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United States Advanced Battery Consortium Battery Abuse Testing Manual for Electric and Hybrid Vehicle Applications

January 2022

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[January] 2022

Prepared for the
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Abstract

This report describes recommended abuse testing procedures for rechargeable energy storage systems (RESSs) for electric vehicles. This report serves as a revision to the USABC Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications (SAND99-0497).

ACKNOWLEDGMENTS

This test procedure manual was prepared for the United States Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office. It describes the tests used to evaluate the performance of batteries developed for the United States Advanced Battery Consortium under abuse conditions. The specific procedures detailed here support the safety and abuse evaluation of advanced battery devices under development for EV applications.

The DOE United States Advanced Battery Consortium (USABC), Technical Advisory Committee (TAC) supported the development of the manual. The points of contact responsible for the development and revision of this manual are Meng Jiang (General Motors), Renata Arsenault (Ford Motor Company), Ron Elder (Stellantis), Oliver Gross (Stellantis), and Haiyan Croft (DOE).

Previous contributors to this manual include Christopher Orendorff, Leigh Anna Steele, Daniel Doughty, and Chris Crafts, who authored previous abuse testing manuals and provided the foundation upon which this document is based. We also thank Peter Roth for his contributions to this work from his years of testing experience, data generated from that work, and the fundamental understanding of energy storage system failures he developed. Additional technical contributions were also made by Jill Langendorf, Chris Grosso, Lucas Gray, and Scott Spangler.

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NOMENCLATURE

AIHA	American Industrial Hygiene Association
ARC	accelerated rate calorimeter or accelerating rate calorimetry
BOL	beginning of life
CVR	current viewing resistor
DOD	depth of discharge
DOE	Department of Energy
EOL	end of life
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
INL	Idaho National Laboratory
OCV	open circuit voltage
PHEV	plug-in hybrid electric vehicle
RESS	rechargeable energy storage system
SAE	Society of Automotive Engineers
SNL	Sandia National Laboratories
SOC	state of charge
TLV	Threshold Limit Value

1. INTRODUCTION

This document represents a revision to the USABC Electric Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications (SAND 99-0497).[1] This document is intended to provide recommended test procedures and practices. The content in this document is based on empirical testing results and data relevant to the end use.

1.1. Scope

This manual defines abuse tests for rechargeable energy storage systems (RESSs) for electric vehicle applications (EV, PHEV, or HEV) to evaluate the response of RESS technologies to conditions or events that are outside of normal use. Such conditions or events are often referred to as abuse conditions and represent conditions well outside of normal operation and are expected to cause a failure of the cell. The intent of the tests in this manual is to understand abuse tolerance, potential vulnerabilities of an RESS, and the potential severity of battery failure early in the development process. Manufacturers can use this information to design and/or implement the necessary hazard mitigations for a given failure mode. **This manual is not intended to provide acceptance or gating criteria for battery development or to characterize any battery as "safe"or "unsafe."** Additionally, the prescription of specific test plans, step-by-step instructions on executing tests, and pass/fail criteria are outside the scope of this document.

1.2. Safety Basis

Abuse testing may result in energetic destruction of devices under test (DUTs) and should only be undertaken by trained personnel in appropriate facilities. 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 are taken to minimize the safety risk to testing personnel, other co-located workers, facility infrastructure, and environmental impact. Testing organizations should follow local safety basis procedures for analyzing and mitigating hazards associated with RESS testing. Generally, a Fault Tree Analysis (FTA) or Failure Modes and Effects Analysis (FMEA) should be performed by experienced personnel and the hazards identified to allow for proper mitigation.[2,3] The risks could be analyzed using a consequence/severity matrix and should be appropriately mitigated by implementing engineered or administrative controls. An example of a risk matrix table of the Department of Defense Standard Practice for System Safety [4] is shown in

Table 1. The risk matrix is intended to be an example and is not a requirement for performing testing procedures. It is also important to note that definitions of consequence and frequency (likelihood) will be institution specific and are often framed in terms of impacts to people, environment, infrastructure, test platform, monetary loss, authority level required for accepting risk, etc.

Table 1. Risk Matrix Example[4]

RISK ASSESSMENT MATRIX				
SEVERITY / PROBABILITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	High	High	Serious	Medium
Probable (B)	High	High	Serious	Medium
Occasional (C)	High	Serious	Medium	Low
Remote (D)	Serious	Medium	Medium	Low
Improbable (E)	Medium	Medium	Medium	Low
Eliminated (F)	Eliminated			

MIL-STD-882E, Department of Defense Standard Practice: System Safety

General hazard mitigation for RESS abuse testing should be considered for each operation including (1) acceptance of an RESS, (2) test set-up, (3) execution of a test, (4) post-test handling and clean-up based on local industrial hygiene requirements. Appropriate engineering and/or administrative controls to mitigate hazards will depend on the operation, RESS, and the testing facility. Examples of engineering controls may include physical separation of workers from a RESS, robust facility infrastructure, fire protection, local exhaust ventilation (LEV) to dissipate potential toxic gases, external ignition sources to consume flammable gases, and real-time monitoring and analysis. Examples of administrative controls may include approved procedures, training, signage, barriers, checklists, and other operator aids. When direct exposure to battery failure products is a risk, appropriate personal protective equipment (PPE) should be donned, including but not limited to respiratory protection, Tyvek coveralls, gloves, and/or safety glasses.

1.3. Definitions

Active Protection Device	Safety device that consists of a sensor and actuator and is intended for protection from or mitigation of abusive, out-of-range conditions experienced by the DUT.
Ambient Temperature	The ambient temperature may include both climate controlled and uncontrolled or outdoor testing. A reasonable ambient temperature range should be 10-30 °C.

