following data shall be collected as part of this test:

a. The temperature of the DUT to be recorded as a function of time. (TEMPERATURE.)

b. Voltage of the DUT to be recorded as a function of time. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE.)

c. Still photographs of the test setup and the DUT, before and after the test, including the post-test observation period. (PHOTOGRAPHS.)

d. Note any venting of the DUT.

e. Measure DUT capacity before and after test.

f. Cell mass before and after test. (MASS.)

g. For pack-level testing in systems which include a high-voltage isolation and/or high-voltage interlock system, changes in the reported high voltage isolation state or high voltage interlock state from initial values will be noted at the end of the test exposure.

h. Steps (a) and (b) and visual inspection of the DUT to be repeated 24 hours after test completion.

4.4.5 Single Cell Failure Propagation Resistance Test (Module or Pack Level)

This test evaluates the response of a DUT to a single cell thermal runaway event, to determine if thermal runaway will propagate to adjacent cells. It is recommended that the DUT manufacturer first perform these tests at the module level.

4.4.5.1 Test Description

The DUT is charged to 100% SOC and powered down (no load). All external circuits, cooling systems, or other devices are turned off or disconnected. If liquid cooling is used, the liquid may remain in the DUT without circulation. The DUT is heated until the cells stabilize at the maximum operating temperature. One cell, the “trigger cell,” within the DUT at locations described below is heated in-situ to a temperature of 400 °C (or until the cell enters thermal runaway) in as short a time as feasible (for example, using resistive heating or thermal conductive heat transfer using an external heat source). The method used to create a thermal runaway in one cell will be described and documented in the report. The methods used to trigger thermal runaway should have minimum influence on neighboring cells or configuration of DUT. After one of the above conditions is met, the heater is turned off and DUT is observed for 1 hour. Other methods to initiate thermal runaway in one cell are allowed. The selection of the thermal runaway initiation method should be described and justified.