



SURFACE VEHICLE RECOMMENDED PRACTICE

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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) Including 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:

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

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.