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FreedomCAR

Electrical Energy Storage System

Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications

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Abstract

This manual defines a complete body of abuse tests intended to simulate actual use and abuse conditions that may be beyond the normal safe operating limits experienced by electrical energy storage systems used in electric and hybrid electric vehicles. The tests are designed to provide a common framework for abuse testing various electrical energy storage systems used in both electric and hybrid electric vehicle applications. The manual incorporates improvements and refinements to test descriptions presented in the Society of Automotive Engineers Recommended Practice SAE J2464 “Electric Vehicle Battery Abuse Testing” including adaptations to abuse tests to address hybrid electric vehicle applications and other energy storage technologies (*i.e.*, capacitors).

These (possibly destructive) tests may be used as needed to determine the response of a given electrical energy storage system design under specifically defined abuse conditions. This manual does not provide acceptance criteria as a result of the testing, but rather provides results that are accurate and fair and, consequently, comparable to results from abuse tests on other similar systems. The tests described are intended for abuse testing any electrical energy storage system designed for use in electric or hybrid electric vehicle applications whether it is composed of batteries, capacitors, or a combination of the two.

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Acronyms and Abbreviations

AIHA	American Industrial Hygiene Association
ARC	accelerated rate calorimeter or accelerating rate calorimetry
DOD	depth of discharge
DOE	Department of Energy
ECSS	electrochemical storage system
EESS	electrical energy storage system
EPA	Environmental Protection Agency
ERPG-2	Emergency Response Planning Guidelines – Level 2.
EUCAR	European Council for Automotive Research & Development
EV	electric vehicle
FMEA	failure modes and effects analysis
FTA	fault tree analysis
HEV	hybrid electric vehicle
ICE	internal combustion engine
INEEL	Idaho National Engineering and Environmental Laboratory
OCV	open circuit voltage
PNGV	Partnership for a New Generation of Vehicles
SAE	Society of Automotive Engineers
SNL	Sandia National Laboratories
SOC	state of charge
USABC	United States Advanced Battery Consortium

1. Introduction

To assist in the further development of advanced transportation technologies, Sandia National Laboratories (SNL) provides expertise in battery abuse testing in cooperation with the U.S. Department of Energy's Office of FreedomCAR and Vehicle Technologies and the United States Advanced Battery Consortium (USABC) Tech Team. SNL acts as an impartial body whose responsibility under the FreedomCAR Program is to perform abuse testing for electrical energy storage systems (EESSs) of the size and type used in electric vehicles (EVs) and hybrid electric vehicles (HEVs). The information gained from this testing will be used to identify, quantify, and report abuse tolerance and potential safety issues related to EESS design.

1.1. Purpose

Abuse testing is performed to characterize EESS responses 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 vulnerabilities, if any, associated with a given EESS design under a given set of circumstances and to help quantify the hazard mitigation efforts that should be taken for a particular EESS design.

Both SNL and the Society of Automotive Engineers (SAE) have previously defined a body of tests for evaluating the safety aspects of electrochemical storage systems (ECSSs)—most specifically, batteries—to be used in EV applications.^{1,2} This manual includes improvements and refinements to those tests based on experience gained during actual testing. Additionally, because HEVs are an important new class of vehicles that were not on the road when the earlier documents were published, this manual has been expanded to include information specific to the use of EESSs in HEV applications. Finally, the manual has been expanded to include abuse testing guidelines for other energy storage technologies (*i.e.*, capacitors).

1.2. Scope

This manual defines a complete body of tests that may be used as needed for abuse testing EESSs for EV and HEV applications to determine the response of a given EESS design to conditions or events that are outside its normal operating range. **Note:** *A test profile for vibration testing EESSs is included as Appendix A. For properly designed and constructed EESSs, vibration is not considered abuse. Nevertheless, it is clearly a hazard for improperly designed systems and, consequently, vibration requirements should be considered in the early stages of EESS development.*

The tests in this manual are designed to yield test results that fairly and accurately measure the severity of the response of test articles to specific types of abuse and to broadly suggest the types of abuse that a safe EESS would need to survive to be considered 'acceptable.' When judging the 'acceptability' of a candidate technology for deployment, it is also useful to evaluate whether the tests themselves could be characterized as '**likely abuse**' (*i.e.*, a condition that is likely to inadvertently occur during 'normal' use [*e.g.*, short circuit]), '**moderate abuse**' (*i.e.*, an abuse condition that is not likely), or '**extreme abuse**' (*i.e.*, an abuse condition that is highly unlikely). The catastrophic response of a cell or module to a 'likely abuse' condition should be treated much more seriously than the catastrophic response of a cell or module to an 'extreme abuse

condition. The characterization of the likelihood of a given abuse condition to occur during ‘normal’ vehicle operation is beyond the scope of this manual, but is recommended and should be conducted by the manufacturer and/or integrator.

It is not the intent of this document to apply acceptance criteria; each vehicle design has its own unique requirements and ancillary support systems. Consequently, the manual does not prescribe specific test plans. That is, it does not give step-by-step instructions for performing any of the tests nor does it apply pass/fail criteria for the tests. Rather, it provides standard test conditions for a large group of tests that could be considered essential to the success or failure of a given EESS design when used in an EV or HEV application.

This manual is intended as a guidance document and, consequently, completion of all (or any subset) of the tests is not required, although it is recommended that manufacturers and engineers be aware of the potential hazards suggested by each test. Generally, the following tests (listed in priority order) are recommended for use in discovering safety design problems at the early stages of EESS development:

- Short Circuit (see Section 5.2)
- Overcharge (see Section 5.1)
- Controlled Crush (see Section 3.1)
- Thermal Stability (see Section 4.1)
- Overdischarge (see Section 5.4)

Note: Successful completion of all (or any subset) of the tests described in this manual does not guarantee the safety of a given EESS design. Integrators should make their own determination as to what measures are to be taken to ensure a sound application of EESS technology when used in an HEV.

1.3. Definitions

Active Devices	Devices external to the cell, or requiring active external controls, that are intended for protection from or mitigation of abusive, out-of range conditions experienced by the cell or module.
Cell	The smallest electrochemical unit, consisting of two electrodes, current collectors, separator, electrolyte, and all associated packaging.
Device Under Test	A general term used to describe the EESS being tested. This term can refer to a single unit (cell), a multiple unit assembly (module), or a complete system (pack).
ECSS	Electrochemical Storage System. This term describes both rechargeable batteries, which store electrical energy by reversible electrochemical reactions (traditionally termed Faradaic reactions), and electrochemical capacitors. The new electrochemical capacitor technology may use Faradaic electrode processes on one or both electrodes which are indistinguishable from those seen in batteries. ³

EESS	Electrical Energy Storage System. This is a more inclusive definition, which includes ECSS as well as any device or array of devices that stores electrical energy in non-Faradaic processes such as double layer capacitance or other types of capacitance.
ERPG-2	Emergency Response Planning Guideline levels that are defined as the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. This guideline is defined by the American Industrial Hygiene Association (AIHA). ⁴
EV	Electric Vehicle. A road vehicle that uses stored electrical energy as its source of energy for motive (traction) power. EVs are generally charged with AC power provided by an electric utility and are on stationary charge between uses.
Extreme Abuse	A type of abuse test that would, in general, be considered highly unlikely to occur during 'normal' vehicle operation.
EUCAR	The European Council for Automotive Research and Development is an organization whose members include the major European automakers. The goal of the organization is to support the achievement of the highest efficiency, effectiveness and economy in research and development to ensure that automobile technology continues to provide high levels of quality, safety, reliability and durability and a decreasing environmental impact, at an acceptable cost.
FreedomCAR	FreedomCAR (Cooperative Automotive Research) is an industry/government research initiative focused on collaborative, pre-competitive, high-risk research to develop the component technologies necessary to provide a full range of hydrogen-powered affordable cars and light trucks that will free the nation's personal transportation system from petroleum dependence and from harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice. This program replaced the Partnership for a New Generation of Vehicles (PNGV) in 2002.
Fully Charged	EESSs for EV applications are considered fully charged at 100% state of charge (SOC). Generally, EESSs for HEV applications are considered fully charged at 80% SOC because at this SOC the EESS is able to deliver energy to the vehicle and accept energy from regenerative braking. However, because a 100% SOC can be considered a 'worst case' for an HEV EESS, 100% SOC is considered 'fully charged' for the purposes of the tests in this manual regardless of application.

