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Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual

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Prepared by
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USABC/SNL CRADA No. SC961447

Abstract

The series of tests described in this procedure manual are intended to simulate actual use and abuse conditions and potential internally initiated failures that may be experienced in electrochemical storage systems. These tests were derived from Failure Mode and Effect Analysis, user input, and historical abuse testing. The tests, designed to provide a common framework for various electrochemical storage systems, have been adopted by the Society of Automotive Engineers as recommended practice in SAE J2464. The primary purpose of the tests is to gather response information to external/internal inputs. Some tests and/or measurements may not be required for some electrochemical storage system technologies and designs if it is demonstrated that a test is not applicable and the measurements yield no useful information.

The outcome of testing shall be documented for use by potential integrators of the tested properties. It is not the intent of this procedure to apply acceptance criteria; each application has its own unique requirements and ancillary support systems. Integrators shall make their own determination as to what measures are to be taken to ensure a sound application of these technologies.

Foreword

A team composed of the United States Advanced Battery Consortium (USABC) and U.S. Department of Energy (DOE) National Laboratories personnel prepared this USABC electrochemical storage system (ECSS) Abuse Test Procedures Manual. It is based on the expertise and methods developed primarily at Sandia National Laboratories (SNL) and Idaho National Engineering and Environmental Laboratory (INEEL). The specific procedures were developed to characterize the performance of a particular ECSS relative to the USABC long-term battery requirements. This abuse manual is the result of an effort ongoing since 1973. Many people contributed to this effort during that time. Special acknowledgment is given to Jeff Braithwaite who was instrumental in the early definition of the electrical abuse tests. The authors of this document are Terry Unkelhaeuser and David Smallwood of SNL. These procedures have been adopted by the Society of Automotive Engineers (SAE) as recommended practice in SAE J2464. Comments regarding this document should be directed to Terry Unkelhaeuser, SNL (505-845-8801).

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Acronyms and Definitions

ARC	Accelerated Rate Calorimeter
BTP	battery test procedure
DOD	depth of discharge
DOE	Department of Energy
DST	dynamic stress test
ECSS	electrochemical storage systems. A device for storing electrical energy in chemical form, for use in mobile or stationary applications.
EPA	Environmental Protection Agency
EPRG-2	Emergency Response Planning Guidelines, Level 2. The maximum airborne concentration levels below which most all individuals could be exposed to for up to one 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. Other world standards with similar intent may be substituted.
EV	electric vehicle
Fully Charged:	100% SOC. The state of an ECSS after a full charge cycle as specified by the ECSS manufacturer. For purposes of this document, an ECSS is considered Fully Charged within 4 hours of the end of the charge cycle provided that the SOC is not expected to fall below 95%.
INEEL	Idaho National Engineering and Environmental Laboratory
SAE	Society of Automotive Engineers
SNL	Sandia National Laboratories
SOC	state of charge
USABC	United States Advanced Battery Consortium

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1. General Information

The series of tests described in this report are intended to simulate actual use and abuse conditions and internally initiated failures that may be experienced in electrochemical storage systems (ECSS). These tests were derived from Failure Mode and Effect Analysis, user input, and historical abuse testing. The tests are to provide a common framework for various ECSS technologies. The primary purpose of testing is to gather response information to external/internal inputs. Some tests and/or measurements may not be required for some ECSS technologies and designs if it is demonstrated that a test is not applicable, and the measurements yield no useful information.

It is not the intent of this procedure to apply acceptance criteria; each application has its own unique requirements and ancillary support systems. Integrators shall make their own determination as to what measures are to be taken to ensure a sound application of these technologies.

There are three levels to the testing. The lowest level tests are for relatively common events where the ECSS is expected to remain essentially intact. The vehicle in which the ECSS was mounted might incur damage, but the ECSS should be salvageable and would be reused after minor repairs. (The ECSS represents a substantial investment and should not be damaged by relatively common events.) For less common, but more serious mid-level events, the ECSS may become inoperable but should not expose humans to known health risks.

The highest level tests are for destructive situations where the ECSS is expected to become inoperable. The ECSS cannot be reasonably protected from severe events. While these events are relatively rare, credible scenarios exist that can lead to these damage levels.

The response of the ECSS to testing may provide useful design information. All tests should be conducted at the lowest level of assembly for which meaningful data can be gathered. This may be the cell or module level in some cases and a complete ECSS at the pack level for other cases. The assembly level required will be a function of the ECSS technology, the ECSS design, and the specific test. The required assembly level could also be a function of the design cycle. For example, cell tests should be run very early in a program, module tests run as modules become available, and tests run at the system or subsystem level later in the design cycle, as required. (Recommended test sequences and levels are defined in Section 6.0.)

The release of hazardous substances should be measured and referenced to the ERPG-2 levels. ERPG-2 refers to the Emergency Response Planning Guidelines, Level 2, from the American Industrial Hygiene Association.[1] ERPG-2 levels are the maximum airborne concentration levels below which most individuals could be exposed for up to one hour without experiencing or developing serious or irreversible health effects or symptoms. Tests should be conducted in a closed volume of appropriate size to accommodate the test article and provide adequate air space to ensure a "normal" atmosphere. Any released gas concentration in that volume shall be normalized to a 1-m^3 volume for quantitative analysis. If it is not practical to perform any test in a closed volume because of test article size, it is permissible to perform said test out of doors, provided that wind speed is $\leq$3 mph. A minimum of three hazardous substances monitors, spaced equally around the unit, should be placed as close to the test as is reasonable and moved as close to the ECSS as is practical after the test. Hazardous substance monitors shall be selected with respect to anticipated release products. If it is reasonable to expect that a specific technology will not vent during a particular test, or gas collected will not be significantly different from that previously collected, gas collection and analysis will not be required.

