SAE International™

SURFACE VEHICLE RECOMMENDED PRACTICE

J2464 NOV2009

Issued 1999-03
Revised 2009-11

Superseding J2464 MAR1999

(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.

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

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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.

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. This document applies to vehicles with RESS voltages above 60 volts. This document does not apply to RESS that uses mechanical devices store energy (e.g., electro-mechanical flywheels).

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.

This document is not intended to certify the RESS for shipping. 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 safety is only one component of the 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 ancillary support systems. 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 (see “Analysis of Battery Safety and Hazards' Risk Mitigation”, Cyrus Ashtiani, ECS Trans. 11 (19), 1 (2008)).

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 Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, 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 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 in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)

SAE J1950 Proving Ground Vehicle Corrosion Testing

SAE J2344 Guidelines for Electric Vehicle Safety

2.2 Related Publications

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

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.

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

2.2.2 Sandia National Laboratories Publications

Available from http://www.prod.sandia.gov/.

Electrochemical Storage System Abuse Test Procedure Manual, February 1999 Version 1.0, T. Unkelhaeuser and D. Smallwood, published as Sandia Laboratories report SAND99-0497

FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications, June 2005, Daniel H. Doughty and Chris C. Crafts, published as Sandia National Laboratories report SAND2005-3123

2.2.3 AIHA Publication

Available from American Industrial Hygiene Association, 2700 Prosperity Ave., Suite 250, Fairfax, VA 22031, Tel: 703-849-8888, www.aiha.org. See the following link for Emergency Response Planning Guidelines, Level 2 (ERPG-2) description.

http://response.restoration.noaa.gov/topic_subtopic_entry.php?RECORD_KEY%28entry_subtopic_topic%29=entry_id,subtopic_id,topic_id&entry_id(entry_subtopic_topic)=663&subtopic_id(entry_subtopic_topic)=24&topic_id(entry_subtopic_topic)=1

2.2.4 EUCAR Publication

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 Publication

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.

Transportation of Dangerous Goods, Manual of Tests and Criteria, 4th Edition Revised, 2003. ST/SG/AC.10/11/Rev.4

3. DEFINITIONS

3.1 Active Protection Device

Safety device that consists of a sensor and actuator and is intended for protection from or mitigation of abusive, out-of range conditions experienced by the DUT.

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

Energy storage device that relies on oxidation/reduction (Faradaic) reactions. See RESS.

3.4 Capacitor

Energy storage device that does not rely on Faradaic reactions. See RESS.

3.5 Capacity

The charge measured in amp-hours (Ah) of a RESS from the fully charged to the fully discharged state using the discharge profile as specified by the manufacturer.

3.6 Cell

See RESS Cell.

3.7 Combustible and Flammable Liquids

A combustible liquid has a flash point between 100 °F to 200 °F (37.8 °C to 93.3 °C); a flammable liquid has a flash point that is below 100 °F (38 °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 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 h 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 (http://www.aiha.org/Content).

3.11 Explosion

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. The kinetic energy of flying debris from the RESS may be sufficient to cause damage as well.

3.12 Fire or Flame

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

3.13 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 thirteen (13) percent by volume; or forms a range of flammable mixtures with air wider than twelve (12) percent 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.

3.14 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."

3.15 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.

3.16 Fully Charged

100% State of Charge. The charge state of a RESS after completion of charging 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.

3.17 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.

3.18 Integrator

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

3.19 Leak

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

3.20 LFL

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

3.21 Overcharge

Supplying current to the RESS exceeding the fully charged state as specified by the manufacturer.

3.22 Percent of Overcharge

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

3.23 OSHA

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

3.24 Over Current Protection Device

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

3.25 Overdischarge

Forced discharge beyond the manufacturer's recommended limits that may lead to voltage reversal. See reversal.

3.26 Pack

See RESS pack.

3.27 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).

3.28 Release

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

3.29 Reversal

Forced discharge (overdischarge) of a RESS to the point that the cell's electrical terminals change polarity.

3.30 RESS

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

3.31 RESS Cell

An assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components. A cell is a self-contained energy storage device whose function is to deliver electrical energy to an external circuit.

3.32 RESS Module

A grouping of interconnected cells in series and/or parallel arrangement into a single mechanical and electrical unit.