BOL	Beginning of Life. The state of the cell after manufacture but before put into use.
Capacity	The charge measured in amp-hours (Ah) of a RESS from the fully charged (100% SOC) to the fully discharged state (0% SOC) using the discharge profile as specified by the manufacturer.
Cell	An assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components. A cell is a self-contained energy storage device whose function is to deliver electrical energy to an external circuit.
Device Under Test (DUT)	A general term used to describe the RESS device being tested. This term includes all levels of integration of the test article and can refer to a single unit (cell), a multiple unit assembly (module or pack), or a complete system.
ERPG-2	Emergency Response Planning Guidelines (ERPG) levels are defined as the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 h without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. This guideline is taken from the American Industrial Hygiene Association (http://www.aiha.org/Content).
Energetic Failure	Fast release of energy sufficient to cause pressure waves (slower than the speed of sound) and/or projectiles that may cause structural and/or bodily damage, depending on the RESS size. The kinetic energy of flying debris from the RESS may be sufficient to cause damage as well.
Fire or Flame	Ignition and sustained combustion of flammable gas or liquid (approximately more than one second). Sparks are not flames.
Flammable Gas	A gas that burns in air when present in concentrations above the lower flammability limit (LFL) and below the upper flammability limit (UFL).
Fully Charged	The condition reached by a device when it is subjected to the manufacturer's recommended recharge profile. In this

	manual, a device is considered "fully charged" at 100% SOC.
Fully Discharged	The condition reached by a device when it is subjected to the manufacturer's recommended discharge profile. In this manual, a device is typically considered "fully discharged" at 0% SOC.
Integrator	For this manual, the integrator is the vehicle manufacturer or vendor who installs the RESS for use in an EV, PHEV, or HEV.
Leak	Loss of hermeticity of the RESS container leading to slow escape of gas or liquid without actuation of a designed vent.
LFL	Lower flammability limit. A minimum concentration where a flammable gas mixture can ignite in air at a given temperature and pressure.
Module	A grouping of interconnected cells in series and/or parallel arrangement into a single mechanical and electrical unit.
Overcharge	Supplying current to the RESS exceeding the fully charged state (100% SOC) as specified by the manufacturer.
OSHA	Occupational Safety and Health Administration, part of U.S. Department of Labor. See http://www.osha.gov/.
Over Current Protection Device	A fuse, circuit breaker, intelligent contactor, or other devices (e.g., positive thermal coefficient (PTC) or current interrupt device (CID)) placed in an electrical circuit to provide current overload protection.
Overdischarge	Forced discharge beyond the manufacturer's recommended limits that may lead to voltage reversal. See reversal.
Pack	Interconnected modules including all ancillary subsystems for mechanical support, thermal management, electronic components, and control hardware (if included).
Passive Protection Device	Safety device intended for protection from or mitigation of abusive, out-of-range conditions experienced by the RESS that does not require active controls or electrical energy supply (e.g., shutdown separator).

Reversal	Forced discharge (overdischarge) of a RESS to the point that the cell's electrical terminals change polarity.
RESS	Rechargeable Energy Storage System. Any energy storage system that has the capability to be charged and discharged (e.g., batteries, capacitors).
Rupture	Loss of mechanical integrity of the RESS container, resulting in the release of contents. The kinetic energy of the released material is not sufficient to cause physical damage external to the RESS.
State of Charge (SOC)	An estimate of the device charge capability expressed as a percentage of the BOL rated or operating capacity and typically reached by obtaining specified voltages.
Test Article	See ‘Device Under Test.’
Thermal Runaway	The uncontrolled increase in the temperature of a RESS driven by internal exothermic processes.
TLV	Threshold limit value. The concentration of a chemical at which a worker can be exposed day after day without experiencing any acute or chronic health effects. TLV is defined by the American Industrial Hygiene Association (AIHA).
UFL	Upper flammability limit. A maximum concentration where a flammable gas mixture can ignite in air at a given temperature and pressure.
Venting	The release of excessive internal pressure from a RESS cell, module, or pack in a manner intended by design to preclude a rupture or explosion failure.

2. TECHNICAL REQUIREMENTS

2.1. General Test Conditions

The test profiles are divided into three categories: mechanical, thermal, and electrical. 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 (DUT).

Before testing begins, the testing organization, the RESS 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, cell constraint/clamping needs, system age, SOC, temperature, numbers of tests, and numbers of test articles should be implemented at the integrator's or developer's discretion based on the most susceptible condition of the technology and resources available. Recommended test procedures and a preferred number of test articles for each test are provided in Table 2 to help guide this decision.

Appropriate safety precautions should be taken to minimize risk to affected workers, facility infrastructure, and the environment. Refer to Section 1.2. Safety Basis for guidance on appropriate safety precautions.

Table 2. Recommended Tests and Preferred Number of Test Articles

Recommended Test	Number of test articles per level of assembly		
	Cell	Module	Pack
Controlled Crush	3	2	2
Penetration	3	2	2
Thermal Ramp[a]	3	2	
Overcharge	3	2	2
External Short Circuit	3	2	2

[a]Thermal ramp testing at the pack level is not recommended due to practical limitations of the test.

2.1.1. Level of Assembly

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

2.1.2. Single cell size/capacity

When testing at the cell level, the cell size and form factor can significantly impact the final results. Abuse testing of small pouch and cylindrical cells (~1-5 Ah) is useful for comparing the response of emerging battery technologies and evaluating potential safety improvements but should not be used to evaluate the safety performance of high capacity cells intended for xEV applications. In the latter case, relevant cell prototypes should be the preferred option.

2.1.3. System Age

Initial tests of a given RESS design are generally conducted using a RESS at BOL (*i.e.*, one that has not undergone cycle life testing or been extensively used). Because RESS test articles may not be available in large quantities for testing at the early stages of the design process, slightly used test articles are permissible. It may be desirable to perform additional testing that evaluates a RESS or subsystem well into their service life or at the end of life (EOL) to understand how the tolerance to abuse conditions changes with use.

2.1.4. State of Charge (SOC)

Abuse tests for all xEV RESSs (HEV, PHEV, EV) should be conducted at 100% SOC unless noted otherwise. For the purposes of this manual, 100% SOC, or "fully charged" is considered the maximum operating voltage specified by the manufacturer. Testing at other SOCs should note the actual voltage as well as SOC at which the testing is performed. A more complete discussion on voltage limits can be found in Section 3.1.1 of the "United States Advanced Battery Consortium Battery Test Manual for Electric Vehicles."

2.1.5. Temperature

Except where specifically stated otherwise (e.g., elevated temperature abuse tests or when the manufacturer's recommended normal operating temperature is different from ambient temperature), the ambient temperature for any test defined in this document shall be within the range of 10-30 °C (with a tolerance of ±2 °C on the defined ambient value), and the RESS environment shall be stabilized at this temperature prior to the start of testing.