The flammability of any expelled materials must also 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 H_2 is 4%. For substances not considered hazardous, the Environmental Protection Agency's (EPA's) reportable release limits are used for reference. A release means any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment.

Initial testing will most likely be with a new ECSS, since systems or subsystems that have seen only part of their useful life will be unavailable. Future efforts may include an ECSS or subsystem that is well into, or near the end of, its useful life. Permutations of state of charge (SOC), system age, and temperature should be implemented at the integrator's/developer's discretion based on the most susceptible condition of the technology.

Abuse testing will be performed to characterize the ECSS response to undesirable conditions or environments associated with carelessness, poorly informed/ trained users or mechanics, failure of specific ECSS control and support hardware, and transportation/ handling incidents involving the ECSS. Some tests are not applicable to all candidate ECSS technologies. The required number of batteries to be subjected to testing will depend on actual performance (e.g., a single ECSS may be capable of passing all but the final crush test, whereas for other technologies, as many as three to four batteries may be required). It is acceptable to use a new ECSS for each test. The electrical and mechanical abuse tests will also cause failure of some ECSS. The purpose is to help quantify the mitigation efforts, that must be taken for a particular ECSS design.

All ECSS test articles shall be in a fully charged state, at normal operating temperature, with any cooling media in place, and with thermal control systems running, unless specifically stated otherwise. All test articles will be observed for a time period of at least one hour, or until such time that the test article is safe to handle after each test, unless specifically stated otherwise.

2. Mechanical Abuse Tests

The mounting and support of the ECSS shall be as similar to the manufacturer's recommended electric vehicle (EV) 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 axes that will cause the most potential damage. Other axes should then be tested at the discretion of the developer or user.

2.1 Mechanical Shock Tests (module level or above)

2.1.1 Test Description

The low-level shock test is a robustness test, that the ECSS is expected to survive without any damage incurred. Mid-level shocks are more severe; the ECSS 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 2-1. 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 (like 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 ECSS manufacturers to keep the pulse duration as long as possible and still meet the specification. However, if the ECSS 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 2-1.

2.1.2 Measured Data

1. Acceleration input to ECSS case, with a minimum of 2 kHz bandwidth.

2. Measurements of the ECSS deformation after the test.

3. Temperature of the ECSS case as a function of time.

4. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.

5. Still photographs of the test setup and the ECSS before and after the test.

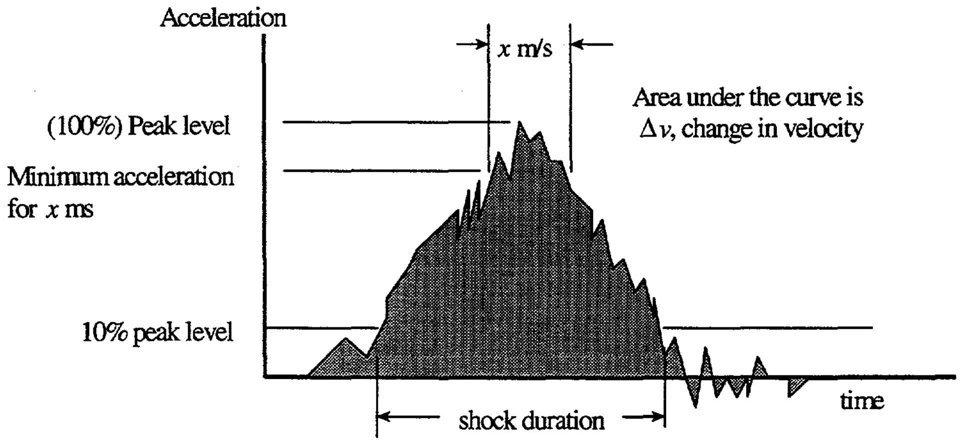

Figure 2-1. Illustration of shock parameter definitions.

Table 2-1. Parameters for Mechanical Shock Test

Level	Δ Velocity (m/s)	Duration (m/s)	Minimum Acceleration	Acceptable Pulse Form
Low	6.7	≤55	20 G for 11 m/s	25 G 30 m/s half-sine
Mid-1	11.1	≤65	30 G for 16 m/s	35 G 51 m/s half-sine
Mid-2	13.3	≤110	20 G for 22 m/s	25 G 60 m/s half-sine

6. High speed motion pictures of test, ≥ 400 frames per second.

7. Air concentrations of hazardous gases, liquids, and solids shall be collected and analyzed as a function of time.

2.2 Drop Test (pack level only)

2.2.1 Test Description

This is a destructive free drop from 10 m (33 ft) onto a centrally located, cylindrical steel object (e.g., a telephone pole) having a radius of 150 mm (Figure 2-2). The ECSS shall impact across the radius of the cylindrical object, but not on the end of the cylindrical object. A horizontal impact with an equivalent velocity change is acceptable. The test should be run with wind speed of ≤3 mph, or in an enclosed facility. A minimum of three hazardous substance monitors, equally spaced around the unit, should be placed as close as reasonable to the test and moved as close as practical to the ECSS after the test. The ECSS should be observed for a minimum of one hour after the test.