3.33 RESS Pack

Interconnected modules including all ancillary subsystems for mechanical support, thermal management, and electronic control.

3.34 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.

3.35 State of Charge (SOC)

The relative capacity of the RESS expressed as a percentage of the fully charged capacity.

3.36 Test Article

See 'Device Under Test.'

3.37 Thermal Runaway

The uncontrolled increase in the temperature of a RESS driven by exothermic processes.

3.38 Thermal Stability Limit

Maximum temperature at which RESS is stable indefinitely.

3.39 UFL

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

3.40 Venting

The release of excessive internal pressure from a RESS cell, module or pack in a manner intended by design to preclude rupture or explosion.

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.

Subjecting the RESS to conditions outside their intended operating range necessarily involves some risk of unintended failures. The responsible testing organization should 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 of the RESS (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 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 AND OPTIONAL ABUSE TOLERANCE TESTS,
INCLUDING THE NUMBER OF RESS CELLS, MODULES AND PACKS FOR EACH TEST

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

1. A third test is required if results of duplicate tests are not in good agreement.
2. Two tests are required, but full cells are not involved.
3. Two tests per crush axis at the cell level. One test per crush axis at the pack level.
4. Presumes that the Thermal Stability Limit is known. Additional cells may be required if Thermal Stability Limit is not known prior to tests.

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 h 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
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. ERPG-2 refers to the Emergency Response Planning Guidelines, Level 2, from the American Industrial Hygiene Association. 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 h without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. 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. Further calculations will be done by the manufacturer 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 (HAZARDOUS SUBSTANCE).

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/sec 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 needed.
3	Minor Leakage/ Venting	Evidence of cell leakage or venting with RESS weight loss < 50% of electrolyte weight.
4	Major Leakage/ Venting	Evidence of cell leakage or venting with RESS weight loss > 50% of electrolyte weight.
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.
6	Fire or Flame	Ignition and sustained combustion of flammable gas or liquid (approximately more than one second). Sparks are not flames.
7	Explosion	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. The kinetic energy of flying debris from the RESS may be sufficient to cause damage as well.

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 h).

a) FLAMMABILITY. 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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.

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. All tests will be performed in duplicate. Smaller cells may be substituted in the series of tests only in the event that the RESS manufacturer's commercial EV/HEV cell size is too large for completion of these tests. However, the RESS manufacturer must provide evidence that the smaller cells give representative performance and have all chemical constituents and passive protection devices of the commercial cells.

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 and scaled to a volume appropriate to human exposure in the vehicle.

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 each of the following three abusive conditions without entering thermal runaway:

a) thermal stability at elevated temperature (4.4.2),

b) overcharge (4.5.3), and

c) overdischarge (4.5.4).

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 h). 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. (See 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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 h 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 3 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.

4.3.2 Drop Test (Pack Level Only)

4.3.2.1 Test Description

Drop the DUT (free drop) from 2 meters 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 h after the test.

4.3.2.2 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) 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.

4.3.3 Penetration Test (Cell Level or Above)

4.3.3.1 Test Description

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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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 3 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) 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) Rate of Penetration will be measured during the test.

4.3.4 Roll-over Test (Module and Pack Level)

4.3.4.1 Test Description

Rotate the DUT one complete revolution in 1 min 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 h at each position and for a minimum of 1 h 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)

4.3.5 Immersion Test (Module or Pack Level)

4.3.5.1 Test Description

With the DUT in its normal operating orientation and at full state of charge, immerse the DUT in ambient temperature salt water (5% by weight NaCl in H_2O) for a minimum of 2 h 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)

4.3.6 Crush Test (Cell Level or Above)

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. 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 3 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 should be used 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.