2.1.6. Test Duration

The duration of each test is a trade-off between being short enough to be practical in terms of dedicating resources, data acquisition, and regular working schedules, but long enough to obtain meaningful data and ensure safety activity-level (e.g., set-up, testing, post-test handling, and clean-up). Generally, test procedures include an abuse portion that is several seconds to 2 hours in duration and subsequent monitoring periods at the conclusion of each test, which depend on the type of test and DUT size. The abuse test itself exceeding 4-6 hours in duration is generally considered too long to be practical.

At the completion of an abusive test, post-test monitoring is a best practice that should be done at all test levels (cell, module, and pack) to ensure there is no further immediate reaction of the test article. The duration of the monitoring period can vary based on the test results. In the test procedures, monitoring periods are suggested for each experiment as a guide. Longer duration wait periods (2-48 hours) to reenter a test area may also be necessary based on local procedures or requirements to ensure personnel safety.

2.1.7. Measured Data

All testing results should be documented in a format that allows for comparison of various RESS 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 upon by the RESS manufacturer (and other development principals, when appropriate) before the test begins. Because of the wide variety of test dynamics, it is difficult to specify absolute data acquisition rates. However, for all abuse tests, data collection rates on the order of 1 Hz are recommended as a practical starting place. It is also recommended that the final collection rates are negotiated with customers based on their requirements. The exceptions are for short circuit and mechanical tests. For short circuit tests, kHz data collection is recommended during the initial several seconds (~5-10s) of the test where the load is first applied. For mechanical tests at even moderate travel speeds, (~1mm/s or greater) data collection should be measured at 10 Hz or higher to generate useful force and displacement data.

Recommended measured data may include, but may not be limited to:

Displacement	Level of intrusion/displacement into a RESS measured during a test (applicable to 3.1. Mechanical Abuse Tests only)
Applied Force	Applied mechanical force on a RESS measured during a test (applicable to 3.1. Mechanical Abuse Tests only)
Temperature	The temperature of the RESS to be recorded at several external and internal (where practical) locations as a function of time.
Pressure	Pressure resulting from a RESS measured for the duration of a test (only recommended where practical)
Voltage	RESS voltage measured between the positive and negative terminals measured as a function of time
Resistance	Resistance of the RESS case with respect to the positive and negative terminals measured before and after the test.
Impedance	Electrochemical impedance of the RESS measured as a function of time
Current	Charge/discharge current measured for the duration of the test (applicable only to tests where the DUT is under electrical load)
Video/Audio	Video and audio recorded for the duration of a test including any observation period

Photographs	Still photographs of the test setup and RESS before and after the test
Mass	Mass of the RESS measured before and after the test to determine any mass loss during the test
Dimensions	Physical dimensions of the RESS before and after testing (applicable to Section 3.1. Mechanical Abuse Tests only)
Heat Flux	Heat flux (kW/m^2) from a battery fire resulting from an abuse condition
Gas Analysis	Qualitative and/or quantitative analysis of gas products evolved as a result of an abuse test

Local environmental conditions should also be noted as a best practice including ambient pressure, temperature, humidity, and exhaust rates/air exchanges of the test area. For example, relative humidity can vary significantly with geography which could impact ignition sensitivity and test results. It is important to take note of these conditions to make comparisons to other locations.

Temperature measurement is typically performed using thermocouples on the surface of the battery. These may be damaged or destroyed during a thermal runaway event. The use of multiple thermocouples both provides for some spacial fidelity in temperature measurement and provides redundancy in the event of thermocouple failure. An example of a thermocouple array is provided in Figure 1.

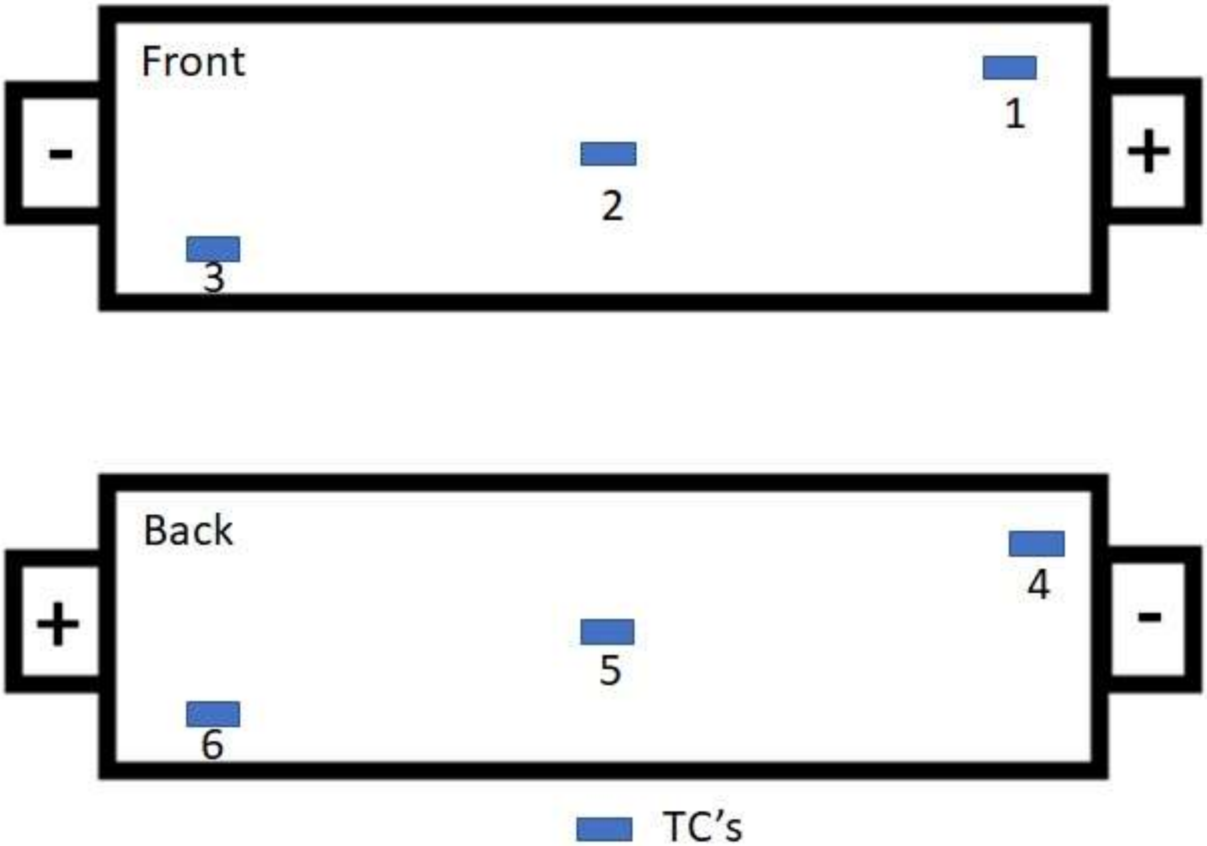

Figure 1 Example thermocouple array on a pouch cell.