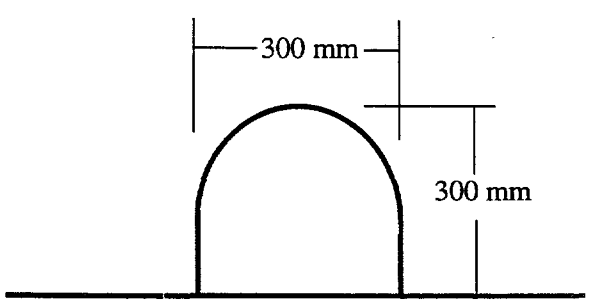

Figure 2-2. Drop test platen.

2.2.2 Measured Data

1. Acceleration input to ECSS case, with a minimum of 10 kHz bandwidth.

2. Measurements of the ECSS deformation after the test.

3. Temperature of the ECSS case as a function of time.

4. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.

5. Still photographs of the test setup and the ECSS before and after the test.

6. High-speed motion pictures of test, ≥ 400 frames per second.

7. Air concentrations of hazardous gases, liquids, and solids shall be collected and analyzed as a function of time.

2.3 Penetration Test (cell level or above)

2.3.1 Test Description

The test article will be penetrated with a mild steel (conductive) pointed rod, which will be electrically insulated from the test fixture. The rate of penetration shall be 8 cm/s nominal. The diameter of the rod and the depth of penetration can be found in Table 2-2. The orientation of the penetration shall be perpendicular to the electrode plates. The test should be run with wind speed of ≤ 3 mph, or in an indoor facility. A minimum of three hazardous substance monitors, equally spaced around the unit, should be placed as close as reasonable to the test and moved as close as practical to the ECSS after the test. The ECSS should be observed, with the rod remaining in place, for a minimum of one hour after the test.

Table 2-2. Test Specifications

Size of Test Object	Diameter of Rod	Minimum Depth of Penetration
Cell	3 mm	Through cell
Module / Pack	20 mm	Through three cells or 100 mm

2.3.2 Measured Data

1. Hazardous substances and their levels as a function of time.
2. Measurements of the ECSS deformation after the test.
3. Temperature of the ECSS case as a function of time.
4. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
5. Still photographs of the test setup and the ECSS before and after the test.
6. High speed motion pictures of test, ≥ 400 frames per second.
7. Air concentrations of hazardous gases, liquids, and solids shall be collected and analyzed as a function of time.

2.4 Roll-over Test (module level or above)

2.4.1 Test Description

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

2.4.2 Measured Data

1. Temperature of the ECSS case as a function of time.
2. Measure air concentrations of hazardous substances, normalized to a 1 m^3 volume, as a function of time.
3. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the test setup and the ECSS before the test and at each position.
5. Any substance that may leak from the battery shall be analyzed and tested for flammability.

2.5 Immersion Test (module level or above)

2.5.1 Test Description

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

2.5.2 Measured Data

1. Temperature of the ECSS case as a function of time.
2. Air concentrations of extremely hazardous substances, normalized to an equivalent 1 m^3 volume, as a function of time.
3. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the test setup and the ECSS before and after the test. The entire test shall be video taped.
5. The ECSS should be observed for a minimum of one hour after the test.

2.6 Crush Test (cell level or above)

2.6.1 Test Description

The ECSS shall be at a nominal operating temperature and have all integrated control and interconnect circuitry in place and operating. An ECSS is to be crushed once in each of the three axes (using a different ECSS for each crush, with the irregular surface of the platen at the most vulnerable location) to 85% of the initial dimension, and held for 5 minutes. After the hold period, continue the crush to 50% of the initial dimension. The crush force may be limited to a maximum of 1000 times the weight of the ECSS. If the test is performed outside, the wind speed should be < 3 mph.

A minimum of three toxic gas monitors, equally spaced around the unit, should be placed as close as reasonable to the test, and moved as close as practical to the ECSS after the crush.

The platen shall have semicircular intruders (Figure 2-3) that have a 75 mm radius and have been placed 30 mm from one another across the face of the platen. The opposing platen shall be flat. Both platens shall be electrically isolated for the test fixture.

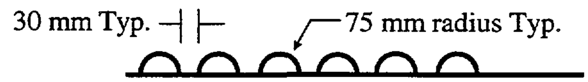

Figure 2-3. Crush test platen.

2.6.2 Measured Data

1. Air concentrations of extremely hazardous substances as a function of time.

2. Internal and external ECSS temperature.

3. ECSS and module voltage, as appropriate.

4. Video and still photographs of the ECSS before, during, and after the test.

3. Thermal Abuse Tests

3.1 Radiant Heat Test (cell level or above)

3.1.1 Test Description

With the electrochemical storage system (ECSS) at ≥80% state of charge (SOC), expose it to high temperature for ten minutes in a radiant-heating circular fixture. The test item should be placed inside a cylindrical metallic fixture. The inside of the fixture should be coated in such a way that the fixture will radiate approximately like a black body. The exterior is exposed to radiant heat, and the test is controlled by thermocouples mounted on the fixture. The fixture shall be programmed to reproduce the temperature experienced in a fuel fire (890°C nominal). The programmed temperature shall be achieved within 90 seconds and held for a period of 10 minutes or until another condition occurs which would prevent the completion of the tests. The ECSS should be in its normal operation orientation and will not be insulated or protected, unless this is the standard configuration for the test article. Should the ECSS ignite, it may be extinguished after gas samples are taken using a method appropriate for the technology.

3.1.2 Measured Data

1. Temperature of the ECSS case as a function of time.
2. Air samples of any released gases are to be analyzed after the test.
3. Potential and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Video and still photographs of the test setup and the ECSS before, during, and after the test.