HEV	Hybrid Electric Vehicle. A road vehicle that typically contains two sources of traction power—a primary power source (<i>e.g.</i> , a gas or diesel ICE or a fuel cell) and an EESS (<i>e.g.</i> , a battery or a capacitor). The EESS is charged by the primary power source and regenerative braking, not from AC electric power. Traditionally, traction power for an HEV is supplied by both a conventional ICE and a battery pack. Newer HEVs may use only the ICE for traction power and use the battery pack for other vehicle functions (<i>e.g.</i> , ‘start-stop’ HEVs and other 42-V ‘mild-HEV’ designs).
Integrator	For the purposes of this manual, the integrator is the vehicle manufacturer or vendor who installs the EESS for use in an EV or HEV.
Likely Abuse	A type of abuse test that would, in general, be considered likely to occur inadvertently during ‘normal’ vehicle operation.
Moderate Abuse	A type of abuse test that would, in general, be considered not unlikely to occur during ‘normal’ vehicle operation.
Module	An integrated assembly of multiple cells in series/parallel configuration with associated control electronics.
Pack	A complete energy storage system for an EV or HEV consisting of multiple modules with control electronics and associated equipment.
Passive Devices	Devices integral to the cell that are intended for protection from or mitigation of abusive, out-of range conditions experienced by the cell that do not require active external controls.
Standard Container	For module and pack assemblies, the packaging that the assembly(ies) would be contained in for use in a vehicle.
Test Article	See ‘Device Under Test.’
Unit	For the purposes of this manual, the minimum test article (<i>e.g.</i> , electrochemical cell, capacitor, etc.).

2. General Information for all Test Profiles

Each abuse test in this manual includes a rating of the abuse level based on the amount of damage the EESS is expected to incur as a result of the test. *Note: Some test profiles may be conducted at more than one abuse level.* Level 1 describes events where the EESS is expected to remain essentially intact. The vehicle in which the EESS was mounted might incur damage, but the EESS should be salvageable and could be reused after minor repairs. Level 2 events are more severe. After a Level 2 test, the EESS may become inoperable but should not expose humans to known health risks. Level 3 describes destructive situations where the EESS is expected to become inoperable.

The test profiles are divided into three categories: mechanical, thermal, and electrical. Within each category, the tests are generally arranged in priority order. Some of the tests are not applicable to all candidate technologies. As noted above, many of the tests may result in intentional destruction of the device under test. Before testing, the responsible testing organization should consult the device manufacturer for information regarding the possible consequences of such failures, including the potential release of hazardous substances, so that appropriate precautions can be taken for the safety of testing personnel.

2.1. General Test Conditions

Before testing begins, the testing organization, the EESS manufacturer, and (when appropriate) other development principals should cooperate in the preparation of a written test plan that lists the tests to be performed and describes in detail the test conditions and data acquisition requirements for the test series. For the test conditions described below, permutations of level of assembly, system age, SOC, and temperature should be implemented at the integrator's/developer's discretion based on the most susceptible condition of the technology.

2.1.1. Level of Assembly

Initial tests of a given EESS design should be conducted at the lowest level of assembly (unit, module, or pack) for which meaningful data can be gathered. The recommended level of assembly is a function of the EESS technology, the EESS design, and the specific test profile. The minimum level of assembly required is included in each test profile.

2.1.2. System Age

Initial tests of a given EESS design are generally conducted using a relatively new EESS (*i.e.*, one that has not undergone cycle life testing or been extensively used). Because used or partially used systems or subsystems may not be available at the early stages of the design process, slightly used test articles are permissible. Ideally, test units would be 5 to 25% into their service lives. It may be desirable to perform additional testing for a given design that evaluates an EESS or subsystem that is well into, or near the end of, its useful life.

2.1.3. State of Charge

Although an HEV EESS may be considered fully charged at 80% SOC, abuse tests should be conducted at 100% SOC unless specifically noted otherwise. An EV EESS is considered fully charged at 100% SOC and should be tested at that level unless specifically stated otherwise.

2.1.4. Temperature

Unless specifically stated otherwise:

- The test should be conducted at room temperature (25°C).
- The device under test should be at its normal operating temperature.
- If the system's level of assembly includes thermal control systems, they should be running.
- If cooling media have been provided, they should be in place.

2.1.5. Test Duration

After each test, all test articles will be observed for a time period of at least one hour and until the test article's temperature is below 50°C, or until such time that the test article is deemed safe to handle.

2.2. Data Recording and Analysis

The results of all testing should be documented in a format that allows for comparison of various EESS designs. The guidelines given below are provided as a recommendation. The testing organization should document specific data recording and analysis methods as part of an overall test plan that is reviewed and agreed to by the EESS manufacturer (and other development principals, when appropriate) before the test begins.

2.2.1. Measurement Rates and Accuracy

Measured data shall be acquired at rates and with accuracies adequate to ensure that the usefulness of the data is not compromised. In the absence of more specific requirements by the test sponsor, the measurement accuracies in Table 1 are acceptable. Because of the wide variety of test dynamics, it is not possible to specify absolute data acquisition rates. However, the data required for a particular test shall be acquired at a rate such that errors due to test dynamics will not exceed the required measurement accuracies. It is recommended that data sample rates increase as the parameter being measured moves away from normal. In general, it is best to acquire the maximum amount of data possible as quickly as is practical.

Table 1. Measurement Accuracies

Parameter	Accuracy
Temperature	±2°C ±5% of reading
Voltage (volts)	
Current (amps)	±1% of reading
Resistance (Ω)	
Vibration	
Deformation	±4% of reading
Hazardous Substance Concentration	±10% of reading

2.2.2. Analysis of Released Gases

Gas, smoke and flames may be released from the test article during the abuse tests. While it is important to analyze these gases, gas analysis may not be desired on all tests, especially if the tests are repetitive in nature. Gas and particulate analysis may be qualitative or quantitative, depending on the test objective. Measurements of hazardous substances, when possible, should be referenced to the AIHA's ERPG-2 recommendations. Other similar standards may be substituted because the concentration levels recommended are for comparison purposes only. It is recommended that when such testing is conducted out of doors wind speed should be ≤ 3 mph. Multiple gas sample locations, spaced equally around the device under test, should be placed as close to the EESS as is practical during the test.

2.2.3. Flammability Analysis

The flammability of expelled materials should be determined. The lower limit of flammability in air is used for flammable gases and liquids. For example, the lower limit of flammability in air for H₂ is 4%. A spark source or other ignition source should be installed near the test article to accurately determine if the vented gas and smoke is flammable.

2.2.4. Fault Tree Analysis

In general, a complete EESS module designed for an application will have more complex safety engineering issues than those of its subassemblies and units. To field an acceptable EESS, it may be necessary to improve unit-level safety measures. Failure modes and effects analysis (FMEA) and fault tree analysis (FTA) can be used to tie the significance of lower level (*i.e.*, unit level) test results to the expected overall safety response of the full EESS. An FTA that indicates a probability of occurrence of 1×10^{-7} or less is recommended as a reasonable guideline for proceeding with a given design.^{5,6}

2.2.5. EUCAR Hazard Levels and Description⁷

EUCAR assigns the hazard levels shown in Table 2 to an EESS technology based on that technology's response to abuse conditions. Manufacturers and integrators may find it useful to consider these levels when evaluating the abuse response a given EESS design.

Table 2. EUCAR Hazard Levels and Descriptions

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).

Table 2. EUCAR Hazard Levels and Descriptions (continued)

4	Venting $\Delta \text{mass} \geq 50\%$	No fire or flame*; no rupture; no explosion. Weight loss $\geq 50\%$ of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (<i>i.e.</i> , no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (<i>i.e.</i> , disintegration of the cell).

* The presence of flame 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. For this reason, we recommend that a spark source be use during tests that are likely to result in venting of cell(s). We believe that “credible abuse environments” would likely include a spark source. Thus, if a spark source were added to the test configuration and the gas or liquid expelled from the cell was flammable, the test article would quickly progress from level 3 or level 4 to level 5.

3. Mechanical Abuse Tests

The mounting and support of the EESS shall be as similar to the manufacturer's recommended EV or HEV installation requirements for mechanical shock and vibration tests as possible. 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. The test article should first be tested in the axis that will cause the most potential damage. Other axes should then be tested at the discretion of the developer or user.

