RESS Isolation Stress Test

(Procedure and Report)

This excerpt is from the **DRAFT** Test Procedures developed by NHTSA to be shared with GTR

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RESS Isolation Stress Test

Procedure and Report

1. PURPOSE

The automotive application of electric propulsion in Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicles (EV) relies on application of Rechargeable Energy Storage Systems (RESS) commonly referred to as batteries. The automotive application and use of a RESS, such as a Lithium-ion (Li-ion) based battery system, poses certain potential risks to vehicle operators and occupants. These potential risks are different than those associated with internal combustion engine equipped vehicles.

Loss or reduction of isolation (loss of isolation) failures can occur with RESS composed of cells from any chemistry. Loss of isolation failures associated with Li-ion based RESS are of particular concern because at the time of this writing Li-ion cells are being used to make widely adopted high voltage and high capacity RESS, and because loss of isolation failure mechanisms have occasionally caused thermal runaway failures in consumer electronics battery packs as well as in RESS in vehicles.

Typically, RESS are designed to electrically isolate high voltage components, including cells, from the battery enclosure and vehicle chassis (often the enclosure and vehicle chassis are referred to as vehicle ground). This electrical isolation is achieved through the use of various types of electrical insulators, including air, between high voltage components and ground (Figure 1). The performance of insulation will depend upon the material used, material thickness, the clearance between the surfaces at different potentials, and the surface path length between two potentials over the insulator (creepage). Insulation performance can degrade in a variety of ways (Figure 2): insulation can become more conductive due to structural changes (for example solid insulation can become charred), insulation can become polluted with conductive compounds, solid insulation can develop cracks which can become a new creepage path for current, or insulation can become thinned. The creepage performance of an insulator can be deteriorated by the pollution of the creepage path, or reduction of the creepage length. The clearance performance can be degraded by reduction of the clearance distance due to mechanical damage or movement of components, the introduction of foreign materials, or by addition of pollutants such as smoke.

High voltage system isolation loss can occur as the result of gross, obvious failures such as battery pack immersion, or as the result of more subtle mechanisms such as slow liquid ingress, condensation, leakage of cells, venting of cells, or solid debris accumulation within the battery pack due to either ingress of externally formed debris or formation of debris due to RESS damage such as chafing during vibration. Loss of isolation can directly lead to discharge of the RESS, or a pollutant can result in premature aging and degradation of various components within a RESS that ultimately can cause an uncontrolled discharge. One possible failure mechanism involves overheating of internal components as a result of an uncontrolled discharge mechanism. This overheating can lead to damage to insulators that could further degrade isolation, it could ignite components, or it could induce thermal runaway reactions of cells within the RESS (See Section 7.1 for further discussion).

High voltage isolation loss after a damage event to the RESS, failure of a device external to the RESS, or after significant RESS aging is an area of active concern. Many standards at the time of this writing incorporate a method for assessing the result of a low impedance short circuit external to the RESS (See Section 7.2). A fast discharge through a hard short circuit in most RESS architectures would be terminated by fuses or switches. However, even a low current uncontrolled discharge can cause an overheating hazard. Protection devices such as fuses and switches are not typically designed to activate due to these low currents, or may not be installed in the current pathway of the uncontrolled discharge.

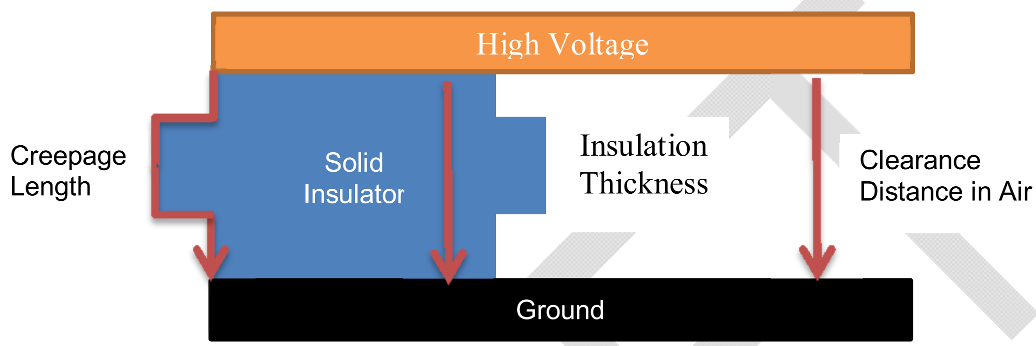

Figure 1 - High voltage insulation.

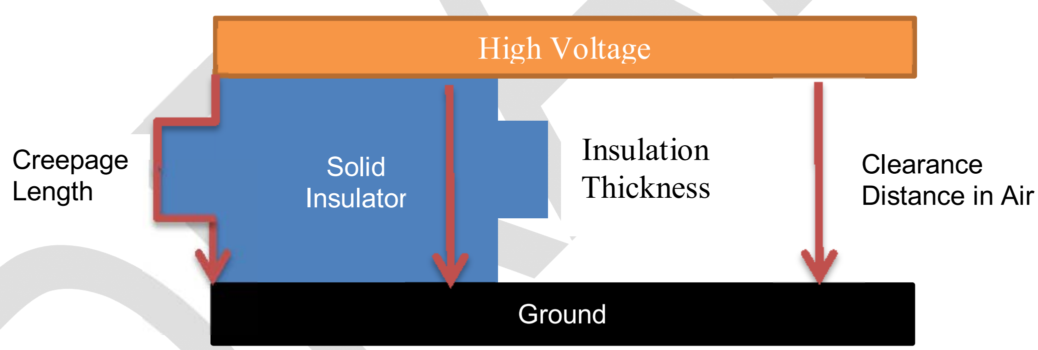

Figure 2 - Examples of deteriorated high voltage insulation: pollution of creepage length, degradation of bulk insulation, reduction of clearance by particulates.

The RESS Isolation Stress (RIS) Test, unlike many standards available at the time of this writing, creates high voltage isolation stress in a RESS that is not likely to result in immediate activation of internal fuses or switches due to high current flow, and might occur as a result of a mechanism that may not provide clear warning properties to a user of a potential problem (for example, extended environmental pollution compared to a single instance of vehicle submersion). The RIS test is intended to allow assessment of the potential hazards to the vehicle occupant or the surrounding environment from a reasonably foreseeable pollutant introduced inside the battery assembly that may cause degradation of isolation

A number of methods were considered for causing degradation of insulation (see Section 7.3 for a detailed discussion). The ideal method would have a high probability of degrading electrical isolation, would be relevant to RESS of many designs, would provide stress throughout the RESS (multi-point), and be somewhat architecture independent, would not directly force high current flows, on its own might provide poor warning properties of a potential problem, and is not well examined in existing standards. Various forms of liquid driven degradation methods were considered; such as liquid ingress, coolant leakage, and condensation. Given that a number of immersion standards already exist, it was difficult to identify a different liquid and method of introduction of that liquid that was relevant to RESS of many designs, and had a high probability of causing degradation of isolation. Introduction of particulates in forms such as solid debris, dust, or smoke was considered. No common form of solid debris appropriate to a wide range of RESS was identified. Road dusts are typically non-conductive and thus not a good candidate pollutant. Smoke application was effective in reducing isolation. Electrolyte vapor from Li-ion cells was also effective in reducing isolation. Cells in a Li-ion based RESS can produce smoke, fine particulates and electrolyte during venting and thermal runaway. The quantity of these potential pollutants and their dispersion method can be defined relative to each specific RESS as those produced during thermal runaway of a single cell within that RESS. Thus, the test methodology will remain appropriate regardless of specific RESS architecture.

2. SCOPE

This test procedure is applicable to all Li-ion RESS-equipped HEV, PHEV and EV vehicles.

This test procedure describes how a reasonably foreseeable pollutant can be introduced into a RESS, and how the effects of that pollutant on internal isolation can be assessed. The pollutant selected for testing is the product of a single cell thermal runaway reaction: electrolyte vapor and possible cell degradation products such as smoke and fine debris. This comprises a complex pollutant that can cause the reduction of isolation at different voltage potentials through a variety of mechanisms such as pollution of insulator surfaces. Two methods of pollutant introduction are described:

a. Application of the Single Cell Thermal Runaway Initiation (SCTRI) method; or

b. Remote introduction of thermal runaway vent gases from a thermal runaway initiation vessel into a RESS.

Two methods for measuring isolation are described: insulation resistance measurements and dielectric withstand test measurements. In addition to these measurements, a stress test is described to allow a more rapid assessment of the effect of reduced internal isolation on the vehicle occupant or the surrounding environment. This stress test is a transient overvoltage test involving the application of a high voltage potential to stimulate latent failure modes such as resistive heating within a RESS.

3. REFERENCES

3.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of the publication shall apply.

3.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA) www.sae.org.

SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology,

"Single Cell Thermal Runaway Initiation Test, Rev 1.0"; April 9 2014; Rechargeable Energy Storage System (RESS) Cooperative Research Program (CRP).

3.2 Related Publications

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

3.2.1 ASTM International

Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959, USA, Tel: 1-877-909-2786, www.astm.org.

ASTM E1352 Test Method for Cigarette Ignition Resistance of Mock-Up Upholstered Furniture Assemblies; or

ASTM E1353 Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture

ASTM E2187, Standard Test Method for Measuring the Ignition Strength of Cigarettes";

3.2.2 CRC Press

Available from the CRC Press 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487, USA, Tel: 800-272-7737, www.crcpress.com.

Hilado, Carlos, J., Flammability Handbook for Plastics 5th edition.

3.2.3 IEC Publications

Available from the International Electrochemical Commission, 446 Main Street

16th Floor, Worcester, MA 01608, Tel: +1 508 755 5663, www.iec.ch.

IEC 60664 Insulation coordination for equipment within low-voltage systems.

IEC 61233 Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications

3.2.4 IEEE Publications

Available from IEEE Standards Activities, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: +1 732 562 5527, www.standards.ieee.org.

IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones

IEEE 1625 Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices

3.2.5 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA) www.sae.org.

SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

SAE J2929Electric and Hybrid Vehicle Propulsion System Safety Standard – Lithium-based Rechargeable Cells

3.2.6 United Nations Publications

Available from UN Economic Commission for Europe, Information Service, Palais des Nations, CH-1211 Geneva 10, Switzerland, Tel: +41-0-22-917-44-44, www.unece.org.

Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, 5th Revised Edition, 2011. ST/SG/AC.10/11/Rev54

3.2.7 Underwriter's Laboratories Publications

Available from Underwriters Laboratories Inc. (UL), 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: +1-847-664-3480, www.ul.com.

UL 840 Standard for Insulation Coordination Including Clearances and Creepage Distances for Electrical Equipment

UL 1642 Standard for Lithium Batteries

UL 1973 Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications

UL 2054 Household and Commercial Batteries

UL 2271 Batteries for Use in Light Electric Vehicle (LEV) Applications

UL 2580 Batteries for Use in Electric Vehicles

4. DEFINITIONS

Except as noted below, all definitions are in accordance with SAE J1715

Ah

Ampere-hour: a measure of battery capacity.