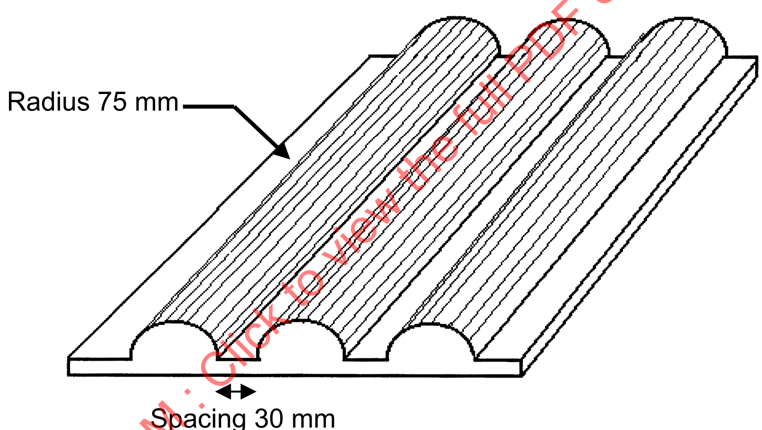

FIGURE 1 - EXAMPLE OF A CRUSH TEST PLATEN FOR MODULES AND PACKS

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 min. After the hold period, continue the crush to 50% of the initial dimension. 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 and 1 cm/min for packs and between 0.5 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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.

4.4 Thermal Abuse Tests

4.4.1 High Temperature Hazard Test (Pack 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.

The objective of this test is to reproduce the temperature experienced in a fuel fire (890 °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 shall be achieved within 90 s and held for a period of 10 min 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 890 °C ± 5%. The thermal environment of the DUT should increase from ambient to 890 °C within 90 sec.

Note that pack level hazardous substance monitoring (4.2.4 Test #4) is recommended during this test.

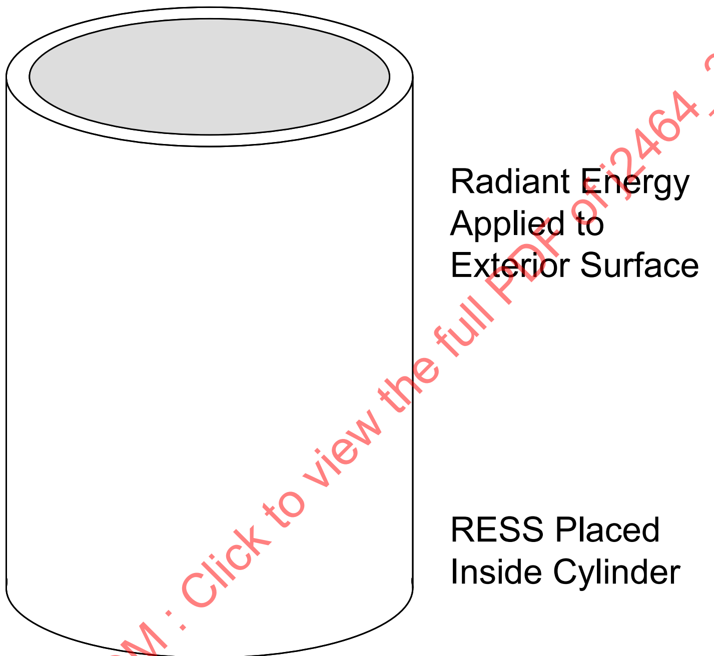

FIGURE 3 - RADIANT HEATING FIXTURE TEST FIXTURE

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.

4.4.2 Thermal Stability Test (Cell Level)

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, 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 min or until, or until any self heating is detected. If self heating (>1.0 °C/min) is detected, hold the chamber temperature until the DUT temperature stabilizes or until (a) the 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.)

If the cell experiences a thermal runaway, the test should be repeated to further define the exact thermal stability limit (maximum temperature at which DUT is stable indefinitely). Increase the temperature at a constant rate to the first step below the event temperature. The temperature will then be increased in 2 °C increments and held for a minimum of 1 h until the event is repeated and the thermal stability limit is defined.

This test should be repeated (heating in 2 °C increments and held for a minimum of 1 h) with cells that have been overcharged. The overcharge conditions: cells should be charged at 1 C-rate to approximately 150% SOC, but may be limited to a value that will not physically damage the cell (e.g., by venting or rupture) prior to conducting the thermal stability test. Additionally, tests should be repeated on cells that are at mid-life and at end-of-life as dictated by the application. When determining the Hazard Severity Level, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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 occurs as well as any 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, degree of overcharge, 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) 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT. (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 in 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 (20) full charge/discharge cycles should be performed as described with no rest period between charge and discharge. When determining the Hazard Severity Level, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT. (FLAMMABILITY)

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 °C to –40 °C. The time for the chamber ambient temperature to reach each temperature extreme shall be 15 min 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 h at the cell level, 6 h 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. a.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.