3.2 Thermal Stability Test (cell level or above)

This test is not designed for an ECSS with an operating temperature >150°C. An appropriate thermal stability test shall be determined by the manufacturer or testing organization for high-temperature ECSSs on a case-by-case basis. The temperature measurement shall be on the surface of a metallic cell or the post of a non-metallic cell. Temperature sensing for a module shall be at the designed temperature sensing position for that module.

3.2.1 Cell Test Description

The cell shall be in a fully charged state and placed in a device capable of maintaining a near adiabatic state (Accelerated Rate Calorimeter (ARC) apparatus or similar). Starting at the operating temperature of the ECSS, the temperature shall be increased in 5°C increments and held at each step for a minimum of 30 minutes, or until any self-heating is detected. If self-heating is detected, the chamber temperature shall track the cell temperature until the exotherm becomes stable. The temperature is then increased to the next 5°C increment and continued as described above until (1) additional self-heating is detected, (2) the temperature reaches 200°C above the operating temperature of the ECSS, or (3) a catastrophic event occurs.

If the ECSS experiences a thermal runaway, the test shall be repeated to further define the exact thermal stability limit. The temperature shall be increased at a constant rate to 10°C below the event temperature. The temperature will then be increased in 2°C increments and held for a minimum of one hour until the event is repeated and the thermal stability limit is defined.

The test should be repeated with cells that have been overcharged to 150% of the rated capacity and cells that have been cycled to 50% and 100% of nominal life.

3.2.1.1 Measured Data

1. Temperatures at which venting occurs.
2. Temperatures of any smoke generation.
3. Cell temperature profile with respect to time.
4. Oven temperature profile with respect to time.

3.2.2 Module Test Description

If a major cell exotherm initiation temperature is known, the starting temperature will be 10% below the absolute temperature of the exotherm. The module shall be in a fully charged state and placed in a device capable of externally heating the module. The temperature shall be increased in 10°C increments and held at each step for a minimum of 120 minutes, or until any self-heating is detected. After completion of self-heating, the temperature is then increased to the next 10°C increment and continued as described above until (1) additional self-heating is detected, (2) the temperature reaches 200°C above the operating temperature of the ECSS, or (3) a catastrophic event occurs.

If a major cell exotherm initiation temperature is not known, the starting temperature will be the operating temperature of the ECSS. The module shall be in a fully charged state and placed in a device capable of externally heating the module. The temperature shall be increased in 20°C increments and held at each step for a minimum of 120 minutes, or until any self-heating is detected. After completion of self-heating, the temperature is then increased to the next 20°C increment and continued as described above until 1) additional self-heating is detected, 2) the temperature reaches 200°C above the operating temperature of the ECSS, or 3) a catastrophic event occurs.

3.2.2.1 Measured Data

1. Temperatures at which venting occurs.
2. Temperatures of any smoke generation.
3. Cell temperature profile with respect to time.
4. Oven temperature profile with respect to time.

3.3 Compromise of Thermal Insulation (module level or above)

3.3.1 Test Description

With the ECSS at nominal operating temperature and fully charged, compromise the insulation system integrity or other applicable device. Allow the Thermal Insulation Case interior and exterior temperature to equalize. Observe the system until the equalized temperatures begin to decrease.

3.3.2 Measured Data

1. Internal temperature distribution.
2. External temperature distribution.

3.4 Overheat/Thermal Runaway Test (module level or above)

3.4.1 Test Description

With the ECSS at nominal operating temperature, fully charged, contained in a closed volume, and with all thermal controls (primary and secondary) disabled, perform C/1 cycling, utilizing the manufacturer's defined charge algorithm for 20 cycles with no rest period between charge or discharge. Perform three baseline C/3 cycles after the test with thermal control active to determine the effects on the ECSS.

3.4.2 Measured Data

1. Note any venting of the ECSS.
2. Internal (if possible) and external ECSS temperature.
3. Voltage and resistance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the ECSS before, during, and after the test.
5. ECSS voltage and current as a function of time.

3.5 Thermal Shock Cycling (cell level or above)

3.5.1 Test Description

With the ECSS at 50% SOC, contained in a closed volume, and with all thermal controls (primary and secondary) disabled, thermally cycle the ECSS with ambient air cycling between 80°C to –40°C. The air temperature shall be measured in close proximity to the ECSS. The time to reach each temperature extreme shall be 15 minutes or less. The ECSS shall remain at each extreme for a minimum of six hours at the module level. The time can be appropriately adjusted for cells and packs. A total of five cycles shall be performed. After thermal cycling, inspect the ECSS for any damage, paying special attention to any seals that may exist. Also, verify that control circuitry is operational. Perform three C/3 discharge cycles using the manufacturer's charge algorithm at 25°C ambient air temperature to determine the immediate effects of the thermal cycling.

3.5.2 Measured Data

1. Note ECSS voltage during thermal cycling.
2. Note any venting of the ECSS.
3. Voltage and resistance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the ECSS before and after the test.

3.6 Elevated Temperature Storage Test (cell level or above)

3.6.1 Test Description

With the ECSS at varying SOC (Table 3-1), place the ECSS in a stabilized ambient environment for a period of two months. On a weekly basis, remove the ECSS from the elevated-temperature environment, allow it to cool to normal operating temperature, and perform two C/3 cycles utilizing the manufacturer's recommended charge algorithm. Return the ECSS to the SOC under test and return it to the elevated-temperature environment. The test will end when 80% of the C/3 rated capacity cannot be returned on the second C/3 cycle or after two months, whichever occurs first. Three C/3 cycles shall be performed utilizing the manufacturer's recommended charge algorithm at the end of cycling to determine the effect of the elevated-temperature storage. (This test is not intended for elevated-temperature systems.)