Battery

A device comprising one or more individual electrochemical cells connected in series and/or in parallel or modules packaged together with associated protection electronics and mechanical enclosure

Battery Cell (Cell)

The basic electrochemical unit of a battery, containing an anode and cathode, electrolyte, and typically separator. A cell is a self-contained energy storage and conversion device whose function is to deliver electrical energy to an external circuit. Energy is stored within the cell as chemical energy.

Battery Management System / Unit (BMS / BMU)

Electronic components that monitor and/or control battery functions such as charge and discharge operations.

Battery Module

A group of interconnected cells in a single mechanical and electrical unit that is a subassembly of a full battery

Brick or Block

One or more battery cells connected in parallel. The voltage of a brick or block is the same as an individual cell. Bricks or blocks are commonly connected in series to create a higher voltage battery. Bricks or blocks are sometimes referred to as voltage series elements.

Dielectric Withstand Test

A test in which an increasing voltage is applied between two points, typically without the capacity to provide current beyond what is needed for detection by the test, up to the point where the dielectric between the points fails and current can flow. If air is serving as the resistor, the conclusion of this test would be characterized by a spark between the conductive elements.

Electrical Isolation:

The electrical resistance between the vehicle high-voltage system and any vehicle conductive structure. Internal electrical isolation is measured inside automatic disconnects (if present) and external electrical isolation is measured outside automatic disconnects (if present).

Emergency Response Guide (ERG)

A document describing the hazards that may be encountered during an emergency response operation involving an “article”. OSHA has defined “article” as a manufactured item other than a fluid or particle; (i) which is formed to a specific shape or design during manufacture; (ii) which has end use function(s) dependent in whole or in part upon its shape or design during end use; and (iii) which under normal conditions of use does not release more than very small quantities (e.g. minute or trace amounts) of a hazardous chemical, and does not pose a physical hazard or health risk to employees.

EV: Electric Vehicle

An automobile type vehicle, powered by an electric motor that draws energy solely from a rechargeable energy storage device.

Explosion

Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage.

Fire

The emission of flames from a battery (approximately more than 1s). Sparks are not flames.

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by powered by an electric motor that draws energy from two or more energy storage systems, one of which is a rechargeable energy storage device.

Initiating Cell

The cell intentionally driven into thermal runaway by use of a thermal runaway initiating method.

Insulation Resistance Measurement

The result of an insulation resistance test, typically conducted by an insulation tester, which can apply a range of voltages to a test point and indicate the resistance at that voltage. Typically resistances up to multiple GΩ can be detected at 1000V.

Loss of Isolation

A reduction of electrical isolation from nominal values. Nominal values are typically greater than 100Ω/V.

Lower Flammability Limit (LFL) or Lower Explosive Limit (LEL)

The minimum fuel concentration required to allow flame propagation. LFL and LEL are very similar and are often used interchangeably.

Lithium-Ion (Li-ion)

The term lithium-ion or Li-ion refers to an entire family of battery chemistries where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ion (Li+). Lithium ions move from the anode to the cathode during discharge and are intercalated into (inserted into voids in the crystallographic structure of) or otherwise react with the cathode. The ions reverse direction during charging and are intercalated into the anode material.

Material Safety Data Sheet (MSDS)

A document that contains information on the potential hazards (health, fire, reactivity and environmental) of a chemical product.

PHEV: Plug-in Hybrid Electric Vehicle

A hybrid vehicle with the ability to store and use off-board electrical energy in a rechargeable energy storage device. A range extended EV is a type of PHEV.

Personal Protective Equipment (PPE)

Clothing, helmets, goggles, or other garments or equipment designed to protect the wearer's body from injury.

Pollutant

Any contaminant, solid, liquid, or gaseous (ionized gases), and moisture that may produce a reduction of dielectric strength or surface resistivity.

Rechargeable Energy Storage System (RESS)

The RESS is a completely functional energy storage system consisting of a battery pack(s), necessary ancillary subsystems for physical support and enclosure, thermal management and control, and electronic systems control.

State of Charge (SOC)

The discharge capacity in ampere-hours of a battery expressed as a percent of the battery ampere-hour capacity.

Thermal Runaway

Thermal runaway refers to rapid self-heating of a battery cell derived from the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. It can occur with batteries of almost any chemistry. In a thermal runaway reaction, a cell rapidly releases its stored energy. At the end of a thermal runaway reaction, no electrical energy will be stored within the cell. Note that a measurement of 0V at cell terminals alone is not evidence of thermal runaway. The cell may also have vented electrolyte, undergone a variety of irreversible chemical reactions, or have melted or burned components or activated internal protection mechanisms.

<u>Thermal runaway initiating device</u>

A testing instrument or device designed to induce single cell thermal runaway

<u>Venting</u>

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

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting thermal runaway testing on any cell chemistry is potentially hazardous. Under thermal runaway conditions a cell or battery can emit flammable or toxic vapors, can become very hot, can ignite, can eject corrosive or toxic liquids, or can undergo an energetic disassembly.

5.1.1.1 Prior to conducting thermal runaway testing, the individuals conducting testing should become familiar with the contents of a battery or cell and the related potential hazards, and assemble appropriate personal protective equipment (PPE). A Material Safety Data Sheet (MSDS) or Emergency Response Guide (ERG) may provide relevant information.

5.1.1.2 Testing should be conducted in a well-ventilated environment with provisions to mitigate smoke, flammable vapors, or toxic vapors. Should an air scrubbing system be used, the system filters should be selected to be appropriate to the specific cell chemistry. System filters should be protected from ignition if emitted gas could be heated, if flammable, or if spark emission is to be expected. If testing will be conducted in open air, the testing agency should secure necessary environmental permits.

5.1.1.3 If thermal runaway will be induced within a pressure vessel, the vessel must be constructed to safely contain or vent any overpressures produced by the thermal runaway reaction.

5.1.1.4 If emission of flammable gases is possible, the testing facility should be prepared to mitigate the hazards of an un-intentional ignition. Potential methods of mitigation include flammable gas monitoring, capability to remotely activate appropriate fire suppression systems, high volume vapor dilution systems, and sparker systems.

5.1.1.5 Personnel conducting testing should be equipped with appropriate PPE such as a respirator with appropriate cartridges or Self-Contained Breathing Apparatus (SCBA), eye protection (safety glasses, googles, or face shield), chemical resistant gloves, high voltage resistant gloves, high temperature resistant gloves, and flame or chemical resistant clothing (e.g. Nomex coveralls, turn-out gear, etc.). The testing agency should make a determination regarding appropriate PPE prior to beginning of testing.

5.1.1.6 Personnel conducting testing should be separated from contact with ejected liquids or debris. This may include use of testing chamber, a testing enclosure, or designation of a minimum safe distance to the test article.

5.1.1.7 Personnel should be aware that test components can achieve high temperatures and can pose a burn hazard.

5.1.2 Working with a RESS to harvest components, to prepare it for RIS testing, or to examine it after testing is potentially hazardous.

5.1.2.1 Systems are heavy and must be removed and remounted in vehicles multiple times. Removal after testing may pose additional difficulties.

5.1.2.2 Opening a RESS can expose personnel to high voltages and arc flash hazards.

5.1.2.3 Modifying and working with potentially energized battery pack high voltage elements can expose personnel to high voltages and arc flash hazards. An element that may carry a voltage above 40 V should be considered to be a lethal shock hazard and treated accordingly. All such elements should be probed using an isolated meter before any contact is made with them even while using high voltage gloves. A typical RESS will include multiple points at which the high voltage chain can be safely broken, and allow safe contact with specific points of the high voltage chain. The best practice would be to break the high voltage chain in multiple, physically separated locations before working with or modifying the high voltage elements. A tester should not assume that high voltage elements are safe and should confirm the absence of voltage using an isolated meter before touching the exposed elements.

5.1.2.4 Modifying a RESS can result in damage to cells or in the production of conductive debris within the RESS.

5.1.2.5 Charging single cells or modules within a RESS can pose electrical hazards.

5.1.2.6 Charging a modified RESS prior to RIS testing may pose hazards. The testing agency should ensure that maximum charging voltage and current limits are not exceeded for each series element.

5.1.3 When performing an RIS test on a battery pack installed in a vehicle, the testing agency should be prepared for a full vehicle fire event.

5.1.3.1 Various vehicle systems besides the RESS can be a source of hazard including: fuel systems (such as tanks, pumps, and fuel lines), hydraulic systems, various liquid reservoirs, airbags, pneumatic cylinders, magnesium components, and inflated tires. The testing agency may choose to mitigate the various hazards by removing various vehicle subsystems prior to testing. However, in such an instance, the testing agency will need to determine if removal of any given subsystem will materially affect test outcome.

5.1.3.2 A vehicle fire can produce a significant quantity of smoke. Should an air scrubbing system be used, the system filters should be selected to be appropriate for vehicle burn testing and the specific cell chemistry implemented in the RESS. System filters should be protected from ignition. If testing will be conducted in open air, the testing agency should secure necessary environmental permits.

5.1.4 Thermal runaway initiation can fail, or be delayed due to test variability. Propagation from cell to cell during a test can also occur after a long latency period. It is often difficult for test personnel to visually determine whether a test article is safe to approach once a test has begun. The testing agency should ensure that there is appropriate monitoring of test articles, or a sufficient delay time requirement to allow testing personnel to make a determination regarding when it is appropriate to approach a test article after a test has begun. Monitoring can be accomplished with sensors such as thermocouples, thermal imaging cameras, voltage sensors, gas sensors, and flammable gas detectors.

5.1.5 After testing has concluded, test articles will be damaged and may pose a hazard during test cleanup. For example, cells may be swollen, heat damaged, or burned; conductors may have damaged insulation, enclosures may have been compromised, coolant systems may be leaking. The testing agency should develop a plan for handling and disposing of damaged test articles.

5.2 Test Specific Precautions

5.2.1 If a remote cell initiation box will be used for supplying pollutant to a RESS, test personnel should be aware of hazards associated with cell electrolyte and cell vent gases. The testing agency should develop appropriate methods for cleaning cell initiation boxes after testing, or employ a single use initiation box.

5.2.2 During the use of high voltage DC power supplies, there is a chance of hazardous electrical shock or electrocution and there exists a chance that a produced spark may ignite flammable materials or gases within the battery pack. A safe clearance from the vehicle should be maintained at all times while DC power supplies are in use for testing.

5.2.3 During the use of high voltage DC power supplies, cell thermal runaway reactions may occur within a RESS.

5.3 Safety Requirements

The testing agency must develop a test specific safety plan for each vehicle RIS test, including a list of required PPE for personnel. This safety plan should be based upon information provided by the manufacturer regarding RESS chemistry, and pack architecture as well as precautions typically associated with burn tests, destructive cell testing, and high voltage systems. See discussion in Sections 5.1 and 0.

5.4 Test Facility/ Equipment Requirements

5.4.1 Facility requirements for full scale in-vehicle testing.

5.4.1.1 The facility must be capable of, and permitted for, conducting a full vehicle burn.

5.4.1.2 The facility must have a thermal chamber for pre-test thermal conditioning of the vehicle to a temperature of 25±2°C.