3.1. Controlled Crush

Abuse Level: 3

Minimum Assembly Level: Module

Description: Crush the test article between a flat platen and a textured platen. The textured platen shall have semicircular intruders with a 75-mm radius that have been placed 30 mm apart across the face of the platen (see Figure 1). The opposing platen shall be flat. One or both platens shall be electrically isolated from the crush fixture to avoid providing an additional current path to the device under test. Unless the intruders of the textured platen are made of non-conductive material, the possibility of a current path through the textured platen is unavoidable.

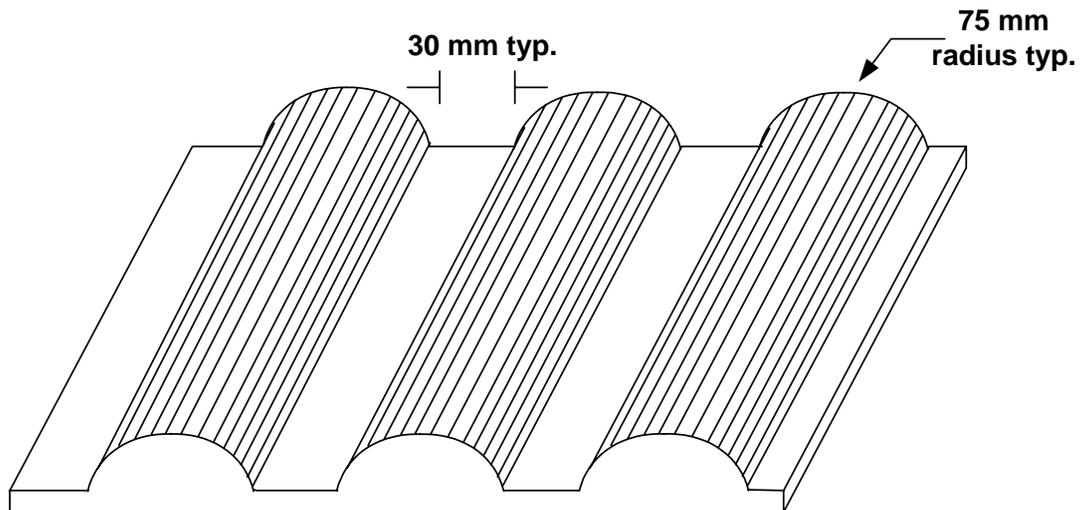


Figure 1. Crush test textured platen surface.

Test modules shall have all integrated control and interconnect circuitry in place and operating. Place the irregular surface of the platen to impact the most vulnerable position on the device under test. **Note:** *Single test units may sometimes be used as the test article, although this will limit the usefulness of the data. If the test article is a single unit (i.e., a cell, the test should be performed using a solid cylindrical impactor half the test article's average diameter. Crush the test article perpendicularly at its midsection.*

This test occurs in two stages. The first stage (displacement control) is a displacement of 15% of the module's height, which is held for 5 minutes. The second stage (force control and

displacement limit) is limited by either a 50% displacement of the module’s height or a force of 1000 times the module’s mass; whichever condition occurs first is held for 5 minutes.

Notes:

- If multiple test articles are available crushing from multiple axes is recommended.
- If additional test articles are available, crushing articles that have had most of their containment boxes (module or pack level) removed (allow the cells to remain mounted to their base) is recommended so that the crush effects on individual components can be seen.

Measured data may include:

- Force and displacement.
- EESS cell and module voltage, as appropriate.
- Video and still photographs of the EESS before, during, and after the test.
- Internal and external EESS temperature.
- Chemical analysis of vent gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

3.2. Penetration

Abuse Level: 3

Minimum Assembly Level: Unit

Description: Penetrate the device under test with a mild steel (conductive) pointed rod that has been electrically insulated from the test article. The rate of penetration shall be 8 cm/sec. nominal. The diameter of the rod and the depth of penetration can be found in Table 3. The orientation of the penetration shall be perpendicular to the electrode plates.

Table 3. Penetration Test Parameters

Assembly Level	Rod Diameter	Minimum Penetration Depth
Cell	3 mm	Through unit
Module/Pack	20 mm	Through three units or 100 mm

Measured data may include:

- Measurements of the EESS deformation after the test.
- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.

- Still photographs of the test setup and the EESS before and after the test.
- High-speed motion pictures of test.
- Air concentrations of hazardous gases, liquids, and solids as a function of time.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

3.3. Drop

Abuse Level: 3

Minimum Assembly Level: Pack

Description: This is a destructive free drop from a pre-determined height not to exceed 10 m (33 ft.) onto a centrally located, cylindrical steel object (*e.g.*, a telephone pole) having a radius of 150 mm. **Note:** *This test may not be suitable for test devices whose enclosures are not independent structural components. Nevertheless, testing of enclosed subassemblies is possible and may yield useful data.* The height of the drop should be determined by evaluating credible abuse conditions during the manufacture, assembly, and normal use of the EESS. The EESS shall impact across the radius of the cylindrical object, but not on the end of the cylindrical object (see Figure 2). A horizontal impact with an equivalent velocity change is acceptable.

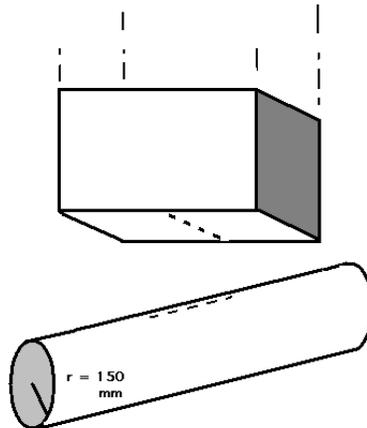


Figure 2. Drop test impact.

Measured data may include:

- Acceleration input to EESS case, with a minimum of 10 kHz bandwidth.
- Measurements of the EESS deformation after the test.
- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the test setup and the EESS before and after the test.
- High-speed motion pictures of test, 2400 frames per second.

- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

3.4. Immersion

Abuse Level: 2

Minimum Assembly Level: Unit

With the EESS at nominal operating temperature in its normal operating orientation, immerse the EESS in salt water (nominal composition of seawater and at 25°C) for a minimum of two hours, or until any visible reactions have stopped. The water must completely submerge the EESS.

Note: Immersion in other common fluids to which the test article might be exposed (e.g., engine coolant or fuel) is also recommended if additional test units are available.

Measured data may include:

- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the test setup and the EESS before and after the test. The entire test shall be videotaped.
- The EESS should be observed for a minimum of one hour after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

3.5. Roll-over Simulation

Abuse Level: 1

Minimum Assembly Level: Module

Description: Rotate the EESS one complete revolution for one minute in a continuous, slow-roll fashion, and observe if any materials leak from the EESS. Then rotate the EESS in 90° increments for one full revolution. Observe the EESS for one hour at each position. The test should be run in a closed volume.

Measured data may include:

- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the test setup and the EESS before the test and at each position.
- Flammability analysis of any substance that leaks from the test article.

- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

3.6. Mechanical Shock

Abuse Level: 1 (low) or 2 (mid)

Minimum Assembly Level: Module

Description: The low-level mechanical shock test is a robustness test that the EESS is expected to survive without any damage incurred. Mid-level shocks are more severe; the EESS may be inoperable after such testing.

The shocks are specified in terms of velocity change and maximum duration. Shock duration is defined as the time between the first and last time the shock pulse crosses the 10% peak level, as illustrated in Figure 3. Maximum duration will place lower limits on the peak acceleration, which must be proven during the test. For example, for the low-level test the lowest acceleration would be achieved if the acceleration was an ideal square wave of about 12.5 G. The minimum peak acceleration is specified at about twice this level, which recognizes that the ideal square wave cannot be achieved in a real design. A simple pulse shape (a half-sine or a haversine) is expected to be used for the test, but the pulse shape is not specified to allow as much flexibility as possible in the testing laboratory. Advanced techniques, which try to simulate actual deceleration time histories more accurately, are not excluded. It is in the interest of EESS manufacturers to keep the pulse duration as long as possible and still meet the specification. However, if the EESS is robust, tests may exceed the peak acceleration, reduce the duration, reduce the test complexity, and hence, reduce the test cost. Test parameters are shown in Table 4.