2.1.8. Measurement Accuracy

Measured data shall be acquired with accuracy and at adequate rates to ensure that the usefulness of the data is not compromised. In the absence of specific requirements by the test sponsor, the measurement accuracies in Table 3 are acceptable. It is also important to note that the data collection rate shall be at a rate such that errors due to test dynamics will not exceed the required measurement accuracies.

Table 3. Recommended Measurements and Accuracies

Parameter	Accuracy
Temperature (°C)	±2 °C or ±5% of reading
Voltage (V)	±0.1% of reading
Current (A)	±0.1% of reading
Resistance (Ω)	±5% of reading
Displacement (mm)	±10% of reading
Applied Force (N)	±4% of reading
Mass (g)	±0.1% of reading
Heat Flux (W/m^2)	±0.3% of reading
Hazardous substance concentration (ppm)	±5% of ERPG-2 value

Temperature logging is typically performed using thermocouples. The type and temperature limits of thermocouples used shall be noted.

2.1.9. EUCAR Hazard Severity Levels and Descriptions

Abuse response in this manual is scored using the EUCAR hazard severity level scale adapted from SAND2005-3123 and SAE J2464.[1,5] These are provided in Table 4. This EUCAR scale is provided with more guidance to provide users more resolution between hazard severity levels and semi-quantitative guidance on assigning EUCAR ratings.

Table 4. EUCAR Rating

Hazard Severity Level	Description	Classification Criteria for Severity Classification
0	No effect	No effect. No loss of functionality.
1	Reversible loss of function	No defect; no leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Temporary loss of battery functionality . Resetting of protective device needed.
2	Irreversible Defect/Damage	No leakage; no venting, fire or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. RESS irreversibly damaged. Repair needed.
3	Leakage Δ mass <50%	No venting, fire, or flame; no rupture; no explosion. Weight loss < 50% of electrolyte weight. Light smoke. (electrolyte = solvent + salt)
4	Venting Δ mass >50%	No fire or flame; no rupture; no explosion. Weight loss ≥ 50% of electrolyte weight. Heavy smoke. (electrolyte = solvent + salt)
5	Fire or Flame	No rupture; no explosion (i.e., no flying parts).
6	Rupture	No explosion. RESS could disintegrate but slowly without flying parts of high thermal or kinetic energy.
7	Explosion	Explosion (i.e., disintegration of the RESS with externally damaging thermal & kinetic forces). Exposure to toxic substances in excess of OSHA limits.

Manufacturers and integrators may find it useful to consider these levels when evaluating the abuse response of a given RESS design. Since defining pass/fail criteria falls outside the scope of this manual, reporting hazard severity levels using a graded approach at defined measured parameters (e.g., temperature, SOC, force, displacement) is recommended to compare the abuse response of RESS technologies. Examples of hazard severity level reporting at measured parameters are provided in Appendix A: Examples of EUCAR Rating Reporting.

2.2. Hazardous Substance Monitoring

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 required or desired on all tests, especially if the tests are repetitive. 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 American Industrial Hygiene Association's (AIHA) Emergency Response Planning Guidelines – Level 2 (ERPG – 2) recommendations. Other similar standards may be substituted because the concentration levels recommended are for comparison purposes only. However, the intent of the ERPG – 2 chemical quantities are to define short term (1 hr) exposure limits, which is more relevant to a RESS field failure scenario than other long term exposure standards (e.g., AIHA Threshold Limit Value (TLV) for an 8-hour work day). 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 RESS as is practical during the test.

3. RECOMMENDED CORE TEST PROCEDURES

3.1. Mechanical Abuse Tests

3.*1.1. Controlled Crush*

The intent of the controlled crush tests is to determine the abuse response of a RESS to mechanical insult by crushing in two stages. The crush tests are performed at slow speeds under controlled conditions to determine the hazard severity at precise levels of intrusion into the RESS. When testing pouch cells, the cells should be constrained to the greatest extent possible to limit cell expansion. Some strategies are discussed in this section.

3.1.1.1. Cylindrical Cell Crush

Minimum Assembly Level: Cell

Description. DUT is crushed in two stages at a speed of 1mm/min. The first stage is performed to 15% of the primary dimension. The second stage is performed to 50% of the primary dimension or a force limit of 1000x the weight of the DUT.

Table 5. Recommended Impactor Diameter and Cell Size Matrix

Cell diameter (mm)	Impactor diameter (mm)
Up to 32	20
32- 60	30
>60	60

The first stage shall proceed until 15% practical deformation of the cell has occurred. Following a hold of 15 minutes, the crush should continue until one of the following end conditions has been met: (1) the applied force has reached the limit of 1000x the weight of the DUT, or (2) the impactor has reached 50% practical displacement into the DUT. An event of EUCAR 5 or greater at any point will cause significant destruction of the cell and the test may be advanced to post-test monitoring. The DUT should be monitored for at least 30 minutes after the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities. Refer to Section 4. Post-Test Considerations for additional information on post-test activities.

Measured Data. At a minimum, data recorded should include:

- Applied force of the impactor ram on the DUT for the duration of the test
- Displacement of the impactor into the DUT
- Voltage of the DUT
- External temperature of the DUT in multiple locations (if applicable)
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Flammability of vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test

- Mass of the DUT before and after the test
- Dimensions of the DUT before and after the test

Reporting. Reporting hazard severity levels using a graded approach at measured force and displacement values is recommended. Examples are shown in Appendix A: Examples of EUCAR Rating Reporting.