5.4.1.3 The facility must have equipment to move and rotate a non-operational vehicle, including moving a vehicle in and out of the thermal chamber.

5.4.1.4 The facility must have equipment to safely remove a battery pack from the vehicle before and after testing. The battery pack will likely be damaged after testing.

5.4.1.5 The facility must have the ability to safely open the battery pack before and after testing to allow examination and charge or discharge of energized components.

5.4.1.6 The facility must have the ability to discharge/neutralize damaged cells, modules, or a full battery pack. The RESS manufacturer must specify a method to discharge/neutralize for the full scope of different potential states; for example, a salt bath methodology for cells that do not have an easily available electrical connection.

5.4.1.7 The facility must be capable of disposing of or recycling damaged or burned RESS or other byproducts of testing in compliance with environmental regulations.

5.4.2 Equipment requirements for full scale vehicle testing.

5.4.2.1 Personal Protective Equipment such as respirators, safety glasses, and high voltage gloves. See discussion 5.3 above.

5.4.2.2 Thermal runaway initiation equipment. See SCTRI Procedure for additional details.

5.4.2.3 If pollutant will be introduced from a remote cell thermal runaway reaction, a thermal runaway initiation vessel will be required, with appropriate gas flow connections to introduce pollutant to the RESS.

5.4.2.4 Sensors and Data Acquisition Equipment:

Thermocouple DAQ (recommend channel-to-channel isolation) capable of a data collection rate of at least 1 Hz
Thermocouple wire (recommend K-type with fiberglass insulation)
Thermocouple bead welder (optional – pre-made K-type thermocouples can be purchased)
Stopwatch with accuracy of ±1 second
Smoke detector with a photoelectric sensor (opacity based detection)
Gas sensor (optional)
Handheld voltage and insulation resistance meter
Hipot tester
Power supply capable of providing approximately 1000V and 0.2A (maximum pack voltage plus 353 V)
Video cameras (3 minimum)

5.4.3 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the facility requirements for conducting single cell testing can be found in the Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP

5.4.4 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the requirements for conducting single cell testing can be found in the Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP

5.5 Test Equipment Calibration

A written calibration procedure shall be provided which includes as a minimum the following information for all measurement and test equipment:

1. Type of equipment, manufacturer, model number, etc.
2. Measurement range
3. Accuracy
4. Calibration interval
5. Type of standard used to calibrate the equipment (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 The RESS Isolation Stress (RIS) test is a destructive full scale in-vehicle test where generated pollutants from initiation of thermal runaway in a single cell either within the RESS or adjacent to the RESS are driven into the RESS. The RESS electrical system (cells, printed circuit boards, cables, harness components, busbars, insulators, etc.) are monitored for losses of isolation resistance or any other adverse reactions. The vehicle cabin and the vehicle surroundings are monitored to determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment.

6.1.2 The RIS test may be conducted in conjunction with SCTRI testing.

6.1.3 In preparation for full-scale-vehicle testing, destructive testing of an individual cell may be required to define and validate an appropriate device to induce a thermal runway reaction of a single cell. An extensive discussion of methods for single cell thermal runaway initiation is provided in the Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP. If single cell thermal runaway initiation will be conducted remotely, considerations related to RESS architecture such as neighbor cell heating and venting direction accuracy may be relaxed.

6.2 Device Under Test

6.2.1 The device under test (DUT) will be a full vehicle with an RESS that has been modified to either intentionally initiate a single cell thermal runaway reaction within the RESS, or to admit vent gases and particulates from an adjacent single cell thermal runaway reaction. The vehicle will be instrumented to measure the result of any subsequent loss of isolation within the RESS.

6.2.2 RIS testing may be conducted using the test article used for SCTRI testing. See Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP.

6.2.3 Prior to full scale testing, additional testing may be required to determine an appropriate methodology for initiating a single cell thermal runaway reaction within the RESS or initiating thermal runaway in a cell adjacent to a RESS and ducting vent gases along with any particulates to an appropriate location within the RESS. This may require testing with a RESS, or cells or modules harvested from a RESS.

6.2.4 Methods and considerations for initiating single cell thermal runaway reactions are discussed in detail in the Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP. If single cell thermal runaway initiation will be conducted remotely, considerations related to RESS architecture such as neighbor cell heating and venting direction accuracy may be relaxed.

6.3 Test Guidelines

6.3.1 This test procedure describes how an appropriate pollutant can be introduced into a RESS, and how the effects of that pollutant on internal isolation can be assessed. The pollutant selected is the product of a cell thermal runaway reaction: electrolyte vapor and possible degradation products such as smoke. Section 7.3 discusses the selection of this pollutant mechanism. Two methods of pollutant introduction are described:

a. Application of the Single Cell Thermal Runaway Initiation (SCTRI) method; or

b. Remote introduction of thermal runaway vent gases into a RESS.

6.3.2 Testing will require one vehicle with its RESS. The vehicle and RESS should be new: less than one year old, with less than five charge discharge cycles applied to the RESS. The RESS may be provided by the Manufacturer or vehicle OEM with the necessary modifications for conducting RIS testing. If the testing agency must modify the RESS for testing, then additional RESS components may be required, for example enclosure components (See Section 8 in the Single Cell Thermal Runaway Initiation Rev 1.0 Test Procedure Document submitted as a part of the RESS CRP for an example).

6.3.3 Testing may require additional cells. These can be provided by the RESS Manufacturer or the vehicle OEM. Alternatively they can be harvested from a second RESS. If they are provided from the RESS Manufacturer or Vehicle OEM they should be of the same type and the same approximate age (within one year) as the ones in the RESS to be tested.

6.4 Test Parameters

RESS Cell Beginning Test Temperature	Either as found within 12 hours of completion of SCTRI test, or, if conducting test with adjacent cell initiation method, then 25 ± 5°C
Beginning Pack Preconditioning state	Cells less than 1 year old Cells accumulated less than 5 electrical cycles
Beginning SOC of RESS and initiation cell	99% to 100% of the maximum operating SOC
Beginning energy of vehicle	Fully charged RESS; full fuel tank (HEV, PHEV)[1]

6.5 DUT Pre Conditioning

6.5.1 All RESS and cells used for testing should be as new and uncycled as practical: they should be less than one year old and have accumulated less than 5 charge discharge cycles prior to testing. See Section 7.7 for discussion.

6.5.2 Full vehicle and RESS conditioning occurs during preparation for testing. The temperature pre-conditioning requirements are described in Section 6.6.2.24. For adjacent single cell thermal runaway initiation, the cell should be at a temperature of 25 ± 5°C prior to test initiation.

6.6 Test Methodology

6.6.1 When RIS testing will be conducted in conjunction with SCTRI testing, follow the SCTRI Procedure with the following additions:

6.6.1.1 A dielectric withstand test (Section 6.8.2) shall be conducted on the RESS before experimental equipment is added to the RESS (Section 6.6.3.6 in SCTRI Procedure). See Section 7.4.2 for a discussion of dielectric withstand testing.

6.6.1.2 A connection shall be installed that allows both positive and negative battery terminals to be electrically accessible from outside the RESS for purposes of measuring RESS voltage and internal electrical isolation, and for applying the transient overvoltage stress test. This connection shall have adequate insulation to avoid affecting isolation measurements (Section 6.6.3.11 in SCTRI Procedure). See Section 7.5 for additional discussion of installation of loss of isolation testing and monitoring leads.

6.6.1.3 An insulation resistance measurement (Section 6.8.1) and a dielectric withstand test (Section 6.8.2) shall be conducted on the RESS after a pack is closed prior to installation on the vehicle (Section 6.6.3.13 in in SCTRI Procedure).

[1] See Section 0

6.6.1.4 An insulation resistance measurement and a dielectric withstand test shall be conducted on the RESS after the RESS is installed on the vehicle (Section 6.6.4.9 in in SCTRI Procedure).

6.6.1.5 Isolation Stress testing should be conducted after the SCTRI test has completed (Section 6.6.6.10 of the SCTRI Procedure); and within 12 hours of the end of the SCTRI test.

6.6.1.6 Measure voltage of the RESS from positive to negative terminal using the installed loss of isolation testing and monitoring leads.

6.6.1.7 Conduct an insulation resistance test both between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.1.8 The vehicle or RESS shall not report an isolation value greater than 100 Ohm/V if the previous insulation resistance test measured less than 100 Ohm/V.

6.6.1.9 Conduct a dielectric withstand test between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.1.10 Conduct a transient overvoltage stress test (Section 6.8.3).

6.6.1.11 Conduct an insulation resistance test both between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.1.12 Conduct a dielectric withstand test between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.1.13 Testing is complete when 4 hours have elapsed and

a. Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,

b. If, thermocouple readings are not available, then if not visible follow-up reaction has occurred after 8 hours or,

c. If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

6.6.1.14 The vehicle shall be photographed after the completion of testing.

6.6.1.15 The RESS should be separated from the vehicle, opened and visually examined. Note the location of smoke deposition, particulate deposition, and any evidence of charring. Determine how to best dispose of the battery pack.

6.6.2 When RIS testing will be conducted independently of the SCTRI testing, the following procedure shall be followed:

6.6.2.1 A single cell thermal runaway initiation method must be selected. Follow SCTRI Procedure Section 6.6.1 with the exception that since a single cell will be initiated external to the RESS, considerations of cell neighbor heating and the effect of interaction between an initiation process and module or RESS architecture may be neglected.

6.6.2.2 A single cell thermal runaway initiation vessel shall be selected or fabricated (Figure 3).

The initiation vessel shall be a pressure vessel sufficiently robust to safely contain vent gases from thermal runaway of a single cell of the type found in the RESS. The vessel and connection to the RESS shall be sealed so as to minimize the leakage of runaway vent gas and particulate and instead duct as much as possible into the RESS.

The vessel shall include a temperature sensor that can be used to determine when temperatures within the vessel have reached a peak.

The vessel shall be connected to the RESS by a tube or duct that has a length to width or diameter ration of 3:1 or less. The cross sectional area of the duct should be no smaller than 4 cm2.

Any electrical leads required to run the initiation vessel should be sufficiently long to allow test personnel to work with the device at a safe distance from the vehicle.

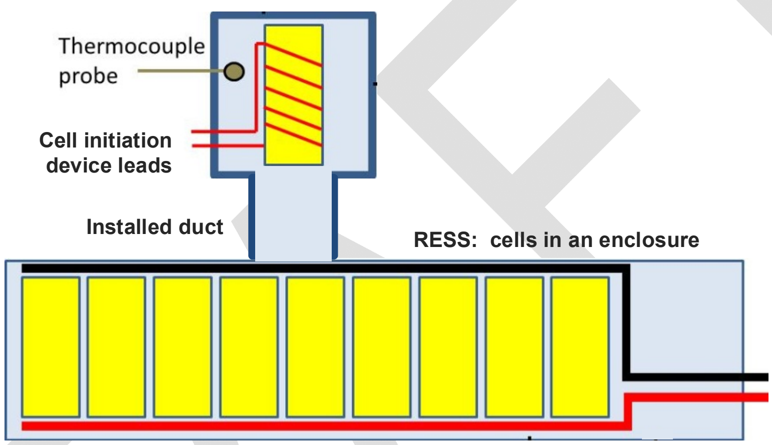

Figure 3 - Schematic of A single cell thermal runaway initiation vessel connected to a RESS.