4.4.5 Passive Propagation Resistance Test (Module or Pack Level)

This test evaluates the ability of a DUT to withstand a single cell thermal runaway event so that a thermal runaway event does not 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. 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 55 °C or the maximum operating temperature, whichever is greater. One cell within the DUT at a locations described below is uniformly heated in-situ to a temperature of 400 °C (or until the cell enters thermal runaway) in less than 5 min (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. After one of the above conditions is met, the heater is turned off and DUT is observed for 1 h. Other methods to initiate thermal runaway in one cell are allowed.

This above procedure shall be repeated with cells in different locations that represent various thermal environments/relationships within the pack.

The following heated cell locations are suggested for a DUT resembling a rectangular prism (See Figure 4 Below):

1) The geometric corner of the Module or Pack.

2) At the midpoint of an edge.

3) At the center of one face.

4) The interior of the Module or Pack 1/4 the distance from the center of a face (B) to the opposite face.

5) The interior of the Module or Pack 1/4 the distance from the center of a face (C) to the opposite face.

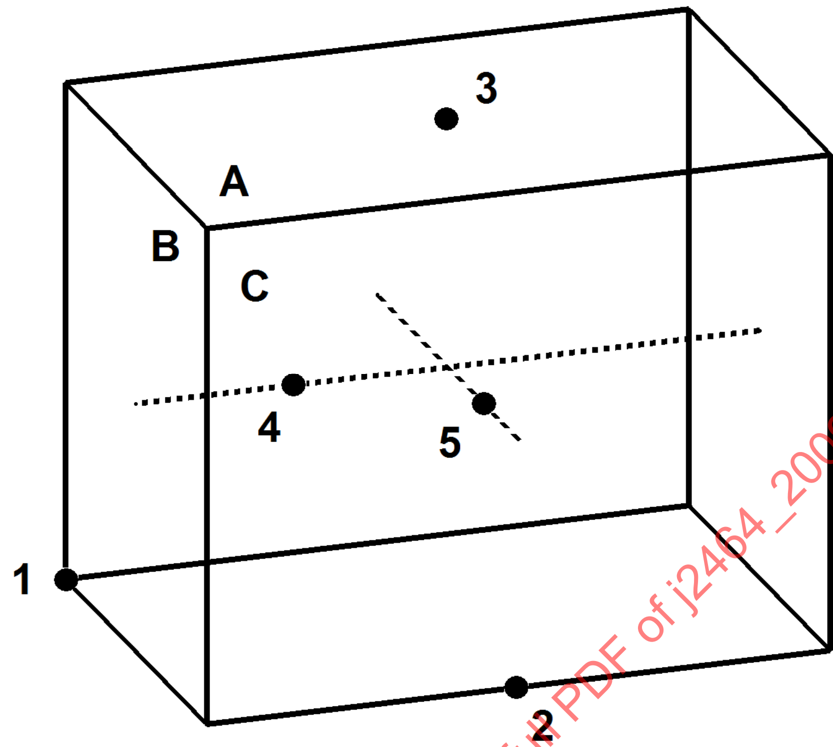

FIGURE 4 - SCHEMATIC REPRESENTATION OF CELL LOCATIONS 1 THRU 5 AT WHICH CELLS ARE TRIGGERED INTO THERMAL RUNAWAY CONDITION IN PASSIVE PROPAGATION TEST

Other Module or Pack shapes should use similar locations.

4.4.5.2 Measured Data

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

b) Voltage of the DUT to be recorded as a function of time. a.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) Notation of any flames or projectiles released from the DUT.

4.5 Electrical Abuse Tests

Except where specifically required to be otherwise, all electrical abuse tests shall begin with the DUT at nominal operating temperature, fully charged, and cooling medium (if any) in place.

4.5.1 Short Circuit Tests (Cell and Module or Pack)

Perform short circuit tests at various impedances and locations within the DUT to test its full response. A hard short circuit method will be conducted ($\leq$5 mOhm and <<DUT DC impedance) while in some cases a second, soft short circuit method will be performed on a separate DUT at a resistance comparable to the total DUT DC resistance but no less than 10 mOhm. The moderate short will assure that the cell response is measured rather than internal connector failure which can occur at high currents. The tests will be performed on cells, modules, and packs. For some electrical architectures, the full pack must be present during the module tests to ensure all potential electrical interactions are included in the test.