3.1.1.2. Prismatic/Stacked Pouch Cell Crush

Minimum Assembly Level: Cell

Description. The intent of this test is to crush a prismatic or stacked pouch cell in either the y- or z-orientation (y-orientation = into the positive/negative terminals; z-orientation = perpendicular to the terminals) as defined in Figure 2. **Note:** *Crush tests in the x-orientation should be performed following the Module/Pack Crush procedure in Section*

3.1.1.3. *Module/Pack* Crush. DUT is crushed in a robust constraint fixture designed to mechanically support the DUT during the test and to mimic a constrained cell in a module or pack. An example of a cell in a constraint is shown in Figure 3. **Note:** *For tests in the y-orientation (into the terminal), care should be taken to electrically isolate the DUT terminals from the test fixture to prevent a current path to the fixture.* The impactor used for this test shall be made of steel and have a semicircular shape with a rectangular base, as shown in Figure 4. The semicircle radius should scale with the width of the crush surface, as shown in Table 6, similar to the scaling described in Section 3.1.1.1. Cylindrical Cell Crush. The impactor shall have a length and width equal to the DUT length and width and a height sufficiently large to achieve 50% intrusion into the DUT.[10]

Table 6. Recommended Impactor Diameter and Cell Width Matrix

Cell width (mm)[a]	Impactor diameter (mm)
Up to 32	20
32- 60	30
60-150	60
>150[b]	150

[a]width of the surface being crushed into by the impactor
[b]to scale with the pack crush semi-cylinder radius of 75 mm (150 mm diameter)

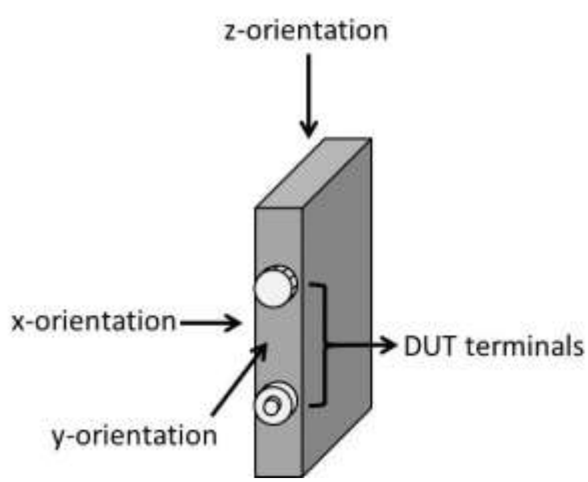

Figure 2. Drawing of a prismatic cell showing the x-, y-, and z-orientations.

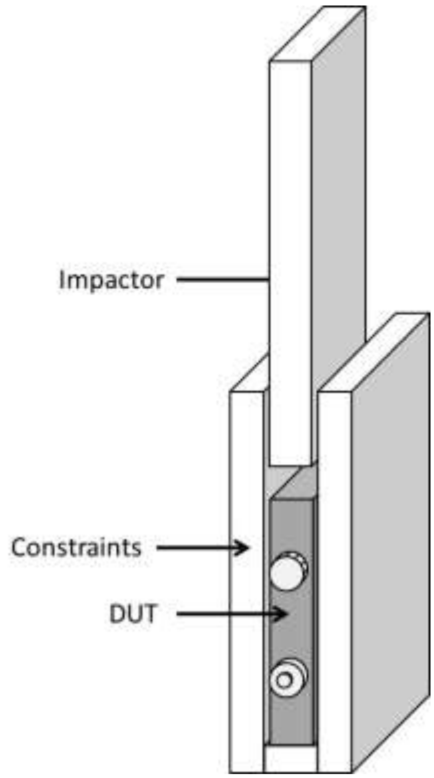

Figure 3. Drawing of a prismatic cell in a constraint fixture to be crushed in the z-orientation.

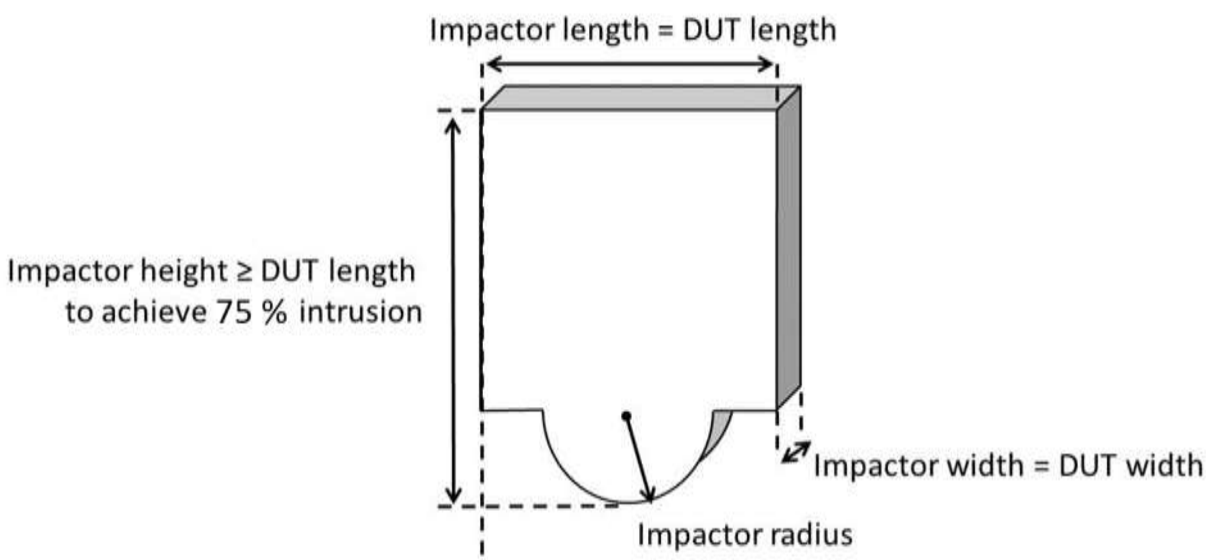

Figure 4. Drawing of the impactor used for controlled crush testing prismatic or pouch cells in the y- and z-orientations.