6.6.2.3 A location shall be selected for vent gas introduction. The location should be the most likely to result in a loss of isolation per the test agency's engineering judgment or results of previous testing. The location should also be in a compartment that contains battery cells and not a separate sealed or partially sealed compartment for electronics or other non-cell components. The testing agency shall report the reasons for their selection of vent gas introduction location, which can include evidence of physical tests.

6.6.2.4 The vehicle shall be photographed in its as-received condition. Any anomalies should be noted.

6.6.2.5 The Vehicle RESS shall be removed from the vehicle and prepared for testing.

6.6.2.6 The battery pack must be charged for testing to the maximum allowable state of charge. This can be accomplished either before or after battery pack opening and/or other preparation activities occur. The testing agency should determine when charging should occur based on pack architecture, hazards associated with working with a fully charged vs discharged battery pack, and estimated pack self-discharge between the time of preparation and the time of testing. A drop of 1% of capacity due to self-discharge of the battery before the test is accomplished is acceptable.

6.6.2.7 It may be most convenient to charge the battery pack with an approved vehicle system as it is installed in a vehicle, and then remove the battery pack to further prepare it for RIS testing prior to re-installing it in a vehicle. However, in some instances, the testing agency may choose to charge the battery pack after other preparation activities occur.

6.6.2.8 Once charging has occurred, and also immediately prior to closing the battery pack, record the voltage of the battery pack.

6.6.2.9 The RESS shall be photographed in its as-received state. Any anomalies to the pack enclosure shall be noted.

6.6.2.10 If the battery pack must be opened to install any experimental equipment, it shall be photographed after opening and prior to the installation of any experimental equipment.

6.6.2.11 If the battery pack must be opened to install any experimental equipment, an internal insulation resistance measurement (Section 6.8.1) should be performed prior to the installation of any experimental equipment. The battery terminals inside the contactors must be accessed, likely by removing the pack cover. Insulation resistance should then be measured between the battery negative terminal and the battery enclosure using an insulation resistance meter. A dielectric withstand test (Section 6.8.2) shall be conducted between the negative terminal and the enclosure.

6.6.2.12 High-temperature insulation for any electrical leads to the initiating device should be used to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of this experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment.

6.6.2.13 Instrumentation shall be installed to detect introduction of cell vent gases and a thermal runaway reaction within the RESS. At a minimum, one sensor should be installed in the battery near the vent gas introduction location. High-temperature insulation for any electrical leads to sensors should be used to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of this experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment. Any connectors to sensors should be sufficiently long to allow a data acquisition system to be located sufficiently far from a vehicle undergoing a complete burn to remain intact.

6.6.2.14 A connection shall be installed that allows both positive and negative battery terminals to be electrically accessible from outside the pack for purposes of measuring pack voltage, measuring internal electrical isolation, and applying the potential for the transient overvoltage stress test (Section 7.5). This connection shall have adequate insulation to avoid affecting isolation measurements. All modifications to within the RESS shall be documented with photographs and appropriate notes: the location of the thermal runaway initiation hardware and all sensors shall be recorded.

6.6.2.15 The RESS shall be closed according to the manufacturer's specifications. Replacing a cover may require additional or replacement materials such as sealants or gaskets. The exterior of the RESS shall be photographed. An insulation resistance measurement and a dielectric withstand test shall be conducted on the RESS after a pack is closed prior to installation on the vehicle.

6.6.2.16 Vehicle components that represent an additional hazard during testing such as airbags, trapped air cylinders, inflated tires, and tanks of flammable liquids may be removed from the vehicle or otherwise disabled if the testing agency can determine their presence or actuation is unlikely to significantly affect the outcome of the test. Components immediately adjacent to the RESS that could be affected by heat or gas emission from the RESS should remain in place on the vehicle. Removal of any components should be documented with notes and photographs.

6.6.2.17 A standard opacity-based smoke alarm shall be installed at the center of the vehicle dashboard. Additional gas sensors or gas sampling equipment may be installed in the vehicle cabin at the discretion of the testing agency. Location of all sensors shall be documented.

6.6.2.18 At least one temperature sensor shall be installed within the vehicle cabin. This sensor shall be at the approximate location of a driver's head. Additional temperature sensors may be installed, for example at locations within the cabin adjacent to the RESS. Location of all sensors shall be documented.

6.6.2.19 The vehicle cabin shall be physically isolated during testing: doors and windows shall be closed and sealed (with provision for experimental equipment leads to exit the vehicle cabin). The vehicle cabin heating, ventilation and air conditioning (HVAC) system shall remain off.

6.6.2.20 The instrumented RESS shall be re-installed in the test vehicle.

6.6.2.21 Battery pack voltage or SOC shall be measured and recorded.

6.6.2.22 An insulation resistance measurement and a dielectric withstand test shall be conducted on the RESS after the RESS is installed on the vehicle. Isolation values should be compared to "as-received" values. If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed, and the cause of the loss of isolation should be found and if possible, eliminated.

6.6.2.23 The vehicle as prepared for testing shall be photographed.

6.6.2.24 The vehicle and RESS as instrumented for testing can be brought to test temperatures by placing the vehicle with installed RESS into a temperature control chamber held at 25±2°C. The vehicle should be held in the chamber for sufficient time to equalize to test temperature, at least 12 hours. Thermal runaway initiation should begin within 30 minutes of removal of the vehicle from thermal conditioning. The RESS temperature at the beginning of thermal runaway initiation shall be 25±5°C as measured by sensors installed within the RESS (Section 6.6.2.13)

6.6.2.25 The vehicle shall be placed in a location suitable for RIS testing (see Section 5.4).

6.6.2.26 A minimum of three video cameras shall be located around the vehicle to record emission of smoke from the vehicle, any sounds associated with cell thermal runaway, and activation of the vehicle interior smoke detector.

6.6.2.27 Cameras should be located at a sufficiently safe distance from the vehicle to allow test personnel to approach them and change recording media (tapes) if necessary during testing, assuming that thermal runaway propagation occurs.

6.6.2.28 Temperature measurement logging devices shall be configured to collect at least one measurement per second.

6.6.2.29 Any connectors to sensors should be sufficiently long to allow a data acquisition system to be located sufficiently far from a vehicle undergoing a complete burn to remain intact. Data acquisition equipment may be protected from heat using shielding or insulation.

6.6.2.30 All sensors shall be connected to data logging systems, and checked to ensure proper reading and configuration.

6.6.2.31 The initiation of temperature logging and video recording should be synchronized: for example all systems should be started within 30 seconds of each other. At least five stable temperature measurements should be recorded per temperature logging channel prior to proceeding with thermal runaway initiation.

6.6.2.32 The single cell thermal runaway initiating device shall be activated and the test monitored closely for any indication that thermal runaway has occurred (sound, smoke, temperature measurements). Once the occurrence of a single cell thermal runaway has been confirmed, the thermal runaway initiating device shall be de-energized.

The testing agency shall have determined an expected time to thermal runaway during single cell testing (See Section 8 of the SCTRI Procedure). If there is no indication of single cell thermal runaway within twice the expected time, then the testing agency shall abort the test and determine the cause of the experimental failure. Personnel shall be aware that a cell within the initiation vessel may have been damaged and could be susceptible to thermal runaway during system examination. They shall conduct the examination in an appropriate location using appropriate tools and PPE.

6.6.2.33 Isolation testing shall be conducted between 30 and 60 minutes after introduction of the pollutant gas.

6.6.2.34 Measure voltage of the RESS from positive to negative terminal using the installed loss of isolation testing and monitoring leads.

6.6.2.35 Measure insulation resistance between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.2.36 The vehicle or RESS shall not report[2] an isolation value greater than 100 Ohm/V if the previous insulation resistance test measured less than 100 Ohm/V.

6.6.2.37 Conduct a dielectric withstand test between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.2.38 Conduct a transient overvoltage stress test (Section 6.8.3).

[2] This is a judgment regarding accuracy of a vehicle system measurement rather than a judgment based on isolation value.

6.6.2.39 Conduct an insulation resistance test both between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.2.40 Conduct a dielectric withstand test between the negative battery terminal and vehicle ground and a second test between the positive terminal and vehicle ground.

6.6.2.41 Testing is complete when 4 hours have elapsed and:

d. Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,

e. If, thermocouple readings are not available, then if not visible follow-up reaction has occurred after 4 hours or,

f. If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

6.6.2.42 The vehicle shall be photographed.

6.6.2.43 Conduct an insulation resistance test.

6.6.2.44 Attempt to communicate with the RESS. If communication is possible, record the reported internal isolation resistance.

6.6.2.45 The RESS should be separated from the vehicle, opened and visually examined. Note the location of smoke deposition, particulate deposition, and any evidence of charring. Determine how to best dispose of the battery pack.

6.7 Measured Data

6.7.1 Full Scale Vehicle RIS test reports shall include the following information:

a. Details of the single cell thermal runaway initiation method, including justification of the selection method.

b. Location of the single cell thermal runaway initiation method, including justification for the selected location. Note if thermal runaway was initiated within the RESS or remotely.

c. If thermal runaway is initiated remotely, note the location of vent gas and particulate introduction, and justification for the selected location.

d. Locations of all installed sensors.

e. Evidence that instrumentation has not significantly affected RESS internal isolation.

f. Results of all voltage, isolation resistance, dielectric withstand, and transient overvoltage stress tests.

g. Video of the test from several angles, at least three.

h. Time that the first thermal runaway occurred.

i. Evidence that the first runaway occurred, visually, audibly, or thermally.

j. Times of any subsequent runaways, vehicle events, ignition, smoke alarm activation. Use t=0 as the time when the initiating device was activated.

k. Temperature data and gas sensor data if measured.

l. Photographs of the battery pack after testing has completed.

6.8 Inspection Method

6.8.1 Insulation resistance test method: measure insulation resistance between vehicle ground and the positive and negative terminals at 1000V. See Section 7.4.1 for additional discussion.

6.8.2 Dielectric withstand test method: Apply a dielectric withstand test between vehicle ground and at least one terminal of the RESS using a Hipot tester. Increase applied voltage linearly over 3 seconds to maximum normal RESS voltage (U) plus 1695VDC, hold for 5 seconds, and ramp linearly back to 0V. This is a typical Hipot test protocol. See Section 7.4.2 for additional discussion.

6.8.3 Transient overvoltage stress test method: Connect a DC power supply with a current limit set to 200mA between the battery enclosure and the negative terminal (positive terminal of power supply to negative terminal of battery). Increase the voltage over 5 minutes to 353VDC and maintain that voltage for 1 hour. If the current limit is reached during the voltage ramp, set the voltage limit to 353VDC. Subsequently over 5 minutes decrease the voltage to 0V. See Section 7.4.3 for additional discussion.