Table 4. Shock Levels and Durations

Level	Velocity	Max Duration	Minimum Acceleration	Acceptable Pulse Form
Low	6.7 m/sec	55 ms	20 G for 11 ms	25 G for 30 ms halfsine
Mid-1	11.1 m/sec	65 ms	30 G for 16 ms	35 G for 51 ms halfsine
Mid-2	13.3 m/sec	110 ms	20 G for 22 ms	25 G for 60 ms halfsine

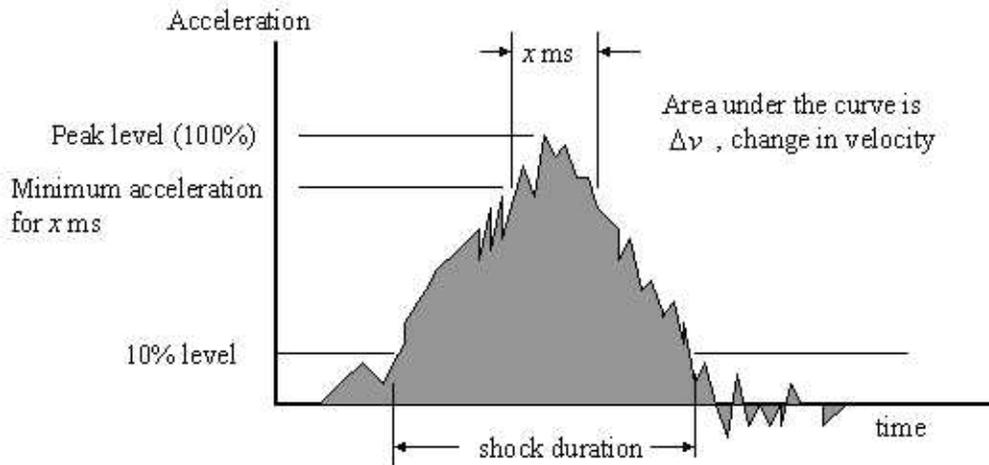


Figure 3. Illustration of shock parameters.

Measured data may include:

- Acceleration input to EESS case, with a minimum of 2 kHz bandwidth.
- Measurements of the EESS deformation after the test.
- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the EESS before and after the test.
- High-speed motion pictures of test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

4. Thermal Abuse Tests

Note: For the tests described below, fuses (which are considered passive devices under the definitions in this manual) should be bypassed if it is believed that they would prevent the performance of the test.

4.1. Thermal Stability

Abuse Level: 3

Minimum Assembly Level: Unit

Thermal Stability Test Description: With the test article fully charged and at its normal operating temperature, increase the temperature in specified increments (see Table 5) until self-heating is detected. For unit-level test articles, measure the temperature on the surface of units with a metallic case and on a terminal of non-metallic units. If possible, place unit-level test articles in a device capable of maintaining a near adiabatic state (*e.g.*, ARC apparatus) and use the chamber temperature to track the unit temperature. Measure the temperature of module-level test articles at the designed temperature sensing position for that module. If only module-level test articles are available, test them using heat tape or a similar method of external heating. Subject the device under test to a pseudo-accelerating rate calorimetry (ARC) test by raising the temperature from 30°C to 200°C at a constant heating rate of 5 to 10°C/min. with the hold periods given in Table 5.

Table 5. Heat-up Rates and Durations

EESS Assembly Level	Heat-up Rate (°C)	Hold Time at Each Temperature Step (min)
Single unit	5	30
Module or higher (known exotherm temperature)	10	120
Module or higher (unknown exotherm temperature)	10	120

If self-heating is detected, track the temperature until the exotherm becomes stable. Then increase the temperature to the next increment and continue as described above until (1) additional self-heating is detected, (2) the temperature reaches 200°C above the operating temperature of the EESS, or (3) a catastrophic event (*e.g.*, venting or major damage to the device) occurs.

If the EESS experiences a thermal runaway, repeat the test to further define the exact thermal stability limit. Increase the temperature at a constant rate to 10°C below the event temperature. Then increase the temperature in 2°C increments and hold for a minimum of one hour until the event is repeated.

Thermal Ramp Test Description: A more sensitive measure of the onset of self-generated heating can be performed by programming a thermal ramp of the cell up to thermal runaway. To perform this test, instrument the test article with thermocouples, wrap it in a layer of insulation, and place it in a thermal block. With the test article fully charged and at its normal operating temperature ramp the thermal block at a fixed rate while monitoring the temperature of the cell and the thermal block until the onset of thermal runaway. The onset of thermal runaway is indicated by a change in the temperature difference between the cell and the block. Differentiating between the cell and block temperatures gives a sensitive measure of cell heating. External spark sources can be used to test for flammability of the vent gases.

Notes:

- This test is not designed for an EESS with an operating temperature $>150^{\circ}\text{C}$. An appropriate thermal stability test for high-temperature EESSs shall be determined by the manufacturer or testing organization on a case-by-case basis.
- Before and after testing, evaluate the test article's capacity by performing three complete charge/discharge cycles at 25°C according to the manufacturer's recommended charge algorithm and at the C/1 discharge rate for batteries and 5C for capacitors. If the test article has leaked, or is otherwise damaged, the post-test capacity evaluation should be cancelled.
- If the temperature at which a major exothermic reaction occurs is known, the test may begin at 10% less than that temperature to save time.
- If multiple units are available, repeat the test with units that have been overcharged to 150% of the rated capacity (as described in Section 5.1) and units that have been cycled to 50% and 100% of nominal life. *Note: The overcharge may be limited to a value that will not physically damage the cell (e.g., by venting or rupture) before conducting the thermal stability test.*

Measured data may include:

- Temperature(s) at which venting occurs.
- Temperature(s) of any smoke generation.
- Test device temperature profile with respect to time.
- Oven chamber/calorimeter temperature profile with respect to time.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

4.2. Simulated Fuel Fire

Abuse Level: 3

Minimum Assembly Level: Module. *Note: Single test units may be used as the test article, although this will limit the usefulness of the data.*

Description: To allow for improved monitoring, this experiment uses radiant heat to simulate fuel fire conditions and is called a 'Radiant Heat' test in earlier documentation.^{1,2} With the EESS at 100% SOC, expose it to high temperature for ten minutes in a radiant-heating cylindrical

fixture (see Figure 4). The inside of the fixture should be coated in such a way that the fixture will radiate approximately like a black body (Figure 5). *Note: If a radiant heat test fixture is not available, this test can be conducted using some other means (e.g., a tube furnace and conveyor mechanism) that would expose the EESS to non-contact heat from a cylindrical radiating surface at 890 °C, where the surface temperature that the EESS is exposed to increases from ambient to the test value within 90 seconds.* Place the EESS inside the fixture in its normal operation orientation and configuration (*i.e.*, no insulation or other protection unless such protection is standard for the test article). Program the fixture to elevate the temperature from ambient to the temperature of a fuel fire (890°C nominal) within 90 seconds. Hold the programmed temperature for 10 minutes or until another condition occurs that prevents the completion of the test. If the EESS ignites, extinguish it only after gas samples are taken using a method appropriate for the technology.

Measured data may include:

- Temperature of the EESS case as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Video and still photographs of the test setup and the EESS before, during, and after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

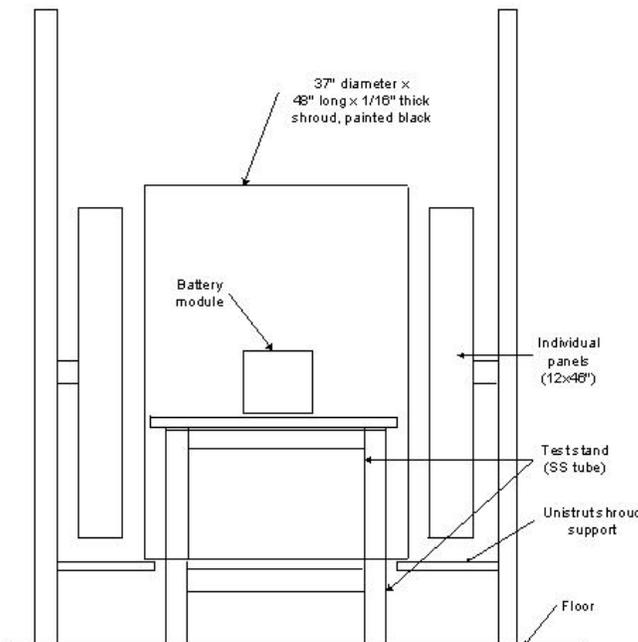


Figure 4. Simulated fuel fire test setup.