DUT is crushed continuously at a speed of 1 mm/min using the steel impactor. The first stage shall proceed until 15% practical displacement into the DUT. Following a hold of 15 minutes, the crush should continue until one of the following end conditions has been met: (1) the applied force has reached the limit of 1000x the weight of the DUT, or (2) the impactor has reached 50% practical displacement into the DUT. An event of EUCAR 5 or greater at any point will cause significant destruction of the battery and the test may be advanced to post-test monitoring. The DUT should be monitored for at least 30 minutes after the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities. Refer to Section 4. Post-Test Considerations for additional information on post-test activities.

Measured Data. At a minimum, data recorded should include:

- Applied force of the impactor ram on the DUT for the duration of the test
- Displacement of the impactor into the DUT
- Voltage of the DUT
- External temperature of the DUT in multiple locations (if applicable)
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Flammability of vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test
- Dimensions of the DUT before and after the test

Reporting. Reporting hazard severity levels using a graded approach at measured force and displacement values is recommended. Examples are shown in Appendix A: Examples of EUCAR Rating Reporting.

3.1.1.3. Module/Pack Crush

Minimum Assembly Level: Module

Description. DUT is crushed between a flat and a textured platen. The textured platen shall have a single semi-cylindrical impactor with a 75 mm radius in the center of the platen (see Figure 5). The opposing platen should 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 or coated with a non-conductive material, the possibility of a current path through the textured platen is unavoidable. An example of an appropriate material for the platen is steel. No constraint is specifically defined for module or pack hardware level of assembly.

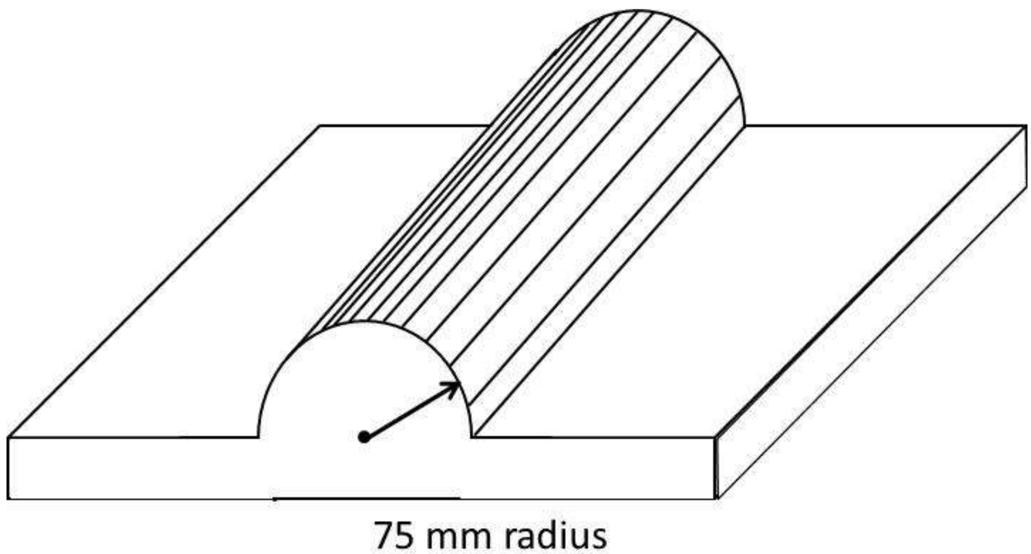

Figure 5. Drawing of the semi-cylindrical impactor plate for module/pack crush testing.

DUTs shall have all integrated control and interconnect circuitry in place and operating (if applicable). Place the textured platen to impact the most vulnerable position on the DUT. DUT is crushed continuously at a speed of 1 mm/min. The first stage shall continue to a practical displacement of 15% into the DUT. Following a hold of 15 minutes, the crush should continue until one of the following end conditions has been met: (1) the applied force has reached the limit of 1000x the weight of the DUT, or (2) the impactor has reached 50% practical displacement into the DUT. An event of EUCAR 5 or greater at any point will cause significant destruction of the battery and the test may be advanced to post-test monitoring. It is important to note that achieving 50% practical displacement ***could require >500 kN of applied force*** depending on construction. Peak applied force should be documented for all tests. ***If available equipment cannot achieve the force to match 50% displacement or 1000x the weight of the DUT the displacement and force at end of condition shall be recorded and noted in reporting.*** The DUT should be monitored for at least 30 minutes after the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities.

Measured Data. At a minimum, data recorded should include:

- Applied force of the impactor ram on the DUT for the duration of the test
- Displacement of the impactor into the DUT
- Voltage of the DUT
- Resistance of the module/pack case to ground (isolation loss)
- Internal and external temperature of the DUT in multiple locations (if applicable)
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Flammability of vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test
- Dimensions of the DUT before and after the test
- Leakage or hazards associated with integrated liquid cooled pack (if applicable)
- Monitoring pack active safety features or actions (e.g. opening contactor relay) (if applicable)

Reporting. Report hazard severity levels at both 15% and 50% is recommended. If a EUCAR 5 or greater event occurs during testing the displacement and force at that point should be reported. ***If available equipment cannot achieve the force to match 50% displacement or 1000x the weight of the DUT the displacement and force at end of condition shall be recorded and noted in reporting.***

3.1.2. Penetration

Minimum Assembly Level: Cell

Description. Penetrate the DUT using a 3 ± 0.2 mm diameter conductive nail that is mechanically robust enough not to deform during the penetration. The electrical nail should be less than or equal to the electrical resistivity of stainless steel (≤ 7.41x10^{-5}

A sharp nail with a 60° tip is used for this test. An example of a typical nail is provided in

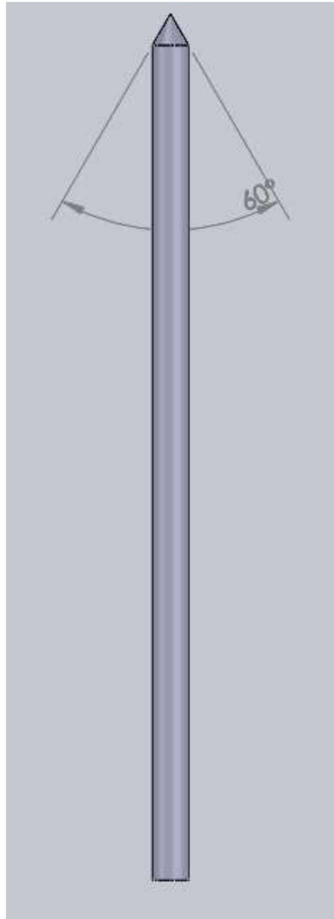

Figure 6. The linear speed of the nail shall be 10 mm/s. Testing is performed at 100% SOC and at ambient temperature. The penetration should continue until one of the following end conditions has been met: (1) complete penetration of the DUT (penetration of the last electrode). An event of EUCAR 5 or greater at any point will cause significant destruction of the cell and the test may be advanced to post-test monitoring. The DUT should be monitored for at least 30 minutes after the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities. If sufficient DUTs are available, pouch cells should be tested under multiple orientations with at least two tests per orientation. When testing pouch cells, the cells should be constrained to the greatest extent possible to limit cell expansion.