6.9 Post-Test Requirements

6.9.1 After full vehicle RIS testing, the vehicle and RESS should be disposed of or recycled in accordance with environmental regulations.

6.9.2 Destructive discharge of portions of the RESS may be required to allow safe disposal. The testing agency should refer to manufacturer specified destructive discharge instructions.

6.10 Acceptance Criteria

The purpose of RIS testing is to assess the potential hazards of a loss of isolation to the vehicle's occupant or the surrounding environment. Acceptance criteria are thus divided into two categories: hazard to the occupant, and hazard to the surrounding environment.

6.10.1 Occupant Hazards

The vehicle or RESS shall not report[3] or indicate an isolation value greater than 500 Ohm/V if the previous insulation resistance test measured less than 500 Ohm/V.

The vehicle cabin must remain tenable except for the presence of gases directly associated with injection of the pollutant[4] until after completion of testing. See Section 7.10 of the SCTRI Procedure for further discussion of cabin tenability.

6.10.1.1 The cabin temperature must remain tenable, assuming vehicle windows are closed, and HVAC system is not operating.

6.10.1.2 The cabin air must remain free of significant inhalation hazards assuming vehicle windows are closed and the vehicle HVAC system is not operating.

6.10.2 Hazards to the Surrounding Environment

The vehicle shall not pose an ignition or mechanical hazard to the surrounding environment.

6.10.2.1 The vehicle shall not ignite as a result of RIS testing.

6.10.2.2 Vent gases emitted by the vehicle as a result of RIS testing shall not ignite.

6.10.2.3 There shall be no explosion as a result of RIS testing.

7. TEST PROCEDURE RATIONALE

7.1 Significance of a Loss of Internal Isolation

For any energy storage system, specific pathways for current flow and any resulting dissipation are designed into the system. For example, in a RESS, current conductors are selected to allow rated current flows without damage due to dissipation (heating), and are protected from excessive current flows with devices such as fuses (Figure 4). In the case of a loss of isolation, new pathways are formed for which current magnitude and duration may not be controlled. Short term overheating and arcing could occur or it may require some time for a loss of isolation failure to develop into a hazardous condition. Besides the case of an external short circuit, some additional scenarios should be considered including: a single point loss of isolation and various multi-point loss of isolation cases.

[3] This is a judgment regarding accuracy of a vehicle system measurement rather than a judgment based on isolation value.
[4] Depending upon RESS architecture, injection of a pollutant to the RESS may result in transmission of the pollutant to the vehicle cabin (for example with RESS architectures that share cabin air). In those instances, the effect of the initial pollutant should be subtracted from the assessment of cabin tenability.

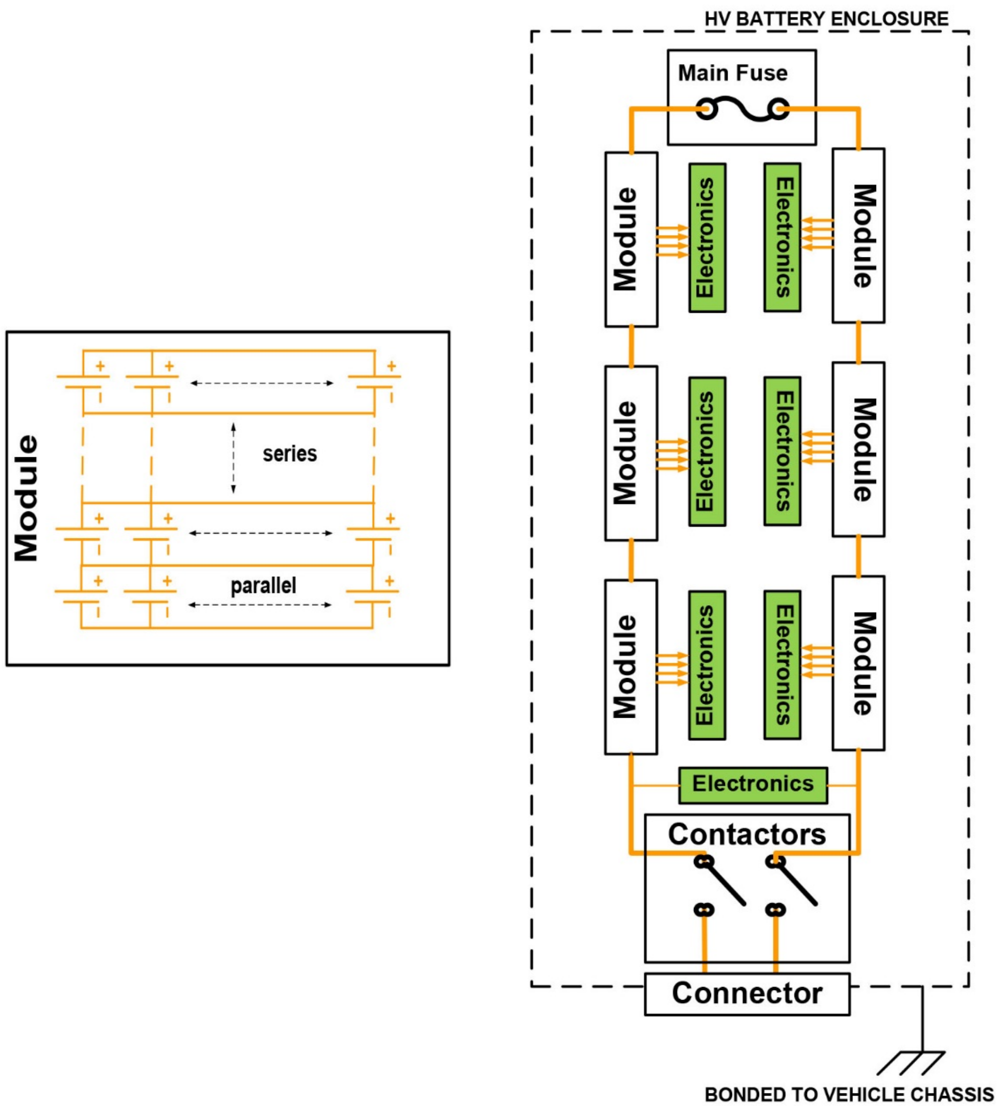

Figure 4 - Schematic of a nominal RESS: cells connected in series and parallel to form modules, modules connected in series with fuses and contactors; electronics connected to modules as well as the overall series string

For a RESS, external short circuit testing is intended to ensure that intended current flow pathways are sufficiently robust or well protected to prevent a dangerous condition (either overheating or arcing) under foreseeable abnormal current flows. For an external short circuit test, a connection is made between the battery terminals, external to the high voltage enclosure of the RESS (Figure 5). Typically, this procedure will test whether the intentional current flow pathways (current conductors, fuses, contactors) are appropriate for maximum expected current flow rates and associated durations. Heating rates of internal components such as cables and modules will be much higher than typical. However, due to the activation of fuses or similar components, current flow should be rapidly interrupted, and typically limited to times on the order of 1-100msec. Thus, components internal to the RESS (with the exception of activated fuses) should not be damaged by resistive heating.

For example, if an external short circuit of 100 mΩ were applied and resulted in a current flow of 1000A for 10 msec, the total energy dissipated would be:

$$E=I^2 Rt$$

$$E=(1000A)^2 * 100\ mOhm * 10msec=1000J=0.0003kWh$$

For reference, a small battery pack in a PHEV will typically have a capacity of approximately 5kWh; and store approximately 15,000 times more energy than dissipated by an external hard short circuit. In addition, the energy dissipated by a brief, hard short circuit will likely be distributed among all of the RESS cells and cabling system.

A number of standards for batteries and RESS describe external short-circuit tests including:

- IEEE 1725 specifies a short circuit test through a maximum resistance load of 50 mΩ.
- IEC 61233 specifies a short circuit test through a maximum resistance load of 100 mΩ.
- SAE J2464 and J2929 specify hard short circuit tests (less than 5 mΩ) of RESS modules and packs. SAE J2464 also specifies a soft short circuit test (short impedance matched to DC impedance of device under test) of cells connected in parallel.
- UL 1642 and UL2054 specify short circuit tests through a maximum resistance load of 100 mΩ.
- UL 1973 and UL2580 specify short circuit tests through a maximum resistance load of 20 mΩ, as well as at a load that draws a maximum current no less than 15% below the operation of the short circuit protection.
- UL2271 specifies a short circuit test through a maximum resistance load of 20 mΩ, as well as at a load that draws 90% of the short circuit protection current.
- UN Manual of Tests and Criteria T.5 specifies a short circuit test through a maximum resistance load of 100 mΩ.

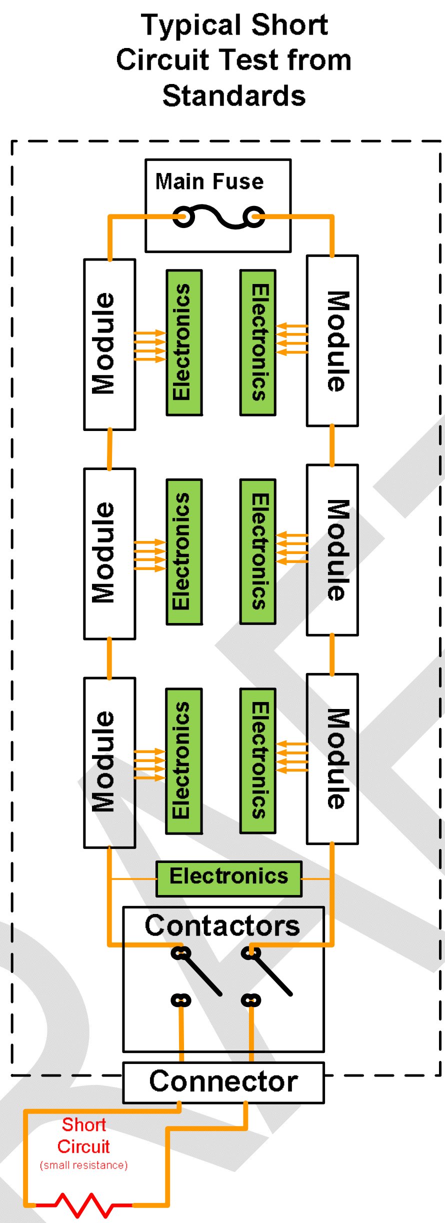

Figure 5 - Schematic of a typical external short circuit test: a short circuit is formed across the external terminals of the RESS.

A loss of isolation within a RESS means that one or more new, unintentional energy flow pathways have been created within the RESS. In the case of a single point isolation failure from the high voltage chain to the enclosure, the current flow is zero if the RESS is otherwise perfectly isolated (Figure 6). However, in practice, typical RESS do not exhibit infinite isolation between components: typical isolation values between high voltage chain and enclosure are on the order of 1 MΩ. Thus, if a single point loss of isolation is formed across this isolated boundary, a small uncontrolled current is likely to flow.