4.5.1.1 General Test Description

Apply a short in less than 1 sec between the positive and negative terminals of the DUT for 60 min or until another condition occurs which prevents completion of the test (i.e., component melting, etc.). Prior to this test, all active protective devices shall be disabled. Separate tests will be performed with passive protective devices intact and then disabled or bypassed wherever possible, as long as it does not compromise the integrity of the DUT. Continue observation for an additional period of 1 h. When determining the Hazard Severity Level, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

4.5.1.1.1 Cell Hard Short

Apply a hard short between the positive and negative terminal of a single cell. If the pack design utilizes cells in parallel then the test shall be performed within a module or with the cell electrically and thermally connected as if it were in a module. For packs with modules in parallel, this test must be performed with all modules connected as expected in the field since they are in parallel with the cell. All passive protection devices should be disabled or bypassed. It is optional to repeat the test with passive protection devices operational.

4.5.1.1.2 Cell Soft Short

Apply a soft short between the positive and negative terminal of a single cell. The impedance of the soft short shall be comparable to the DC impedance of the elements within the DUT that are being shorted. If the pack design utilizes cells in parallel then the test shall be performed within a module or with the cell electrically and thermally connected as if it were in a module. For packs with modules in parallel, this test must be performed with all modules connected as expected in the field since they are in parallel with the cell. All passive protection devices should be disabled or bypassed. It is optional to repeat the test with passive protection devices operational.

4.5.1.1.3 Module Hard Short

Apply a hard short between the positive and negative terminal of a single module. For packs with modules in parallel, this test must be performed with all modules connected as expected in the field since they are in parallel with the module. All passive protection devices should be disabled or bypassed. It is optional to repeat the test with passive protection devices operational.

4.5.1.1.4 Pack Hard Short

Apply a hard short between the positive and negative terminal of the pack. The terminals of the pack should be live prior to the short as in a driving condition and active protection elements shall not be used. Repeat the test with all passive protection devices disabled or bypassed.

Examples of test implementation are given in Appendix B.

4.5.1.2 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 at a minimum of three locations to determine temperature extremes. (TEMPERATURE)

b) DUT current, voltage and, at pack level, individual cell voltages will be monitored whenever possible. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE)

c) Video monitoring for the duration of the test, including the post-test observation period 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 any venting of the DUT.

e) DUT mass before and after test. (MASS)

f) 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT. (FLAMMABILITY)

4.5.2 Overcharge Test (Cell and Module or Pack)

4.5.2.1 Test Description

DUT should be fully charged. The cell fixtures or holders should be configured to simulate the mechanical and thermal environment in a module or pack. Two overcharge tests for cells, one overcharge test for modules or packs will proceed at the charging conditions described below:

Cells should be charged at two rates – a) 1 C-Rate constant current and b) High-Rate overcharge at the maximum current that can be supplied by the regenerative braking or charging system (scaled to cell level current when multiple cells are in parallel) - until at least 200% SOC has been reached or the test is terminated by some other factor (such as thermal runaway), whichever time is longer. If this maximum system charge current is not known for the eventual application, high-rate charging should be performed at a charge rate of 3C.

Modules and Packs should be charged at 1 C-Rate constant current until at least 200% SOC has been reached or the test is terminated by some other destructive factor (such as thermal runaway), whichever time is longer. The module or pack should be subjected to an overvoltage limit of 20% of the maximum pack voltage in addition to the maximum operating voltage of the DUT. When performing this test at less than the module or pack level, the voltage (series pack configuration) or the voltage/current (series/parallel pack configuration) shall be divided equally among the cells.

Passive integrated overcharge protection shall remain operational throughout the test. All active protective devices shall be disabled prior to this test. When determining the Hazard Severity Level, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT.

4.5.2.2 Measured Data

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

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

b) DUT current, voltage will be monitored during the test. (VOLTAGE)

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

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

e) 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, a spark source should be present to ignite any potentially flammable vent gases or vapors from DUT. (FLAMMABILITY)

The following data shall be collected as part of this test on Modules or Packs:

a) The temperature of the DUT to be recorded as a function of time at a minimum of three locations to determine temperature extremes. (TEMPERATURE)

b) DUT current, voltage and, at pack level, individual cell voltages will be monitored whenever possible. Voltage and resistance of the DUT case with respect to the positive and negative terminals before and after the test. (VOLTAGE and RESISTANCE)