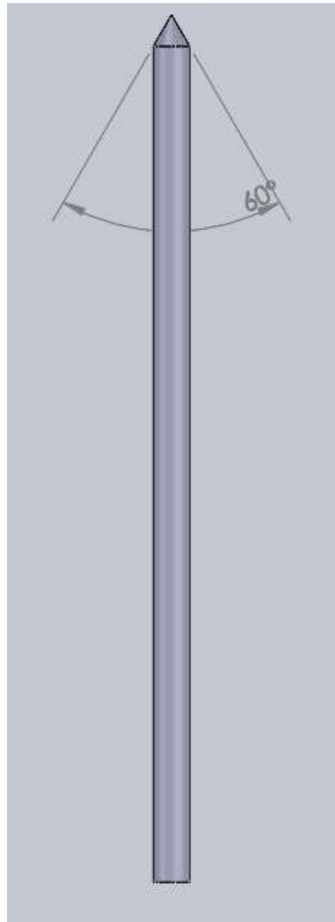

Figure 6 3 mm diameter nail used for the penetration test.

Measured Data. At a minimum, data recorded should include:

- Applied force of the blunt rod on the DUT for the duration of the test
- Displacement of the blunt rod into the DUT
- Voltage of the DUT (recorded at ≥ 10 Hz)
- Internal and external temperature of the DUT in multiple locations (if applicable)
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Flammability of vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test

Reporting. Report EUCAR rating after full penetration of the DUT. If an event occurs when removing the nail, the EUCAR level afterwards should be reported as well. Examples are shown in Appendix A: Examples of EUCAR Rating Reporting.

3.2. Thermal Abuse Tests

3.2.1. Thermal Ramp

Minimum Assembly Level. Cell

Description. The intent of the thermal ramp test is to heat a DUT to the point of failure to quantify the magnitude or consequence of failure. A DUT is instrumented with an appropriate number of thermocouples, wrapped in a layer of insulation, and placed in a heated fixture. Examples of a heated fixture may include a brass block for a cylindrical cell, parallel brass plates for a pouch cell, or heater mats for larger format pouch cells. Starting from the normal operating temperature and a DUT at 100% SOC, the DUT is heated at a nominal, constant heating rate of 2° C/min rate (±0.5 °C/min). If this rate cannot be reliably met, stepped heating in intervals to average ~2° C/min average rate is an acceptable alternative. The end conditions for the test are (1) the DUT temperature reaches 250 °C and is held at 250 °C for 15 minutes. A longer hold time may be necessary when testing at the module assembly level to ensure cells are able to reach the target temperature. An event of EUCAR 5 or greater at any point will cause significant destruction of the cell and the test may be advanced to post-test monitoring. The DUT should be monitored for at least 30 minutes after the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities. If additional test articles are available, tests at lower SOCs should be performed to understand how the DUT failure changes with SOC. DUT operating SOCs should be used as a guide for testing at lower SOCs and will be dependent on final application (HEV, PHEV, or EV). Pouch cells should be physically constrained to the greatest extent possible to limit cell expansion during testing.

Measured Data. At a minimum, data recorded should include:

- Voltage of the DUT
- External temperature of the DUT in multiple locations (if applicable)
- Temperature of the heater fixture
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Flammability of vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test

Reporting. Reporting hazard severity levels using a graded approach at measured DUT temperatures is recommended. The approximate onset of EUCAR rated events and peak event temperatures should be recorded as well. Examples are shown in Appendix A: Examples of EUCAR Rating Reporting.

3.3. Electrical Abuse Tests

3.3.1. Overcharge

Minimum Assembly Level: Cell

Description. Starting with a test article at its normal operating temperature and 100% SOC, the DUT is overcharged at a constant current. A suggested list of charge currents and compliance voltage limits are provided in Table 7. Charge current specifications are tiered based on the rated capacity of the DUT. 1C overcharge is the primary rate for performing overcharge tests and is the preferred option when only one overcharge rate will be performed. When additional tests are possible, secondary rates include 4C and constant power charging of 7.2 kW. 4C charging is intended for cells used in extreme fast charge applications. 7.2 kW is intended for module and pack assemblies and is intended to represent power delivered from a level 2 charging station. Pouch cells should be constrained to the greatest extent possible to limit cell expansion during testing. ***Note:*** *Tiered test conditions are intended to be realistic but not overly aggressive (e.g., an 80 A charge current for a 2 Ah cell is considered overly aggressive). In general, overly aggressive test conditions result in outcomes that are predictable, do not provide value to the cell manufacturer, and are considered outside the scope of this document.*

Table 7. Cell and Module-level Overcharge Test Matrix

DUT capacity	Recommended test point - Charge current (C-rate or A)[a]			Cell voltage limit	Module voltage limit	Pack voltage limit
≤16 Ah	1C	4C		20 V	20 V per cell/parallel group or pack voltage	1.5× pack voltage
16 Ah < C ≤ 40 Ah	1C	4C	7.2 kW[b,8,9]			
>40 Ah	1C	4C	7.2 kW[b,8,9]			

[a]4C rates are primarily intended for cells to be used in extreme fast charge applications, with extreme fast charge defined here as full charge in 15 minutes.
[b]7.2 kW is intended for module and pack assemblies and as a typical power delivered by a level 2 charging station.