For example, if a loss of isolation were to occur between a RESS internal potential at 400 V and vehicle ground, the current (I) flowing through the 1 MΩ insulation (a typical value) would be:

$$I = \frac{\Delta V}{R} = \frac{400\ V}{1\ M\Omega} = 400\mu A$$

The resulting power would be:

$$P = I^2R = (400\mu A)^2(1M\Omega) = 0.16\,W$$

The resulting current flow would dissipate 0.16 W or less of power in the RESS. This low current level would be unlikely to cause a hazardous condition. In addition, this type of fault should be routinely tested as part of system design.

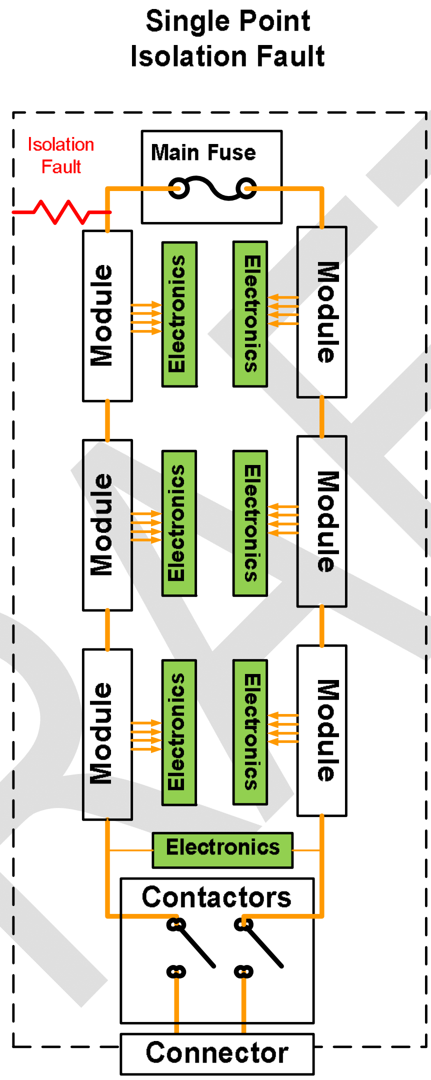

Figure 6 - Schematic of a single point isolation fault; note that a new current pathway has been formed, but current flow will not occur unless the circuit is completed.

Applying pollution to a RESS is likely to create multiple points of reduced isolation within the RESS, and a number of different uncontrolled discharge pathways could form (Figure 7). If a pathway with significant current carrying capability is formed, and a circuit is completed it is possible that installed current interrupt devices will activate, but if none exist within the current path, the affected RESS components will become rapidly drained, and significant heating can occur.

In one scenario (Figure 7; right side), a low impedance short circuit could develop between two adjacent modules and the RESS enclosure. If a fuse were not located between these modules then it would not interrupt the resulting current and all of the energy within the modules could be dissipated within the short circuit pathway, resulting in significant heating. For example, if there was a 100 V potential difference between the two modules, and a 1000A current developed, the short circuit would dissipate

$$P = IV = (1000A)(100V) = 100kW$$

For reference, if 50kW were dissipated into 40kg of aluminum then the aluminum would be heated at a rate of approximately 3°C per second. If the short circuit lasted for one minute, approximately 1.6kWh would be dissipated (the temperature of 40 kg of aluminum would be raised by 180°C)

If a pathway with low current carrying capability is formed, and a circuit is completed significant bulk heating may not occur, but significant localized heating may occur. Localized heating may be sufficient to destroy the new current path (for example by melting a dendrite, boiling away a conductive liquid, or fusing open a fine gage wire that was selected for a low current application, but that became part of a high current short circuit), or it may cause an expansion of damage such as carbonization of insulation leading to a more serious fault such as thermal runaway of an affected cell or a fire.

In a second scenario (Figure 7; left), if a 1kOhm short circuit were to develop on a printed circuit board between traces with a 50V potential difference, then 2.5W would be dissipated on the printed circuit board, which could be sufficient to cause a fire on the printed circuit board or failure of nearby wiring or cells.

$$P = \frac{V^2}{R} = \frac{(50V)^2}{1k\Omega} = 2.5W$$

In a third scenario (Figure 7; middle), if a 1kOhm short circuit were to develop on a printed circuit board between traces with a 300V potential difference, then 90W would be dissipated on the printed circuit board, which would be sufficient to cause a fire on the printed circuit board or failure of nearby wiring or cells.

$$P = \frac{V^2}{R} = \frac{(300V)^2}{1k\Omega} = 90W$$

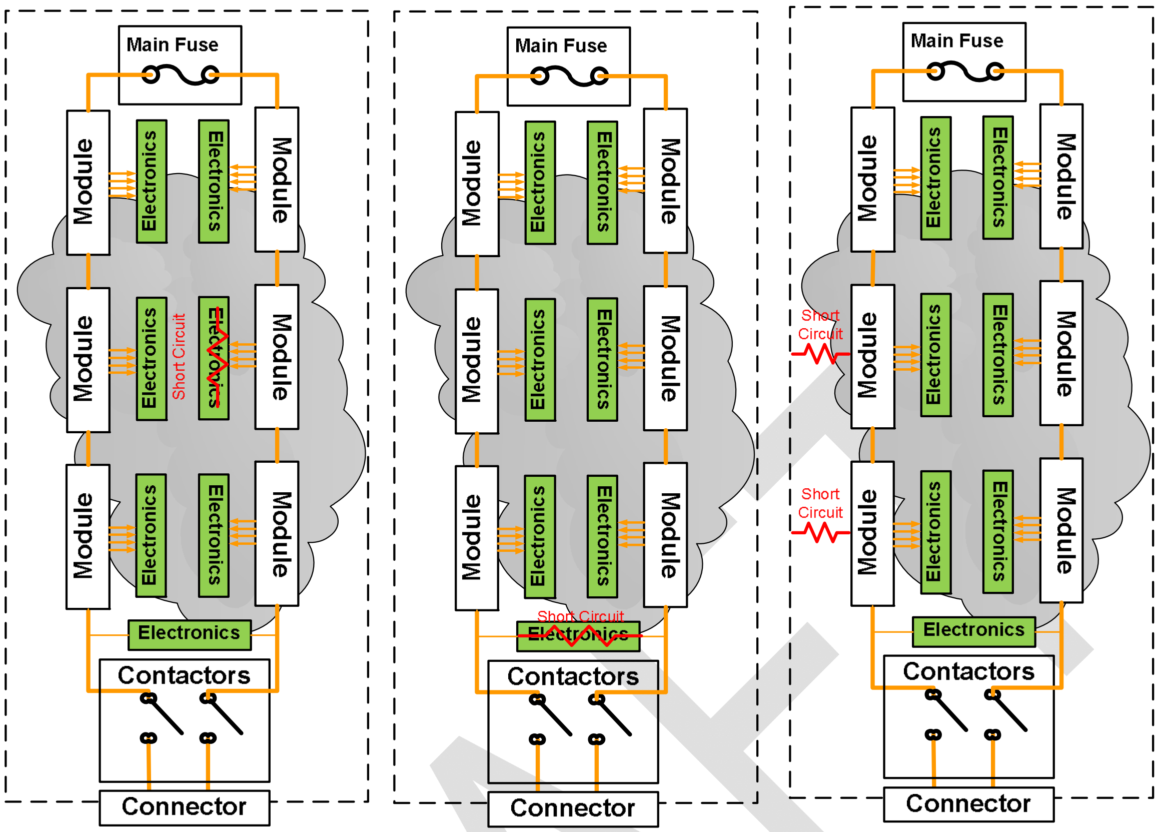

Figure 7 - Schematic of some possible short circuit pathways that could be created due to pollution of a RESS; a short circuit could form (from left to right) on module connected electronics components, on pack level electronics components, or between modules and the RESS enclosure.

7.2 Isolation Stress Testing Background

Preventing a loss of internal isolation or breakdown in high voltage electrical equipment due to environmental factors is an integral part of system design. Standards such as UL840 and IEC 60664 provide design requirements for creepage, clearance, and high voltage withstand in electrical equipment. Standards such as IEC 60664 also address some of the issues associated with a possible loss of isolation due to environmental factors such as humidity, altitude, and pollution. These standards do not typically address loss of isolation from specific field failures such as corrosive liquid ingress, mechanical debris, severe smoke ingress, or cell leakage or venting. In addition, these standards do not specifically address losses of isolation at different potentials in an RESS configuration. RESS architectures are rapidly evolving, and there is little direct discussion regarding addressing loss of isolation within a RESS.

For a complex system such as a RESS, without conducting either an extensive design review or extensive durability testing, it is difficult to predict points of susceptibility to loss of isolation failures that can be caused by conditions encountered in the field, which can result in severe events. An extensive design review or extensive durability testing are not be practical in the context of a regulatory standard test. Similarly, testing points of susceptibility individually would also not be practical in the context of a regulatory standard test. Ideally, a regulatory test could quickly assess the effects of isolation stress throughout a RESS and would be representative of a failure that may occur in the field.

For RESS, a number of standards require testing of conditions that might lead to single or multi-point reductions of internal isolation. For example, standards such as UL 2771 require testing of the RESS under high humidity conditions, with subsequent insulation resistance measurement to ensure that the RESS shall remain touch safe. Similarly, extended duration RESS immersion testing is described in standards such as SAE J2464, SAE 2929, UL2580, and UL 2771.

- SAE J2464 requires that a fully charged RESS be immersed in ambient temperature salt water (5% NaCl by weight) for a minimum of 2h or until any visible reactions have stopped.
- SAE J2929 requires immersion testing of an operational RESS per SAE J2464.
- UL2580 prescribes a salt water immersion test described in SAE J2464.
- UL 2271 includes a 2 hour salt water immersion test. The RESS is submerged in normal orientation for 2 hours or until visible reactions have stopped. After the RESS is removed from the water a dielectric withstand test or an isolation resistance test is conducted.

These tests are intended to ensure that a RESS can be safely immersed for relatively brief periods and remain touch safe. They do not directly pollute a RESS, but rather subject a RESS to a condition that might cause a loss of internal isolation. In most cases a RESS will be designed to prevent liquid intrusion, to meet requirements of the standards.

7.3 Assessment of Various Methods for Isolation Stress Testing

Reduction of internal isolation can occur through a variety of mechanisms. An attempt was made to identify a mechanism that:

- Would have a high probability of degrading electrical isolation,
- Would be relevant to RESS of many designs,
- Would provide stress throughout the RESS, and be somewhat architecture independent,
- Would not directly force high current flows to activate fuses within the battery pack (for example hard short circuits of cells would typically activate fuses),
- On its own might provide poor warning properties of a potential problem, and
- Was not well examined in existing standards.

A discussion of methods considered follows.

7.3.1 Liquid Ingress

External water spray and even brief RESS immersion is addressed with typical vehicle durability testing: vehicles must function when exposed to rain, road spray, and wading conditions. Immersion testing of a RESS (up to 2 hours in salt water) is described in a number of existing standard tests. Test requirements are likely to be met by designs to prevent liquid intrusion rather than robustness to degradation of isolation

Extended flooding of a RESS with a conductive liquid such as salt water or dirty water is likely to ultimately result in loss of isolation within the RESS. A number of parameters can affect the results of a flooding event including: depth of submersion or volume of the liquid, conductivity of the liquid, RESS location within the vehicle, dimensions of a RESS relative to submersion level, susceptibility of the RESS to flooding, orientation of the RESS during and after flooding, duration of the flooding event, and the volume of liquid that ultimately enters the RESS. As a result it is difficult to use vehicle immersion as a source of a controlled stressor to examine the effect of a loss of internal isolation. In addition, flooding of a vehicle can provide stresses to a range of electrical systems within a vehicle, not just the RESS, and thus a vehicle immersion test would examine the behavior of more than the vehicle RESS.