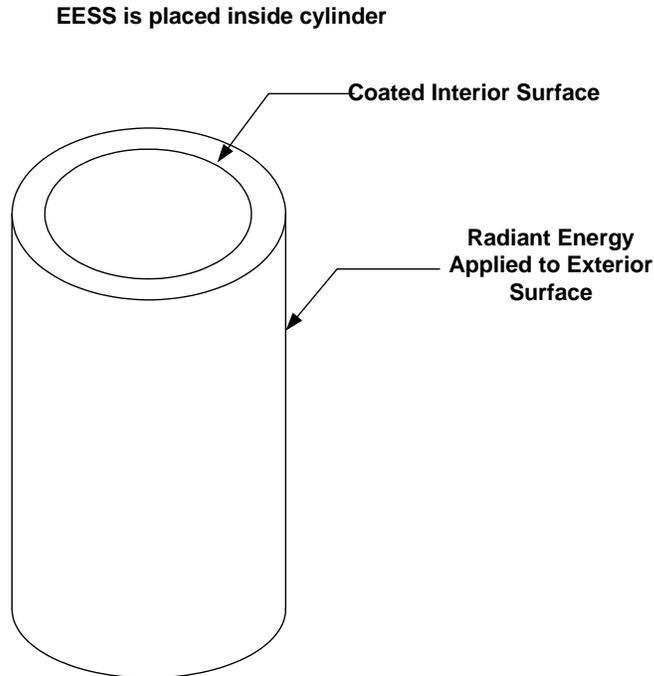


Figure 5. Simulated fuel fire test fixture.

4.3. Elevated Temperature Storage

Abuse Level: 2

Minimum Assembly Level: Unit

Description: With the EESS at varying SOC (see Table 6), place the test article in a stabilized ambient environment for a period of two months. Remove the EESS from the elevated-temperature environment weekly and allow it to cool to normal operating temperature. Evaluate unit capacity through two complete charge/discharge cycles charging according to the manufacturer’s recommended charge algorithm and discharging at a rate comparable to a 3-kW constant power rate for the entire EESS. *Note: For discharging, the FreedomCAR 42V Battery Test Manual or another similar test procedure may be used as a guideline.*⁸ Return the test article to the test-level SOC and return it to the elevated temperature environment. Stop the test when 80% of the rated capacity is not returned during the weekly testing or when the two-month testing period is complete.

Table 6. SOCs and Ambient Environments for Elevated Temperature Storage Tests

	40°C	60°C	80°C
Float at 100% SOC	X	X	X
50% SOC	X	X	X
20% SOC	X	X	X

Notes:

- Before and after testing, evaluate the test article's capacity by performing three complete charge/discharge cycles according to the manufacturer's recommended charge algorithm and at the C/1 discharge rate for batteries and 5C for capacitors.

Measured data may include:

- The temperature of the test article and the test chamber temperature.
- EESS voltage during thermal cycling.
- Venting of the EESS.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Storage temperature.
- Still photographs of the EESS before and after the test.

4.4. Rapid Charge/Discharge**Abuse Level: 2****Minimum Assembly Level: Module**

Description: With the test article at nominal operating temperature, fully charged (100% SOC), contained in a closed volume, and with all thermal controls (primary and secondary) disabled, evaluate the test article through 20 complete charge/discharge cycles using the manufacturer's recommended charge algorithm and a discharge rate comparable to a 3-kW constant power rate for the entire EESS. **Do not allow a rest period between charge and discharge.**

Note: Before and after testing, evaluate the test article's capacity by performing three complete charge/discharge cycles according to the manufacturer's recommended charge algorithm and at the C/1 discharge rate for batteries and 5C for capacitors.

Measured data may include:

- Note any venting of the EESS.
- Internal (if possible) and external EESS temperature.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the EESS before, during, and after the test.
- EESS voltage and current as a function of time.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

4.5. Thermal Shock Cycling

Abuse Level: 2

Minimum Assembly Level: Unit.

Description: With the test article at 50% SOC, contained in a closed volume, and with all thermal controls (primary and secondary) disabled, thermally cycle the EESS with ambient air cycling between 80°C to -40°C (the air temperature should be measured in close proximity to the test article). The time to reach each temperature extreme shall be 30 minutes or less (15 minutes or less is preferable, especially for unit-level tests, but not always practical). If it is logistically possible, given equipment limitations and safety considerations, the device under test can be moved between two test chambers each set at the opposite end of the temperature range. The EESS shall remain at each extreme for a minimum of one hour for single test units, 6 hours for modules, and as required to reach uniform temperature for packs. A total of five thermal cycles shall be performed. After thermal cycling, inspect the EESS for any damage, paying special attention to any seals that may exist. Verify that control circuitry is operational.

Note: Before and after testing, evaluate the test article's capacity by performing three complete charge/discharge cycles according to the manufacturer's recommended charge algorithm and at the C/1 discharge rate for batteries and 5C for capacitors.

Measured data may include:

- EESS voltage during thermal cycling.
- Venting of the EESS.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the EESS before and after the test.

5. Electrical Abuse Tests

Note: For the tests described below, fuses (which are considered passive devices under the definitions in this manual) should be bypassed if it is believed that they would prevent the performance of the test.

5.1. Overcharge/Overvoltage

This section contains three test descriptions that address the different abuse scenarios that result from overcharge/overvoltage conditions. **Note:** *In a fuel-cell HEV (as opposed to an ICE-based HEV), there are two possible voltage sources—the electric motor/inverter and the fuel cell system. Because the fuel cell system voltage can be twice the inverter voltage, when testing overcharge/overvoltage abuse scenarios for a fuel cell HEV, the voltage of the fuel cell system should be used to determine the amount of overcharge/overvoltage the EESS may incur as a result of the testing.*

Overcharge is considered an abuse condition for batteries. Testing for the effects of overcharge on a battery is accomplished by applying a controlled amount of current to the battery and allowing the voltage to ramp up to a pre-set limit (generally 200% SOC, as determined by the battery's capacity in Ah). Overcharge scenarios differ for EV and HEV applications. Most significantly, overcharge for EVs is likely to occur when a vehicle is left plugged in to an AC electric source after the EESS has reached 100% SOC (*i.e.*, a long-duration overcharge at a relatively low level, 60 A, of current). In HEVs, EESSs can be charged (and overcharged) via high-current (100+ A), short-duration pulses from the regenerative braking system or via lower-current (50-90 A), continuous recharge from the engine. In general, HEVs are not plugged in to recharge the EESS. **Note:** *EESSs for use in 'plug-in' HEVs should be tested according to the EV test description.*

Overvoltage is considered an abuse condition for capacitors. Testing for the effects of overvoltage on a capacitor is accomplished by applying an established amount of voltage (generally 2× the rated voltage of the device under test) to the test article and allowing the current to ramp up until the voltage limit is reached. Overvoltage scenarios are fundamentally the same for EV and HEV applications.

Abuse Level: 2

Minimum Assembly Level: Module. **Note:** *Single test units may sometimes be used as the test article to examine overcharge/overvoltage behavior. Although testing at this level of assembly provides limited data on the overcharge/overvoltage behavior of an EESS that is at a higher level of assembly, it allows test articles to be enclosed for the test which results in better gas analysis of any materials vented during the testing.*

EV Overcharge Test Description: With the EESS at its designed operating temperature, fully charged (100% SOC), and in its standard container with the cooling system operating, overcharge the test article at a constant current of 32 A and voltage not to exceed 450 V (the power level of a standard 60-A/240-V AC wall outlet). Continue charging until the test article reaches 200% SOC, for 4 hours, or until the test article fails, depending on the agreement between the test team and the manufacturer. Continue data acquisition/monitoring for two hours after charging is stopped.

HEV Overcharge Test Description: With the EESS at its designed operating temperature, fully charged (100% SOC), and in its standard container with the cooling system operating, overcharge the test article at a constant current of choice. The recommended charge current is 32 A. The upper limit for the power-supply voltage should be set not to exceed the maximum voltage that can be delivered by the HEV's energy generation source (*e.g.*, ICE or fuel cell) and other sources of charging (*e.g.*, regenerative braking, motor/inverter). Perform this test with passive overcharge protection devices operational. Active charge monitoring and control should be disconnected. Continue charging until the test article fails or until it reaches 200% SOC, depending on the agreement between the test team and the manufacturer. Continue data acquisition/monitoring for two hours after charging is stopped.