The temperature shall be measured on the ECSS post and in the test chamber.

Table 3-1. Results of Temperature on Varying SOC

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

3.6.2 Measured Data

1. Note ECSS voltage during thermal cycling.
2. Note any venting of the ECSS.
3. Voltage and resistance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the ECSS before and after the test.

3.7 Extreme-Cold Temperature Test (cell level or above)

3.7.1 Test Description

With the ECSS at a specific SOC and internal temperature as indicated in Table 3-2, the ECSS shall be discharged at C/1 or charged at the normal primary charge rate for the specific system. The ECSS will be charged with the manufacturer's recommended algorithm, within the maximum time that the normal charge algorithm should be completed at the temperature indicated on the table. If equipped with liquid cooling, the coolant shall be present but not circulating. The test shall be stopped if abnormal conditions or physical damage to the ECSS becomes evident.

Initialize: Fully charge the ECSS per the manufacturers algorithm and discharge to the depth of discharge (DOD) indicated on Table 3-2 at C/3 at normal operating temperature.

After the complete set of tests is performed, three C/3 cycles are to be performed at 25°C ambient to determine the performance level of the ECSS.

Table 3-2. Charge and Discharge Rates of ECSS

Temperature (°C)	Depth of Discharge (%)	Charge/ Discharge (D)
25	0	Initialize
0	0	20% D
–20	20	20% D
–40	40	20% D
25	50	Initialize
0	50	20% C & 20% D
–20	50	20% C & 20% D
–40	50	20% C & 20% D
25	100	Initialize
0	100	20% C
–20	80	20% C
–40	60	20% C
25	0	C/3 Performance

3.7.2 Measured Data

1. Internal resistance.
2. Voltage and current with respect to time.
3. Derive the power capability.
4. Internal, if possible, and external temperature change of the test article.
5. Observe for cracks or damage to the external case.
6. Observe any venting or leaks.

4. Electrical Abuse Tests

4.1 Short Circuit Test (cell level or above)

4.1.1 Test Description

With the electrochemical storage system (ECSS) at nominal operating temperature, fully charged, and cooling medium in place, apply a hard short in less than one second to the ECSS with an adequate conductor of ≤5mΩ for 10 minutes, or until another condition occurs which prevents completion of the test (i.e., component melting, etc.). For systems with less than ≤5mΩ internal resistance, a conductor of 1/10 of the minimum resistance of the cell/module shall be used. This test will be performed with integrated, passive short circuit protection devices operational (e.g., integrated devices that require no external input). All non-passive protective devices shall be disabled prior to this test. Continue observation for an additional two-hour period.

4.1.2 Measured Data

1. Air concentrations of hazardous substances, normalized to a 1 m^3 volume, as a function of time.
2. External ECSS temperature.
3. Module voltage and current, as appropriate.
4. Voltage and resistance of the ECSS case with respect to the positive and negative terminals before and after the test.
5. Video and still photographs of the ECSS before, during, and after the test.

4.2 Partial Short Circuit Test (module level or above)

4.2.1 Test Description

With the ECSS at the maximum normal operating temperature, fully charged, and cooling medium in place, hard short adjacent cells of the ECSSs as described in Table 4-1, with an adequate conductor (≤5mΩ) for 10 minutes or until another condition occurs which prevents completion of the test (e.g., component melting, etc.). This test will be performed with integrated, passive short circuit protection devices operational (e.g., integrated devices that require no external input). All non-passive protective devices shall be disabled prior to this test. Continue observation for an additional two hour period.

Table 4-1. Shorting Specifications for Module and Pack

	2–5 cells/ modules	6–10 cells/ modules	> 10 cells or modules
Module	Short at least one centrally located cell	Short at least two centrally located adjacent cells	Short at least five centrally located adjacent cells
Pack	Short at least one centrally located module	Short at least two centrally located adjacent modules	Short at least five centrally located adjacent modules

4.2.2 Measured Data

1. Air concentrations of hazardous substances, normalized to a 1-m^3 volume, as a function of time.
2. External ECSS cell/module temperatures.
3. Module voltage and current, as appropriate.
4. Voltage and resistance of the ECSS case with respect to the positive and negative terminals before and after the test.
5. Video and still photographs of the ECSS before, during, and after the test.

4.3 Overcharge Test (cell level or above)

4.3.1 Test Description

With the ECSS at its designed operating temperature, fully charged (100% SOC), contained in a closed volume with the cooling system operating, the ECSS is to be overcharged at a constant charge current of 32 Adc and voltage not to exceed 450 Vdc (corresponds to the power level of a standard 60A/240V AC - 14.4 kW outlet) until the ECSS reaches 200% SOC or a test duration of four hours is reached. Passive integrated overcharge protection shall remain operational throughout the test. All non-passive protective devices shall be disabled prior to this test. When performing this test at less than the pack level, the voltage (series pack configuration) or the voltage/current (series/parallel pack configuration) shall be scaled down appropriately.

4.3.2 Measured Data

1. Air concentrations of extremely hazardous substances, normalized to a 1 m^3 volume, as a function of time.
2. External ECSS temperature.
3. ECSS voltage and current, as appropriate.
4. Voltage and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
5. Still photographs of the ECSS before the test.

4.4 Overdischarge Test (cell level or above)

4.4.1 Test Description

With the ECSS at its designed operating temperature, fully charged, and with the cooling system operating, the module is to be fully discharged at the C/1 rate for one hour and 30 minutes, or until every cell is reversed for 15 minutes. Passive integrated overdischarge protection shall remain operational throughout the test. All non-passive protective devices shall be disabled prior to this test.