Using a controlled liquid ingress test method (injecting a specific volume of liquid into a RESS) also has a number of shortcomings: depending upon the volume of liquid injected, its conductivity, and the location of injection, it may or may not cause a loss of isolation within the RESS. The same volume of liquid injected into two different places within a RESS could perform differently, or a smaller or larger volume could perform differently in the same injection location. A smaller volume might boil away leaving insufficient capability to carry hazardous power levels, or a larger volume might sufficiently cool the local components to allow discharge before resulting in a severe event. It is difficult to distribute a liquid to all susceptible locations within a RESS without a substantial understanding of the RESS architecture. Even methods such as inverting a RESS multiple times after liquid injection have shortcomings – some RESS may include drains or other openings that would result in loss of the injected liquid. Optimizing the pack orientation to cause loss of isolation stresses in the most susceptible location within the RESS would require significant testing of multiple test samples of each RESS design.

7.3.2 Coolant Leakage

Coolant flood as a source of loss of internal isolation stress within a RESS shares the shortcomings of a controlled liquid ingress test method, and furthermore it is much less valid in RESS which do not contain liquid coolants.

7.3.3 Condensation/ Presence of Water Vapor

Condensing environment tests in the interior of the RESS are practical and relatively simple to conduct and condensation tests are described in UL 2271. Typical vehicle durability tests also address condensation. Coupon level testing was conducted to assess the effect of water vapor and condensation on loss of isolation between cells and between traces on typical printed circuit boards and to provide a comparison with other pollutant methodologies.

Water vapor and condensation exposure coupons were constructed of four small cylindrical cells that were not electrically connected, but were placed in close proximity of each other: cells were placed within millimeters or each other, consistent with the architecture in Manufacture A RESS (see SCTRI Procedure for further discussion). The coupon was placed in a 500 ml chamber containing 0.5 g of liquid water. The chamber was heated to 25 C, and the air within the chamber became saturated with water vapor. Isolation measurements were conducted between cells within the coupon. A similar test was conducted with a typical printed circuit board.

The results of testing of cells[5] and printed circuit boards are shown in Table 1 and Figure 8. The presence of pure water vapor resulted in an average loss of isolation of approximately 60% of pre-test values. After 1400 minutes, condensation was produced by a rapid drop in chamber temperature. Isolation dropped to approximately 1% of the pre-test value. Once chamber temperature was re-established and condensation was no longer present, isolation stabilized at approximately 9% of the pre-test value, however, the condensation event likely dissolved and re-distributed ions present on the test coupon, affecting subsequent isolation measurements. Applying a voltage bias across two cells in the coupon had no significant effect on isolation values compared to the test without a voltage bias. As water vapor was lost from the chamber, isolation recovered to pre-test values.

The presence of water vapor was able to reduce isolation on a typical printed circuit board by approximately one order of magnitude. Isolation loss was sporadic, and isolation rebounded to pre-tests levels once the chamber dried out.

Test results are consistent with expectations that water is a good conductor only due to dissolved ions or other material in solution. Water vapor does not contain the majority of these ions, and will thus only provide significant transient low current paths when it condenses on surfaces. Depending upon whether condensation occurs, isolation values could vary significantly. Since a majority of RESS include design features for controlling humidity levels, such as moisture vapor barrier vents or desiccant pellets, using water vapor to cause a loss of isolation is not experimentally convenient.

Table 1 - Summary of Water Vapor and Condensation Tests

Test ID	Test Article	Experiment Type	Pre-test resistance at 1000 V	Average resistance at 1000 V	Resistance at 1000 V post-test
1	Cell Coupon	Pure water vapor (0-400 minutes)	>11000 MΩ	6260 MΩ	
1	Cell Coupon	Condensed water (400 – 1500 minutes)		190 MΩ	
1	Cell Coupon	Water vapor after condensation event (1500 – 4300 minutes)		1010 MΩ	
1	Cell Coupon	Water vapor after condensation event with voltage bias (4300 – 8500 minutes)		1200 MΩ	>11000 MΩ
2	Printed Circuit Board	Pure water vapor (0-8500 minutes)	>11000 MΩ	2000 MΩ	>11000 MΩ

[5] Testing with cell coupons was sequential, one test condition followed another.

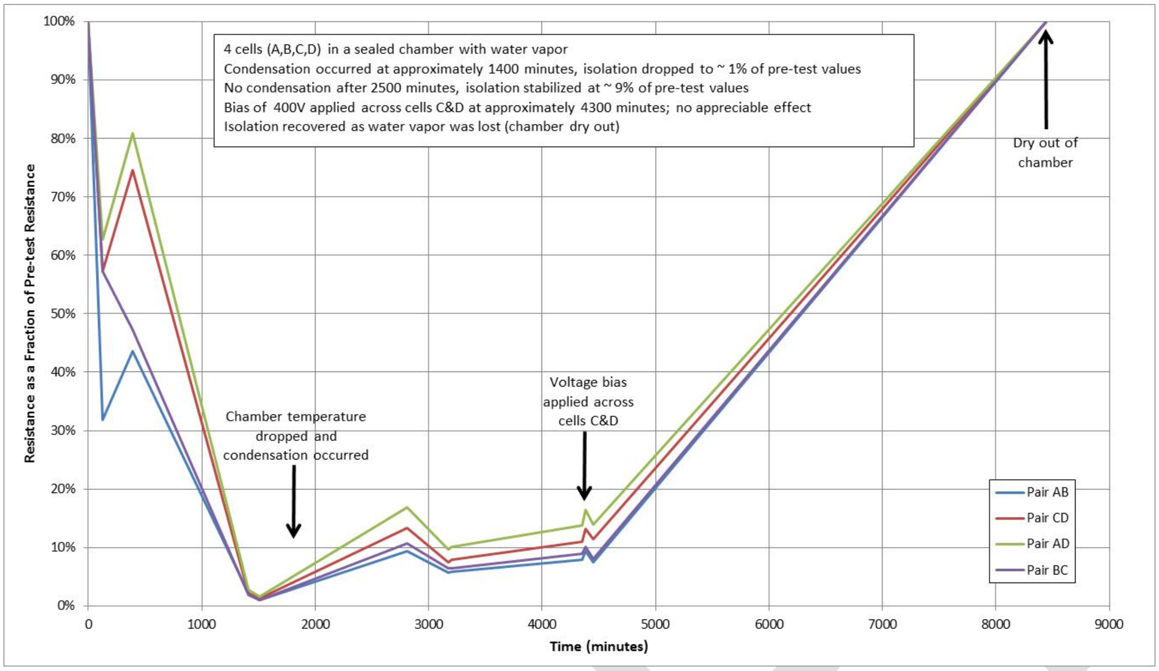

Figure 8 - Results of small cylindrical cell coupon isolation testing with water vapor, condensed water vapor, and water vapor subsequent to condensation.

7.3.4 Solid Debris or Dust Accumulation

Conductive debris can directly bridge terminals, bus bars and grounded surfaces. Solid debris should be characteristic of material that could enter a RESS or be formed within a RESS over time. Road dusts are typically non-conductive and thus not a good candidate pollutant. Fasteners could fail or loosen, components could become deformed, chafed, or corrode and also produce solid debris. However, determination of an appropriate material for application to each RESS could require extensive testing of each RESS. In addition, applying a solid debris test to a RESS suffers from many of the same shortcomings as applying a liquid ingress test: even if an appropriate solid debris material is selected, a location of application and a quantity to apply remain difficult to determine. Finally, vehicle durability testing will provide an appropriate method for evaluating the effect of sold debris accumulation or dust within a RESS.

7.3.5 Smoke

Injection of smoke as a pollutant was considered as a test method. Smoke can be conductive and can deposit conductive debris or residue on surfaces; it is straightforward to introduced smoke into a RESS and it will readily spread throughout the RESS. Smoke intrusion in the field could occur as the result of overheating of electrical insulation on components within the RESS. At the time of this writing there are no standards specifying smoke intrusion for RESS.

Small scale (coupon level) tests were conducted to examine the use of smoke as a source of pack pollution to induce a loss of insulation. Smoke exposure coupons were constructed of pairs of small cylindrical cells. Each coupon consisted of a pair of cells that were not electrically connected, but were placed in close proximity of each other: cells were placed within millimeters or each other, consistent with the architecture in Manufacture A RESS (see SCTRI Procedure for further discussion). Each coupon was exposed to a smoke environment for a minimum of 60 minutes. Two coupons were tested with each smoke condition (Figure 9).

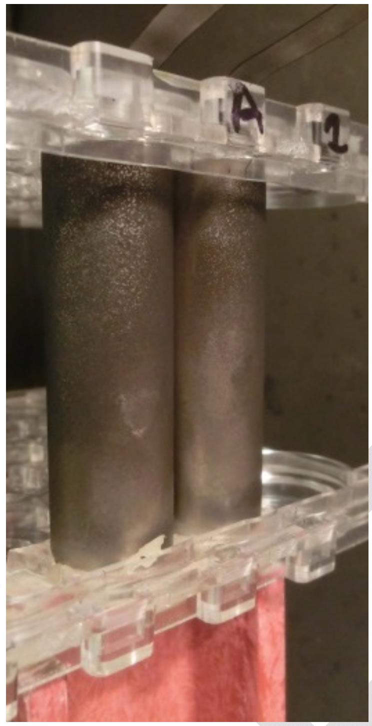

Figure 9 - Cylindrical cell coupon (2 cells) after exposure to smoke from smoldering electrical wiring.

A review of literature relating to burning materials[6] revealed that smoke from different sources will have varying composition, with varying conductivity and varying propensity for adherence to surfaces. Products of combustion will also vary depending upon the combustion regime: flaming versus smoldering combustion. Since smoldering combustion generally produces greater quantities of smoke, with a higher variability of constituent species, smoldering processes were used to generate smoke for this testing. A few different sources of smoke were considered:

- Smoldering cigarettes: a classic smoldering combustion test article is an ignited cigarette. Cigarettes are designed to smolder and produce smoke. They are readily available and a number of test procedures specify proper handling methods for combustion testing[7]
- Smoldering electrical wiring: each RESS will include insulated wiring that could be subject to smoldering in a fault condition. A test could be developed to harvest a specified fraction of wiring from a RESS, and heat it to the point of smoldering (Figure 10).
- Smoldering printed circuit board: each RESS will include printed circuit boards that could be subject to smoldering in a fault condition. A test could be developed to harvest a specified fraction of printed circuit board material from a RESS, and heat it to the point of smoldering.