Overvoltage Test Description: With the EESS at its designed operating temperature, fully charged, and in its standard container with the cooling system operating, apply a constant-current, rapid overvoltage equal to $2\times$ the rated voltage of the device under test. Perform this test with passive overvoltage protection devices operational. Active charge monitoring and control should be disconnected. Continue applying the voltage until the test article fails or until the test article is charged to 5 V or $2\times$ its rated voltage (whichever is larger), depending on the agreement between the test team and the manufacturer. Continue data acquisition/monitoring for two hours after charging is stopped.

Notes:

- The 32-A recharge rate was chosen because 1) overcharge tests for EESSs for both applications have already been performed and documented at this rate of charge, so it provides a good basis for comparison; 2) the test is fast enough to be performed quickly (reaching 200% SOC on a 10 Ah cell would take just under 19 minutes), but not so quickly that data acquisition becomes an issue; and 3) overcharge at too high a current would more accurately be considered a thermal (rather than electrical) abuse test. This overcharge test is designed to determine if the chemistry within the EESS can be forced outside its normal capacity and voltage ranges successfully. Consequently, it requires a more moderate current and a longer duration.
- When performing this test at less than the pack level, scale down the voltage (series pack configuration) or the voltage/current (series/parallel pack configuration), as appropriate.
- If multiple modules are available, test a module that has been removed from its standard container.
- Overcharged cells and modules can become thermally unstable. The test plan should include post-test precautions to safely and remotely release the stored energy in the test article in the event that an open circuit condition occurs and normal electrical discharge is not possible.
- If additional test articles are available, the test team should choose two or more relevant charge currents (*e.g.*, 32 A and 1C) for the overcharge tests.

Measured data may include:

- External and internal EESS temperature.
- EESS voltage and current, as a function of state of charge.
- Voltage across the positive and negative terminals before and after the test.

- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the EESS before and after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

5.2. Short Circuit

Abuse Level: 3

Minimum Assembly Level: Module. *Note: Single test units may sometimes be used as the test article to examine short circuit behavior. Although testing at this level of assembly provides limited data on the short-circuit behavior of an EESS that is at a higher level of assembly, it allows test articles to be enclosed for the test which results in better gas analysis of any materials vented during the testing.*

Description: With the EESS at nominal operating temperature, fully charged, and inside its standard container, use an appropriately sized conductor of $\leq 5 \text{ m}\Omega$ to apply a ‘hard short’ in less than one second for 10 minutes, or until another condition occurs that prevents completion of the test (e.g., component melting). For test articles with $\leq 5 \text{ m}\Omega$ internal resistance, use a conductor of 1/10 the minimum resistance of the test article. Perform the test with integrated, passive short circuit protection devices operational. Disable all non-passive protective devices. After the test article has been shorted as described above, continue observation of the test article for two hours.

Notes:

- If multiple modules are available, test a module that has been removed from its standard container.
- If additional modules are available, increase the resistance in order to apply reduced short circuit currents that avoid burnout of cell interconnects within the test article. The load resistance chosen for such testing depends on the rated voltage of the module in question.

Measured data may include:

- External EESS temperature.
- Module voltage and current as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Video and still photographs of the EESS before, during, and after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

5.3. Overdischarge/Voltage Reversal

This section contains two test descriptions that address the different abuse scenarios that result from overdischarge/voltage reversal conditions. Overdischarge is considered an abuse condition for batteries. Voltage reversal is considered an abuse condition for capacitors. *Note: In addition to the voltage reversal test described below, it may also be desirable under some circumstances to perform a ‘negative overvoltage’ test. In this test, the voltage of the test article would be reversed to 2× the rated voltage.*

Abuse Level: 2

Minimum Assembly Level: Module. *Note: Single test units may sometimes be used as the test article to examine overdischarge/voltage reversal behavior. Although testing at this level of assembly provides limited data on the overdischarge/voltage reversal behavior of an EESS that is at a higher level of assembly, it allows test articles to be enclosed for the test which results in better gas analysis of any materials vented during the testing.*

Overdischarge Test Description: With the test article at its normal operating temperature, fully charged (100% SOC), and with the cooling system (if available) operating, fully discharge the test article at the C/1 rate. The test should continue for 1.5 hours, or until 50% of all subassemblies (for module- or pack-level tests) have achieved voltage reversal for 15 minutes. Perform this test with integrated, passive overdischarge protection operational but with all non-passive protective devices disabled.

Voltage Reversal Test Description: With the test article at its normal operating temperature, at 0 V, and with the cooling system (if available) operating, charge the test article to its rated voltage at the 5C rate. The upper limit on the power supply should be set not to exceed the rated voltage of the test article. When the test article reaches its rated voltage, reverse the polarity of the charge and charge the test article at the 5C rate to negative its rated voltage. The lower limit on the power supply should be set not to exceed the negative of the rated voltage of the test article. The test should continue for 1.5 hours, or until 50% of all subassemblies (for module- or pack-level tests) have achieved voltage reversal for 15 minutes. Perform this test with integrated, passive overdischarge protection operational but with all non-passive protective devices disabled.

Measured data may include:

- External EESS temperature.
- EESS voltage and current.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Still photographs of the EESS before and after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

5.4. Partial Short Circuit

Abuse Level: 3

Minimum Assembly Level: Module.

Description: The partial short circuit test is designed to evaluate the effects of short circuits that occur across a significant portion of, but not the entire, test unit. This test is only performed on modules or packs. With the test article at the maximum normal operating temperature, fully charged (100% SOC), and cooling media in place, use an adequate conductor of $\leq 5 \text{ m}\Omega$ to ‘hard short’ adjacent units/modules as described in Table 7 for 10 minutes or until another condition occurs that prevents completion of the test (*e.g.*, component melting). Perform this test with integrated, passive short circuit protection devices operational. Disable all non-passive protective devices. After the test article has been shorted as described above, continue observation of the test article for two hours.

Table 7. Number and Type of Devices to be Shorted

	2-5 units/modules	6-10 units/modules	> 10 units/modules
Module	Short at least one centrally located unit	Short at least two centrally located adjacent units	Short at least five centrally located adjacent units
Pack	Short at least one centrally located module	Short at least two centrally located adjacent modules	Short at least five centrally located adjacent modules

Measured data may include:

- External EESS unit/module temperatures.
- Module voltage and current as a function of time.
- Voltage across the positive and negative terminals before and after the test.
- Resistance between the EESS case and the positive and negative terminals before and after the test.
- Video and still photographs of the EESS before, during, and after the test.
- Chemical analysis of vented gas and smoke to determine the presence of extremely hazardous substances as a function of time.
- Flammability of vented gas and smoke.

6. Recommended Test Sequences

The recommended test sequences shown in Table 8 simulate both moderate and severe abuse scenarios although some of the tests are not applicable to all candidate EESS technologies. The tests in a given sequence are expected to be run in the stated order (A through D) with a single test article. The tests within a sequence are arranged in order of increasing severity. It is expected that the test article will survive each test in the sequence with sufficient integrity so that it can be used for the next test in the sequence. Nevertheless, the required number of test articles to be subjected to this phase of testing will depend on actual performance (*e.g.*, a particular design may be capable of passing all but the final crush test, whereas for other designs, as many as three or four test articles may be needed). It is acceptable to use a new EESS for each test. If an EESS survives a complete sequence and is still functional, it can be used for another sequence, although this is not required.

The intent of the test sequences is to generate meaningful data while minimizing the number of test units used. For example, Recommended Test Sequence 1 exposes the test article to a Level 1 shock that is not expected to cause damage. The same test article is then exposed to a Level 2 shock, which may cause damage. The test article is then exposed to a rollover test to help confirm that serious damage has not been done. Finally, the test article will be exposed to an immersion test, which likely will damage the EESS. The sequence will also expose any synergistic effects of shocks followed by immersion. Recommended Test Sequence 2 is similar, except that the last test is a simulated fuel fire.