4.4.2 Measured Data

1. External ECSS temperature.
2. ECSS voltage and current.
3. Voltage and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the ECSS before, during, and after the test.

4.5 AC Exposure (pack level only)

4.5.1 Test Description

With the ECSS at its designed operating temperature, fully charged, and the cooling system operating, the test article is to be subjected to a 50/60Hz (AC) not to exceed 60A from a 240V/60A standard outlet for a period of one hour. Only AC will be applied to the system during the test.

4.5.2 Measured Data

1. External ECSS temperature.
2. ECSS voltage and current.
3. Voltage and impedance of the ECSS case with respect to the positive and negative terminals before and after the test.
4. Still photographs of the ECSS before, during, and after the test.

5. ECSS Vibration Testing

The vibration testing, as outlined in this section, is considered a normal automotive environment. However, this level of vibration can be considered "abusive" to ECSS technology.

The mounting and support of the ECSS shall be as similar as possible to the manufacturer's recommended electric vehicle (EV) 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.

5.1 Purpose

This test is intended to characterize the effect of long-term, road-induced vibration and shock on the performance and service life of candidate batteries. Depending on the maturity of the ECSS, the intent of the procedure is either (a) to qualify the vibration durability of the ECSS, or (b) to identify design deficiencies that must be corrected. Either swept sine wave vibration or random vibration can be used for the performance of this procedure. Separate sections are included in this report to explain these alternatives.

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 procedure 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 contained in this procedure were designed to approximate this cumulative exposure envelope. The envelopes shown in Figure 10-1 of the USABC Electric Vehicle Battery Test Procedures Manual[2] summary of this procedure (page 25, not repeated here) correspond to approximately 100,000 miles of usage at the 90th percentile.

This procedure describes the performance testing of a single test unit (pack, module, or cell). For statistical purposes, multiple samples would normally be subjected to this testing. Additionally, some test units may be subjected to life-cycle testing (either after or during vibration testing) to determine the effects of vibration on ECSS life. Such life-testing is not described in this procedure. (Note: The random vibration portion of this specification is published as SAE J-2380.)

5.2 Prerequisites

1. An ECSS test plan or other test requirements document for testing using this procedure. The test plan specifies the appropriate test conditions for the Reference Performance Tests and ascertain vibration frequencies to be used, along with safety precautions and any special handling/ testing instructions specified for the ECSS by the manufacturer and/or the United States Advanced Battery Consortium (USABC).

2. Prior to the performance of this procedure, USABC Electric Vehicle Battery Test Procedures Manual[2] No. 1A, Battery Pre-Test Preparation, and No. 1B, Readiness Review should normally have been completed. These activities are not a part of this procedure. This procedure may be executed as a stand-alone test activity or as part of a sequence of tests provided that the information required by Step 1 (above) is available.

3. Performance of the Reference Performance Tests specified in USABC Procedure 14C is required before and after the conduct of vibration testing. This sequence includes a C/3 Constant Current discharge, a DST discharge to 100% of rated capacity, and a Peak Power discharge.

4. Unless otherwise specified, the test unit shall be tested early in its life (i.e., prior to the performance of any life cycle testing.)

5.3 Test Equipment

1. Performance of the swept sine wave version of this 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 Tables 5-1 and 5-2. (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 5-1. 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 5-2. 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

2. Performance of the random vibration version of the procedure requires a one- to three-axis table capable of producing accelerations up to 1.9 G over the vibration spectra detailed in Figure 5-1, extending from 10 to 200 Hz. If the unit to be tested can be vibrated only while in a particular physical orientation, a multi-axis table will be required. Additionally, 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.

3. Test fixtures are required to properly secure the test unit to the shaker table. The exact nature of these fixtures depends on the type of table used, the test unit itself, and any restrictions on physical orientation of the test unit.

4. Special instrumentation hookups capable of withstanding the vibration are required so that important ECSS conditions can be monitored during testing. (See Section 5.7)

5.4 Determination of Test Conditions and Test Termination

1. Electrical test conditions are determined according to Procedure 14C, Reference Performance Tests.[2]

2. The SOC to be used for each vibration test regime in Section 5.5 should be reviewed and adjusted for each specific ECSS technology (if necessary) to assure that a worst-case state of charge (SOC) is used for each vibration regime.

3. The specific vibration frequencies for maximum vibration explained in the Section 5.5, Step 3b and Section 5.5, Step 5b should be specified in the test plan. If these are not specified, the vertical and longitudinal testing of Section 5.5, Steps 3b and 5b will be done at 15 and 12 Hz respectively. Other vibration test conditions are specified in the procedure steps in Sections 5.5 and 5.6.

4. Vibration testing shall be suspended or terminated if any observed component degradation threatens safe operation of the ECSS as specified by the manufacturer. Conditions to be monitored are defined in Section 5.7.

5.5 Procedure Steps for Swept Sine Wave Vibration Testing

1. Perform USABC Reference Performance Tests using Procedure 14C. These are itemized in Section 5.2, Step 3.

2. Charge the ECSS, fully, using the manufacturer's recommended charge method.

3. Vertical Axis Vibration (first half at full charge)

   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 2000 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 testing duration of six hours. The profile of G-levels in Table 5.1 shall be used.

4. Discharge the ECSS to approximately a 40% depth of discharge (DOD) at the C/3 rate.

5. Longitudinal Axis Vibration (at 40% DOD)

   a. Mount the ECSS 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 4000 sinusoidal cycles at 3.5 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 test duration of six hours. The profile of G-levels in Table 5.2 shall be used.