The end conditions for the overcharge test are (1) 200% SOC. An event of EUCAR 5 or greater at any point will cause significant destruction of the battery and the test may be advanced to post test monitoring. Charging may continue beyond 200% SOC, if failure of the cell is desired to render it inert for cleanup. If charging is continued, the EUCAR characterization shall be performed based on the state at 200% SOC. The DUT should be monitored for at least 30 minutes at the end of the test. If thermal runaway does not occur, changes to the cell resistance may make discharging of the cell practically impossible. If this occurs additional steps may be needed to establish a zero energy state for the cell. Further charging to 250% SOC or more is often able to destroy the cell and render it inert. In some cases, other abuse tests, including nail penetration or thermal ramp, may be used to destroy the cell and render it inert. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities.

Measured Data. At a minimum, data recorded should include:

- Voltage of the DUT
- External temperature of the DUT in multiple locations (if applicable)
- Charging current applied to the DUT
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test

Reporting. *EUCAR rating should be reported at 200% SOC at minimum and is considered the primary result of this test. A more in-depth analysis can include reporting of EUCAR rating at multiple SOCs*. Examples of this reporting matrix are shown in Appendix A.

3.3.2. External Short Circuit

Minimum Assembly Level: Cell

Description. The intent of the test is to determine the DUT response to external short circuit. Short circuit resistance (load) is defined relative to the DC resistance of the DUT. Pouch cells should be constrained to the greatest extent possible to limit expansion during testing.

Table 8. Cell and Module Short Circuit Resistance Matrix

Short circuit[a]	Short circuit resistance	Standard values for li-ion and other devices with DUT resistance <5 mΩ[b]
Hard short	≈ 1/10-1× DUT DC resistance	1-5 mΩ
Standard short	≈ 5-10× DUT DC resistance	10 mΩ

[a]Recommend performing external short circuit tests under both the hard and medium short conditions
[b]These values are provided as a guideline for technologies with characteristically low device resistance, particularly when testing individual lithium-ion cells.

For DUTs with an internal resistance < 5 mΩ, a practical short circuit load of 10 (±5%) mΩ should be used and documented based on local capabilities. For unknown DUT resistances, a 10 (±5%) mΩ load resistance should be used. Cells with high discharge current capabilities may be within normal operating conditions with a 10 mΩ load, in which case a secondary resistance of 1 mΩ or 1x the DUT resistance can be used to generate additional data. If testing cells with a high DUT resistance (> 10 mΩ) a resistance of 1x the DUT resistance should instead be used as the primary test condition. The short circuit test should reach the intended load level in less than 1 second. The load is then applied for a total of 60 minutes. *Note: The short circuit load includes the contact resistance and the cable resistance.* The end conditions for the test include (1) application of the short circuit load for 60 minutes. An event of EUCAR 5 or greater at any point will cause significant destruction of the battery and the test may be advanced to post test monitoring. **Note:** *At the module or pack level, DUT failures have been observed where the short load has been applied for >120 minutes.* ***Consideration of longer duration short circuit tests at the module/pack level may be appropriate.*** DUT should be monitored for at least 30 minutes at the end of the test. Refer to established local procedures for hazard mitigation upon reentering the test area, rendering the DUT in a safe handling condition, and post-test activities.

Measured Data. At a minimum, data recorded should include:

- Voltage of the DUT (recommended data collection at 1 kHz for at least the first 5 seconds of the applied short, followed by 1 Hz data rate for the remainder)
- External temperature of the DUT in multiple locations (internal at the module/pack level) (if applicable)
- Measured short circuit current (using two separate CVRs) (recommended at 1 kHz during the first 5 seconds of the applied short)
- Chemical analysis of the hazardous substances from vented gas and smoke (if applicable)
- Video/audio for the duration of the test
- Still photographs before and after the test
- Mass of the DUT before and after the test

Reporting. Reporting the EUCAR rating at the end of the test is recommended.

4. POST-TEST CONSIDERATIONS

Post-test processes may include reentering a testing area, physically handling a DUT, and cleaning a testing area. The hazards and mitigations associated with tested DUTs will depend on the chemistry, size, and design of the DUT.

Potential hazards may include:

- Residual stored energy (unanticipated thermal runaway or release of stored energy)
- Heavy loads (depending on physical size of the DUT)
- Electric shock
- Chemical exposure (from electrolyte, active materials, degradation products)
- Toxic gas exposure (from degradation products)
- Exposure to respirable particulates.

Hazard mitigation strategies may include both engineered and administrative controls. Examples of engineered controls to mitigate these hazards include local exhaust ventilation (LEV) to dissipate potential toxic gases, real-time monitoring and analysis, and lock-out tag-out (LOTO) of electrical equipment to prevent electrical exposure. Examples of administrative controls may include approved procedures describing waiting times and/or DUT temperature thresholds to reenter a test area, training (electrical and/or chemical safety, lifting or rigging), signage, barriers, checklists, other operator aids, and personal protective equipment (PPE) including but not limited to respiratory protection, Tyvek coveralls, gloves, and/or safety glasses.

In the testing procedures, recommended post-test monitoring times are included. These are intended to ensure adequate data collection and a minimum amount of time to allow all reactions to be complete. In the procedures, the statement is made to follow any local or established procedures in order to meet any regulatory, institutional, or other facility requirements.

5. REFERENCES

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APPENDIX A: EXAMPLES OF EUCAR RATING REPORTING

Example of EUCAR reporting at the DUT skin temperature during a thermal abuse test:

DUT Skin Temperature (°C)	EUCAR
150	2
175	4
200	4
225	**5**

Example of EUCAR reporting at the DUT %SOC during an overcharge abuse test:

DUT %SOC	EUCAR
160	2
180	2
200[a]	**2**
206	5 (Failure)

[a]For overcharge abuse testing, always report out the hazard severity level at 200% SOC.

Example of EUCAR reporting at the displacement into the DUT and measured force during a mechanical crush abuse test:

Displacement (mm)	Force (kN)	EUCAR
10	2	2
20	10	2
30	50	3
40	**100[a]**	**4**
50	250	5

[a]For mechanical testing of modules and packs, always report out the hazard severity level at 100 kN.

Example of EUCAR reporting at the displacement into the DUT and cell open circuit voltage during a penetration abuse test:

Displacement (mm)	Cell Voltage (V)	EUCAR
10	4.2	2
20	4.2	2
30	4.2	2
40	**0.5**	**5**