Table 8. Recommended Test Sequences

Name	Category	Abuse Level	Min. Assembly Level	Test Sequence					
				1	2	3	4	5	6
Shock – Low	Mechanical	1	Module	A	A	B			
Shock – Mid 1	Mechanical	2	Module		B				
Shock – Mid 2	Mechanical	2	Module	B					
Drop	Mechanical	3	Pack						
Penetration	Mechanical	3	Unit			C			
Roll-over	Mechanical	1	Module	C	C				B
Immersion	Mechanical	3	Module	D					
Crush	Mechanical	3	Unit						C
Simulated Fuel Fire	Thermal	3	Unit		D			C	
Thermal Stability	Thermal	3	Unit						
Compromise of Thermal Insulation	Thermal	2	Module				B		
Overheat/Thermal Runaway	Thermal	2	Module						
Thermal Shock	Thermal	2	Unit						
Elevated Temperature Storage	Thermal	2	Unit						
Extreme-cold Temperature	Electrical	2	Unit				A		
Short Circuit	Electrical	3	Module				C	B	
Partial Short Circuit	Electrical	3	Module						
Overcharge	Electrical	2	Module					A	
Overdischarge	Electrical	2	Module						
Vibration	Mechanical	1	Unit			A			A

7. References

7.1. Works Cited

- (1) SAND 99-0497. Unkelhaeuser, Terry and Smallwood, David. *Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual*. Sandia National Laboratories. Albuquerque, NM. July 1999.
- (2) SAE Surface Vehicle Recommended Practice J-2464. *Electric Vehicle Battery Abuse Testing*. SAE International, Warrendale, PA. March 1999.
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- (4) AIHA #303-EA-98. *Emergency Response Planning Guidelines*. American Industrial Hygiene Association. Fairfax, VA. 1998.
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- (6) SAND 89-2312C. *Fault Tree Analysis: A Tool for Battery Safety and Reliability Studies*. Levy, Samuel C. Sandia National Laboratories, Albuquerque, NM. October 1989.
- (7) 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 & Exhibition*. Monaco, EU. April 2-6, 2005. p. 6.
- (8) DOE/ID-11070. *FreedomCAR 42V Battery Test Manual*. April 2003.
- (9) USABC. *Electric Vehicle Battery Test Procedures Manual—Revision 2*. Section 13, Safety and Abuse Testing. Detroit, MI. January 1996.

7.2. Related Reading

- DOE/ID-11069. FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles. October 2003. **Note:** This work focuses on the batteries' electrical performance.
- EPRI/DOE #1001834. Handbook of Energy Storage for Transmission and Distribution Applications. Chapter 14, Electrochemical Capacitors. Electric Power Research Institute. Palo Alto, CA. 2003. **Note:** Although this work focuses on electrochemical capacitors for stationary applications, it contains valuable information on the relevant safety concerns and potential environmental and health hazards for various types of electrochemical capacitors.
- NHTSA/DOT CFR 571.305. "Electric-powered vehicles: electrolyte spillage and electrical shock protection." October 2002.

Appendix A – Vibration Testing

Vibration testing, as outlined in this appendix, is considered a normal automotive environment. However, this level of vibration can be considered ‘abusive’ to EESS technology. The mounting and support of the EESS shall be as similar as possible to the manufacturer’s recommended HEV 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. Unless otherwise specified, the test article should be tested early in its life (*i.e.*, before life-cycle testing). This testing may be performed as a stand-alone activity or as part of another series of tests.

Purpose

This testing is intended to characterize the effect(s) of long-term, road-induced vibration and shock on the performance and service life of candidate EESSs. Depending on the maturity of the EESS, the intent of the test regime is either (a) to qualify the vibration durability of the EESS, or (b) to identify design deficiencies that must be corrected. Either swept-sine-wave vibration or random vibration can be used to perform this testing. Each of these alternatives is explained in greater detail below.

For testing efficiency, a time-compressed vibration regime is specified to allow completion of the test in just over 24 hours of exposure per test article for swept-sine-wave excitation. For random excitation, the test regime requires a minimum of 13.6 hours and a maximum of 92.6 hours of testing, depending on the type of shaker table available and the choice of acceleration levels. The test regime was synthesized from rough-road measurements at locations appropriate for mounting of traction batteries in EVs. The data were analyzed to determine an appropriate cumulative number of occurrences of shock pulses at any given peak acceleration (G) value over the life of the vehicle. The vibration spectra specified in this test regime were designed to approximate this cumulative exposure envelope and correspond to approximately 100,000 miles of usage at the 90th percentile.⁹

This appendix describes the vibration testing of a single test article (pack, module, or unit). For statistical purposes, multiple samples would normally be tested. Additionally, it is recommended that some test articles be subjected to life-cycle testing (either after or during vibration testing) to determine the effects of vibration on EESS life.

Prerequisites

- Prepare a test plan or other similar requirements document for testing according to this profile. The test plan should specify the appropriate test conditions for the Reference Performance Tests, ascertain the vibration frequencies to be used, and describe the safety precautions and special handling/testing instructions specified for the EESS by the manufacturer.
- Perform Pre-test Preparation and a Readiness Review according to USABC (Procedures 1A and 1B) or similar guidelines.
- Perform Reference Performance Tests according to USABC (Procedure 14C) or similar guidelines. For Reference Performance Testing use either a C/1 (batteries) or 5C

(capacitors) constant current discharge, a device specific test discharge to 100% of rated capacity, and a peak power discharge.

Test Equipment

- Performance of the swept-sine-wave procedure requires a single-axis shaker table capable of producing a peak acceleration of 5 G within the range of 10 to 30 Hz, as well as G-loading at the values and within the frequency ranges shown in Table A-1 and Table A-2. *Note: If the unit to be tested can be only vibrated while in a particular physical orientation due to leakage or other constraints, a multi-axis table will be required.*

Table A-1. Frequency and G-values for Vertical Axis

Frequency Range (Hz)	Peak Acceleration (G)
10-20	3.0
20-40	2.0
40-90	1.5
90-140	1.0
140-190	0.75

Table A-2. Frequency and G-values for Longitudinal Axis

Frequency Range (Hz)	Peak Acceleration (G)
10-15	2.5
15-30	1.75
30-60	1.25
60-110	1.0
110-190	0.75

- Performance of the random vibration procedure requires a one- to three-axis table capable of producing accelerations up to 1.9 G over the vibration spectra shown in Figure A-1, extending from 10 to 200 Hz. If the test article can be vibrated only while in a particular physical orientation, a multi-axis table is required. The time required to perform the test can be reduced significantly if the longitudinal and lateral axis vibration (or all three axes) can be performed concurrently.

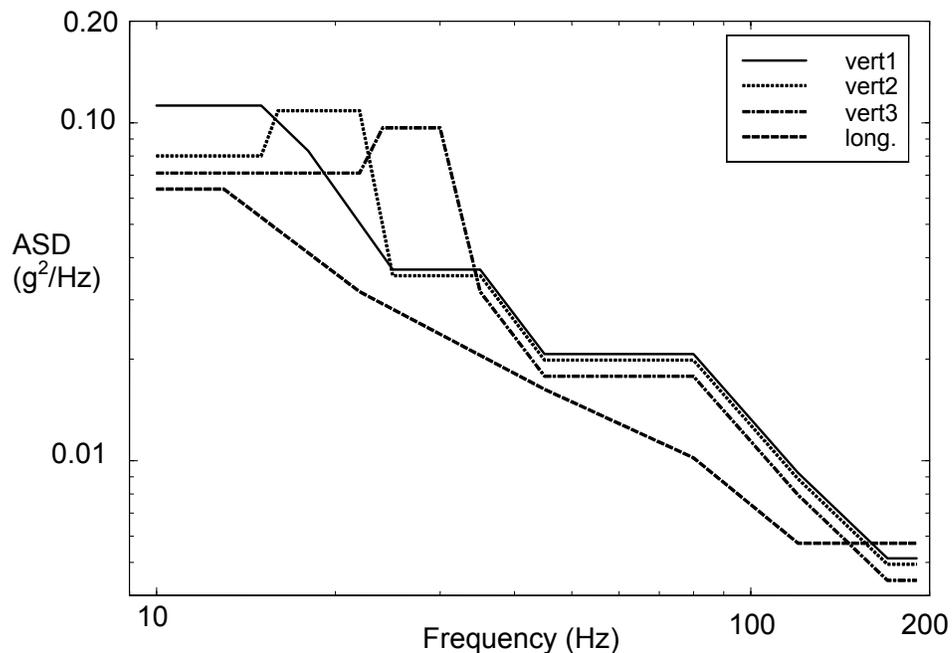


Figure A-1. Vertical and longitudinal vibration spectra expressed in G^2/Hz .