6. Lateral Axis Vibration (at 40% DOD)

   a. Mount the ECSS 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 5b and 5c with the test unit mounted in this configuration.

7. Discharge the ECSS to approximately an 80% DOD at the C/3 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 USABC Reference Performance Tests using Procedure 14C. These are itemized in Section 5.2, Step 3.

5.6 Procedure Steps for Random Vibration Testing

1. Perform USABC Reference Performance Tests using Procedure 14C. These are itemized in Section 5.2, Step 3.

2. Charge the ECSS fully, using the manufacturer's recommended charge method.

3. For each of the vertical, longitudinal, and lateral axes of the ECSS, select either the normal or alternative G-levels from Table 5-3 and program the shaker table appropriately. This choice will determine the vibration time required for each axis, also in accordance with Table 5-3. (The vibration spectra, shown in Table 5-4 and Figure 5-1, are expressed in G^2/Hz, so they can be scaled for either set of G-levels.)

4. Mount the test unit so that it will be subjected to vibration along the appropriate axes, based on the manufacturer's recommended physical orientation. 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 (refer to Section 3.4 for other considerations).

5. Perform the programmed vibration for the required times, while ECSS DOD is varied from 0% (full charge) to 80% (minimal charge) over the course of the vibration testing of a given ECSS. Two approaches are permitted to accomplish this:

Table 5-3. Vibration Schedule for Random Vibration Test

Test Conditions		Normal Test			Alternative 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]	1.5	0.09	24.62[1]
Longitudinal spectrum	60	0.4	19.0	73.47[1]	0.75	6.7	31.32[1]
Longitudinal spectrum	60	1.5	0.09	73.56[1]	1.5	0.09	31.41[1]
Longitudinal spectrum	60	0.4	19.0	92.56[1]	0.75	6.7	38.11[1]

[1] These cumulative times apply only if all three axes are done separately.

Table 5-4. 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 (Hz)	Amplitude (G^2/Hz)	Frequency (Hz)	Amplitude (G^2/Hz)	Frequency (Hz)	Amplitude (G^2/Hz)	Frequency (Hz)	Amplitude (G^2/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				

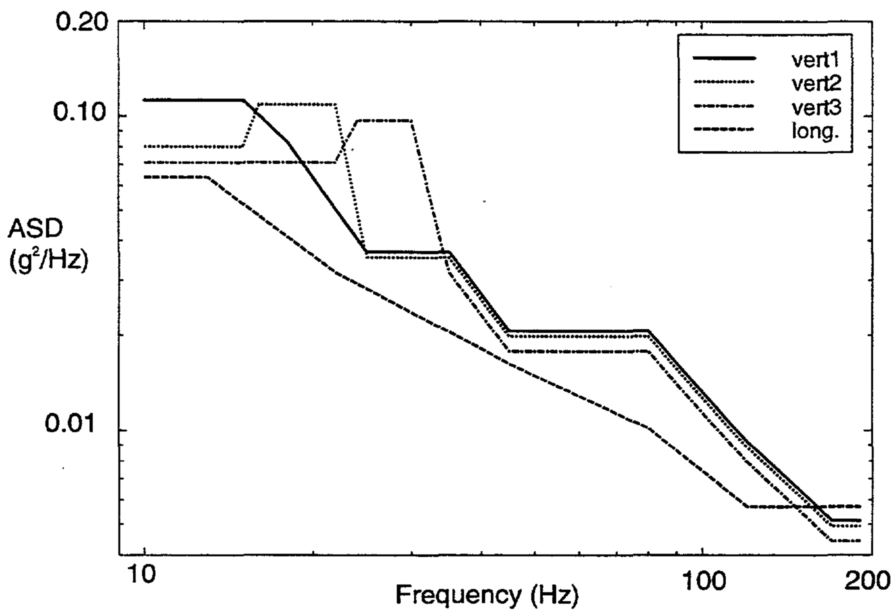

Figure 5-1. Vertical and longitudinal vibration spectra expressed in G^2/Hz.

a. 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.

b. 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 ECSS fully charged, the second interval with the ECSS at 40% DOD, and the third interval at 80% DOD.

6. Between each pair of the (above) three intervals of vibration specified in Section 5.6, Steps 5 and 6, the ECSS should be discharged at a C/3 constant current rate for 40% of the rated capacity of the ECSS. Following the third vibration interval, the ECSS should be fully recharged.

7. Repeat the USABC Reference Performance Tests using Procedure 14C. These are itemized in Section 5.2, Step 3.

5.7 Safety Considerations for Testing

During the application of the vibration regimes, the test unit shall be instrumented to determine the presence of any of the following conditions:

1. Loss of electrical isolation between the ECSS positive connection and the ECSS 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 within the USABC trial criterion of 0.5 MΩ or greater isolation (1.0 mA or less leakage at 500V DC).

2. Abnormal ECSS voltages indicating the presence of open- or short-circuit conditions.

3. Unexpected resonance conditions within the ECSS, indicating failure of mechanical tie-down components.

4. Abnormal temperature conditions indicating possible damage to ECSS cells or thermal management system components.

Detection of any of the conditions listed in Steps 1 through 4 shall cause testing to be suspended 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.

5.8 Data Acquisition and Reporting

1. Data to be acquired during the Reference Performance Tests of Sections 5.5 and 5.6 of this document shall be required for the normal conduct of those tests. Data from these measurements (other than summary results) need not be retained if no anomalous behavior is observed during testing.

2. The general reporting requirements for USABC testing are given in Section 4 of Appendix B, Reporting and Data Acquisition Outline, of the Battery Test Procedure (BTP) Manual.[2]

3. A report shall be prepared detailing 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 ECSS design, installation procedures, or test methods. Also, the pre- and post-vibration electrical performance data confirming the adequacy of the ECSS design to withstand the vibration environments shall be summarized.

6. Recommended Test Sequences

The test sequences simulate both moderate and severe abuse scenarios. The tests in a given test sequence are expected to be run in the stated order with a single electrochemical storage system (ECSS). The tests within a sequence are arranged in order of increasing severity. It is expected that an ECSS will survive each test in the sequence with sufficient integrity so that the ECSS can be used for the next test in the sequence. In some cases the sequence is ordered so that a certain environment will precede another environment. If an ECSS survives a complete sequence and is still functional, it can be used for another sequence, although this is not required.

The tests are categorized by the classification of the test stimulus (mechanical, thermal, electrical) and by the severity of the input.

Level 1 testing is expected to be benign to most systems. The lowest level tests are for relatively common events, and the ECSS is expected to survive essentially intact. The system is expected to be functional after the test, with little or no repair. These tests simulate events which would be encountered by many systems during their lifetimes. This is particularly true for those systems fielded in a transportation setting. The vehicle in which an ECSS is mounted might be damaged, but the ECSS should be salvageable, with little or no repair. It could be reused. The ECSS represents a substantial investment and should not be damaged by relatively common events.

Level 2 tests are more severe, but severity levels are such that some systems may survive with little or no damage. It is expected that some systems will have an adverse response to these inputs. These tests simulate environments for which it is reasonable to assume that a system could be exposed during the system's lifetime, but which are sufficiently severe enough so that the system is not expected to be operational after the exposure. For the more serious, but less common, mid-level events, the ECSS may become inoperable but should not expose humans to known health risks.

Level 3 tests are destructive environments. These tests are for destructive situations where the ECSS is expected to become inoperable. The ECSS cannot reasonably be protected from these events. Generally it would not be prudent to design for these events. While these severe events are relatively rare, credible scenarios exist that lead to these damage levels. Level 3 testing is to be performed to characterize the ECSS response to undesirable conditions or environments associated with carelessness, poorly informed/trained users or mechanics, failure of specific ECSS control and support hardware, or transportation/handling incidents involving the ECSS. These conditions can be expected to be encountered infrequently, but nevertheless represent conditions for which the ECSS was not designed or intended for use. Some of the tests are not applicable to all candidate ECSS technologies. The required number of batteries to be subjected to this phase of testing will depend on actual performance (e.g., a single ECSS may be capable of passing all but the final crush test, whereas for other technologies, as many as three to four batteries may be required). It is acceptable to use a new ECSS for each test.

The purpose of the Level 3 tests is to observe the system response to extreme events and to help quantify the mitigation efforts, that must be taken for a particular ECSS design. The response of the ECSS to these tests can provide useful design information.

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

Several recommended test sequences are listed in Table 6-1. Single tests of Level 3 tests are not listed because they do not result in a sequence of tests. It is expected that a single Level 3 test will result in the loss of the test item. The test sequence is not complete and will be refined in future versions of this manual.

Initial testing most likely will be with a new ECSS, since systems or subsystems which have seen part of their useful life will be unavailable. Future efforts may require an ECSS or subsystem that is well into, or near the end of, its useful life. Permutations of SOC, system age, and temperature should be implemented at the integrator's/developer's discretion based on the most vulnerable condition of the technology.

Table 6-1. Recommended Test Sequences

Test Name	Test Category	Test Level	Min ECSS Level	Seq. 1	Seq. 2	Seq. 3	Seq. 4	Seq. 5	Seq. 6
2.1 - Shock Low	Mechanical	1	Module	A	A	B			
2.1 - Shock M1	Mechanical	2	Module		B				
2.1 - Shock M2	Mechanical	2	Module	B					
2.2 - Drop Test	Mechanical	3	Pack						
2.3 - Penetration	Mechanical	3	Cell			C			
2.4 - Roll-Over	Mechanical	1	Module	C	C				B
2.5 - Immersion	Mechanical	3	Module	D					
2.6 - Crush	Mechanical	3	Cell						C
3.1 - Radiant Heat	Thermal	3	Cell		D			C	
3.2 - Thermal Stability	Thermal	3	Cell						
3.3 - Compromise of Thermal Insulation	Thermal	2	Module				B		
3.4 - Overheat/ Thermal Runaway	Thermal	2	Module						
3.5 - Thermal Shock	Thermal	2	Cell						
3.6 - Elevated-Temperature Storage	Thermal	2	Cell						
3.7 - Extreme-Cold Temperature	Electrical	2	Cell				A		
4.1 - Short Circuit	Electrical	3	Cell				C	B	
4.2 - Partial Short Circuit	Electrical	3	Module						
4.3 - Overcharge	Electrical	2	Cell					A	
4.4 - Overdischarge	Electrical	2	Cell						
4.5 - AC Exposure	Electrical	2	Pack						
5.0 - Vibration	Mechanical	1	Cell			A			A

Min. ECSS Level: Lowest level of assembly recommended for test.

7. References

1. "Emergency Response Planning Guidelines, 1998 ERPG Complete Set," Stock No. 303-EA-98, American Industrial Hygiene Association., Fairfax, Virginia.

2. *USABC Electric Vehicle Battery Test Procedures Manual Revision 2:* Battery Terminology such as definitions of cells, modules and rated capacity can be found in Appendix F.

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