- Test fixtures are required to properly secure the test article to the shaker table. The exact nature of these fixtures depends on the type of table used, the device under test, and any restrictions on physical orientation of the test article.
- Instrumentation capable of withstanding the vibration is required to ensure that all necessary safety conditions can be monitored during testing. *Note: Safety considerations are described in greater detail below.*

Determination of Test Conditions and Test Termination

- Electrical test conditions are determined according to USABC (Procedure 14C) or similar guidelines.
- The SOC to be used for each vibration test procedure should be reviewed and adjusted for each specific EESS technology (if necessary) to assure that a worst-case SOC is used.
- The specific vibration frequencies for maximum vibration should be specified in the test plan. If these are not specified, the vertical and longitudinal testing should be performed at 15 and 12 Hz, respectively.
- Vibration testing shall be suspended or terminated if any observed component degradation threatens safe operation of the EESS as specified by the manufacturer. Conditions to be monitored are defined in ‘Safety Considerations,’ below.
- Other test conditions are specified in the test procedures themselves.

Safety Considerations

During vibration testing, the test article shall be instrumented to determine the presence of any of the following conditions:

- Loss of electrical isolation between the EESS positive connection and the EESS case and/or test equipment ground. The degree of isolation shall be verified regularly (*e.g.*, daily during any period of vibration testing) to be $\geq 0.5 \text{ M}\Omega$ (1.0 mA or less leakage at 500 Vdc).
- Abnormal EESS voltages indicating the presence of open- or short-circuit conditions.
- Unexpected resonance conditions within the EESS, indicating failure of mechanical tie-down components.
- Abnormal temperature conditions indicating possible damage to EESS cells or thermal management system components.

Suspend testing upon detection of any of the conditions listed above until the condition has been evaluated and a determination has been made that either it is safe to proceed or the testing should be terminated.

Data Acquisition and Reporting

Data acquired during the Reference Performance Tests should be available during vibration testing. This data (other than summary results) need not be retained if no anomalous behavior is observed during testing.

Data reporting should follow USABC or similar guidelines. This report should detail the actual vibration regimes applied, a compilation and interpretation of all data acquired, any results of detailed component failure analyses, and any recommendations for improvements in EESS design, installation procedures, or test methods. Also, the pre- and post-vibration electrical performance data confirming the adequacy of the EESS design to withstand the vibration environments should be summarized and included.

Procedure Steps for Swept-sine-wave Vibration Testing

1. Perform Reference Performance Tests according to USABC or similar guidelines.
2. Fully charge the EESS according to the manufacturer's recommended charge algorithm.
3. Vertical Axis Vibration (first half at 0% DOD):
 - a. Mount the test unit so that it will be subjected to vibration in the vertical axis, based on the manufacturer's recommended physical orientation.
 - b. Subject the test unit to 2,000 sinusoidal cycles at 5 G peak acceleration, applied at a frequency to be specified in the test plan within the range from 10 Hz to 30 Hz.
 - c. Subject the test unit to 60 sine sweeps from 10 Hz up to 190 Hz, and back to 10 Hz, to be conducted at a sweep rate of 1 Hz/s for a total of six hours using the profile of G-levels provided in Table A-1.

4. Discharge the EESS to approximately a 40% DOD at either the C/1 (batteries) or 5C (capacitors) rate.
5. Longitudinal Axis Vibration (at 40% DOD):
 - a. Mount the EESS so that it will be subjected to vibration in the longitudinal axis, based on the manufacturer's recommended physical orientation.
 - b. Subject the test unit to 4,000 sinusoidal cycles at 3.5 G peak acceleration, applied at the frequency specified in the test plan (within the range of 10 to 30 Hz).
 - c. Subject the test unit to 60 sine sweeps from 10 Hz to 190 Hz and back to 10 Hz at a sweep rate of 1 Hz/s for a total of six hours using the profile of G-levels provided in Table A-2.
6. Lateral Axis Vibration (at 40% DOD):
 - a. Mount the EESS so that it will be subjected to vibration in the lateral axis (assumed to be orthogonal to the longitudinal axis), based on the manufacturer's recommended physical orientation.
 - b. Repeat Steps 5b and 5C with the test unit mounted in this configuration.
7. Discharge the EESS to approximately an 80% DOD at either the C/1 (batteries) or 5C (capacitors) rate.
8. Vertical Axis Vibration (second half at 80% DOD):
 - a. Repeat 3a through 3c with the test unit at this reduced SOC.
9. Repeat the Reference Performance Tests.

Procedure Steps for Random Vibration Testing

1. Perform Reference Performance Tests according to USABC or similar guidelines.
2. Fully charge the EESS according to the manufacturer's recommended charge algorithm.
3. For each of the vertical, longitudinal, and lateral axes of the EESS, select either the normal or alternative G-levels from Table A-3 and program the shaker table appropriately. This choice will determine the vibration time required for each axis, also in accordance with Table A-3. **Note:** *The vibration spectra, shown in Table A-4 and Figure A-1, are expressed in G^2/Hz , so they can be scaled for either set of G-levels.*
4. Mount the test article so that it will be subjected to vibration along the appropriate axes, based on the manufacturer's recommended physical orientation. **Note:** *This procedure permits the required vibration to be performed in one, two, or all three axial directions simultaneously, depending on the capabilities of the shaker table used.*

Table A-3. Vibration Schedule for Random Vibration Test

Test Conditions		Normal Test			Alternate Test		
Vibration Spectrum	SOC (%)	Accel. (G rms)	Time (hr)	Cumul. Time (hr)	Accel. (G rms)	Time (hr)	Cumul. Time (hr)
Vertical Axis Vibration							
Vertical 1 spectrum	100	1.9	0.15	0.15	1.9	0.15	0.15
Vertical 1 spectrum	100	0.75	5.25	5.4	0.95	3.5	3.65
Vertical 2 spectrum	100	1.9	0.15	5.55	1.9	0.15	3.8
Vertical 2 spectrum	100	0.75	5.25	10.8	0.95	3.5	7.3
Vertical 3 spectrum	20	1.9	0.15	10.95	1.9	0.15	7.45
Vertical 3 spectrum	20	0.75	5.25	16.2	0.95	3.5	10.95
Longitudinal Axis Vibration							
Longitudinal spectrum	60	1.5	0.09	16.29	1.5	0.09	11.04
Longitudinal spectrum	60	0.4	19.0	35.29	0.75	6.7	17.74
Longitudinal spectrum	60	1.5	0.09	35.38	1.5	0.09	17.83
Longitudinal spectrum	60	0.4	19.0	54.38	0.75	6.7	24.53
Lateral Axis Vibration							
Longitudinal spectrum	60	1.5	0.09	54.47*	1.5	0.09	24.62*
Longitudinal spectrum	60	0.4	19.0	73.47*	0.75	6.7	31.32*
Longitudinal spectrum	60	1.5	0.09	73.56*	1.5	0.09	31.41*
Longitudinal spectrum	60	0.4	19.0	92.56	0.75	6.7	38.11*

* These cumulative times apply only if all three axes are done separately.

5. Perform the programmed vibration for the required times, varying the DOD from 0 to 80% over the course of the test using one of the following two methods:

- If a one- or two-axis vibration table is used, approximately half of the vertical axis testing should be done at full charge, followed by the longitudinal and lateral vibration at 40% DOD, and then the remaining vertical axis vibration at 80% DOD.
- If a three-axis table is used to perform all vibration regimes simultaneously, the total testing period can be divided into three intervals of roughly equal length. The first interval should be performed with the EESS fully charged, the second interval with the EESS at 40% DOD, and the third interval at 80% DOD.

Note: Discharge the EESS at either the C/1 (batteries) or 5C (capacitors) rate for 40% of its rated capacity between each pair of the three vibration intervals. Fully recharge the test article after the third vibration interval.

Table A-4. Break Points for Random Spectra Scaled to Specified rms Level

Vertical 1	1.9 g rms	Vertical 2	1.9 g rms	Vertical 3	1.9 g rms	Longitudinal	1.5 g rms
Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
(Hz)	(G²/Hz)	(Hz)	(G²/Hz)	(Hz)	(G²/Hz)	(Hz)	(G²/Hz)
10	.113	10	.08	10	.071	10	.064
15	.113	15	.08	22	.071	13	.064
18	.083	16	.11	24	.097	22	.032
25	.037	22	.11	30	.097	45	.016
35	.037	25	.036	35	.032	80	.01
45	.021	35	.036	45	.018	120	.0057
80	.021	45	.02	80	.018	190	.0057
120	.0092	80	.02	120	.0079		
170	.0052	120	.0088	170	.0044		
190	.0052	170	.005	190	.0044		
		190	.005				

6. Repeat the Reference Performance Tests.

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