[6] See for example: Flammability Handbook for Plastics 5th edition
[7] See for example: "ASTM E2187, Standard Test Method for Measuring the Ignition Strength of Cigarettes"; E1352 Test Method for Cigarette Ignition Resistance of Mock-Up Upholstered Furniture Assemblies; or E1353 Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture

The temperature of smoke could also play a role in its effect on loss of isolation. Tests were conducted to evaluate the effects of smoke residue, hot smoke, and cold smoke.

- Smoke Residue: A coupon consisting of multiple cell pairs was held above smoldering or burning material, in its smoke path. Isolation between cells in each pair was evaluated before smoke exposure and after smoke exposure.
- Hot smoke chamber: A coupon consisting of a number of cell pairs was held above smoldering of burning material, in its smoke path. Isolation between cell pairs was evaluated before, during, and after smoke exposure.
- Cold circulating smoke: A coupon consisting of multiple cell pairs was held in a sealed chamber. A separate chamber contained smoldering or burning material. The two chambers were connected by a delivery line, and a return line, with a circulating fan present in the delivery line. In this experiment one of the cell pairs was subject to a bias voltage during smoke exposure.

An insulation resistance tester capable of evaluating resistances up to 11 GΩ at 1000V.was used to test cell isolation periodically during testing. For some tests, during smoke exposure, a voltage bias was applied to cells within a coupon to simulate typical voltage differentials that might exist within RESS between series elements that could be packaged in close proximity. A voltage bias of 25V was tested. When a voltage bias was applied, it was only removed when the insulation tester was used to test cell isolation. The power source used to apply the voltage bias was capable of measuring current flow greater than 1 mA, which would have indicated development of a current path. Figure 11 shows a cold smoke circulation test setup.

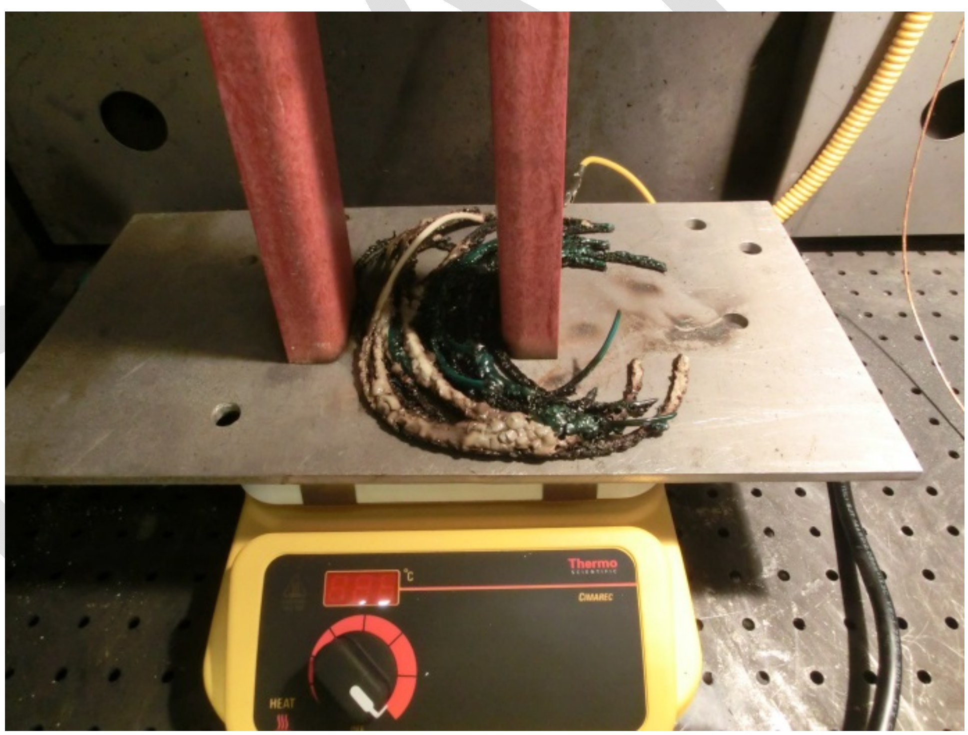

Figure 10 - Electrical wire after it was heated to the point of smoldering to produce smoke for testing.

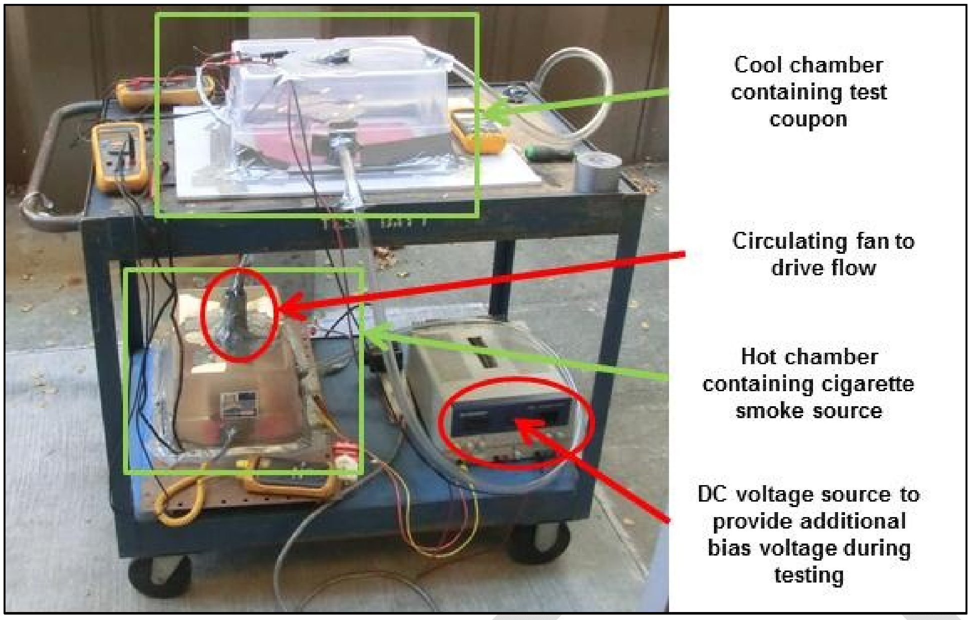

Figure 11 - Cold smoke circulation test: smoke chamber is separated from the coupon chamber so that smoke applied to the coupon is cool.

Data from smoke exposure tests is presented below (Table 2 and Figure 12 through Figure 14). The presence of a smoke pollutant from any source temporarily lowered insulation resistance between cells up to two orders of magnitude comparable to the effect of water vapor condensation. When smoke cleared, insulation resistance rebounded to pre-test levels. The effect of smoke source appeared to be minor, compared to the effect of temperature. Heated smoke resulted in one order of magnitude lower insulation resistance in these tests. However, this effect was also temporary: insulation resistance rebounded after coupons had cooled. Application of a voltage bias did not increase isolation loss between cells. 24 hours after smoke exposure, all the coupons had recovered to an isolation greater than >11000 MΩ at 1000 V.

Testing with smoke showed that smoke is a viable pollutant for isolation stress testing. It can provide a loss of isolation comparable with that observed during condensation of water vapor. For application to RESS testing, an appropriate source of smoke must be defined, as well as a total smoke volume, smoke temperature, and a duration of application.

Table 2 - Summary of Smoke Exposure Testing

Test ID	Smoke Source	Experiment Type	Pre-test resistance at 1000 V	Minimum resistance at 1000 V	Resistance at 1000 V post-test (24 hours after smoke exposure)
1A	Electrical Wiring	Smoke residue	>11000 MΩ	4300 MΩ	>11000 MΩ
1B	Electrical Wiring	Smoke residue	10500 MΩ*	3000 MΩ	>11000 MΩ
2A	Cigarettes	Hot Smoke Chamber	5600 MΩ*	510 MΩ	>11000 MΩ
2B	Cigarettes	Hot Smoke Chamber	980 MΩ*	150 MΩ	>11000 MΩ
3A	Circuit Board	Hot Smoke Chamber	2000 MΩ*	230 MΩ	>11000 MΩ
3B	Circuit Board	Hot Smoke Chamber	>11000 MΩ	125 MΩ	>11000 MΩ
4A	Cigarettes	Cold Circulating Smoke with voltage bias	>11000 MΩ	5200 MΩ	>11000 MΩ
4B	Cigarettes	Cold Circulating Smoke (no voltage bias)	>11000 MΩ	1450 MΩ	>11000 MΩ

* Pre-test resistance was measured before epoxy had fully set.

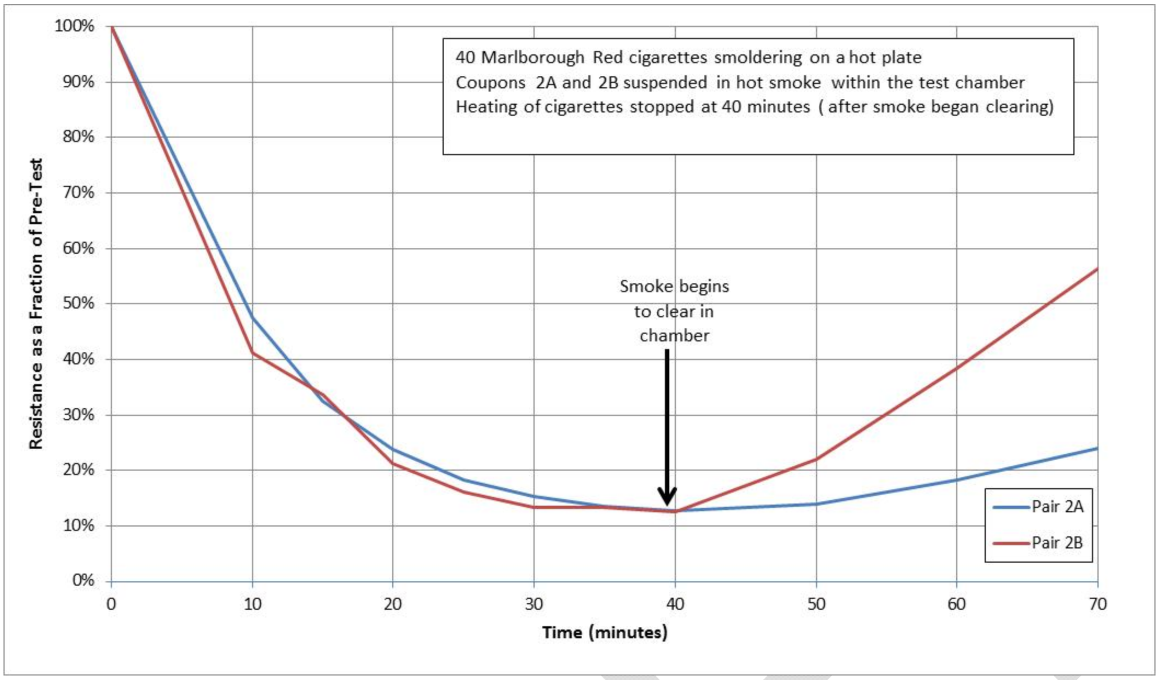

Figure 12 - Insulation resistance between cell pairs 2A and 2B when subjected to hot cigarette smoke: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application, rebounds after smoke clears.

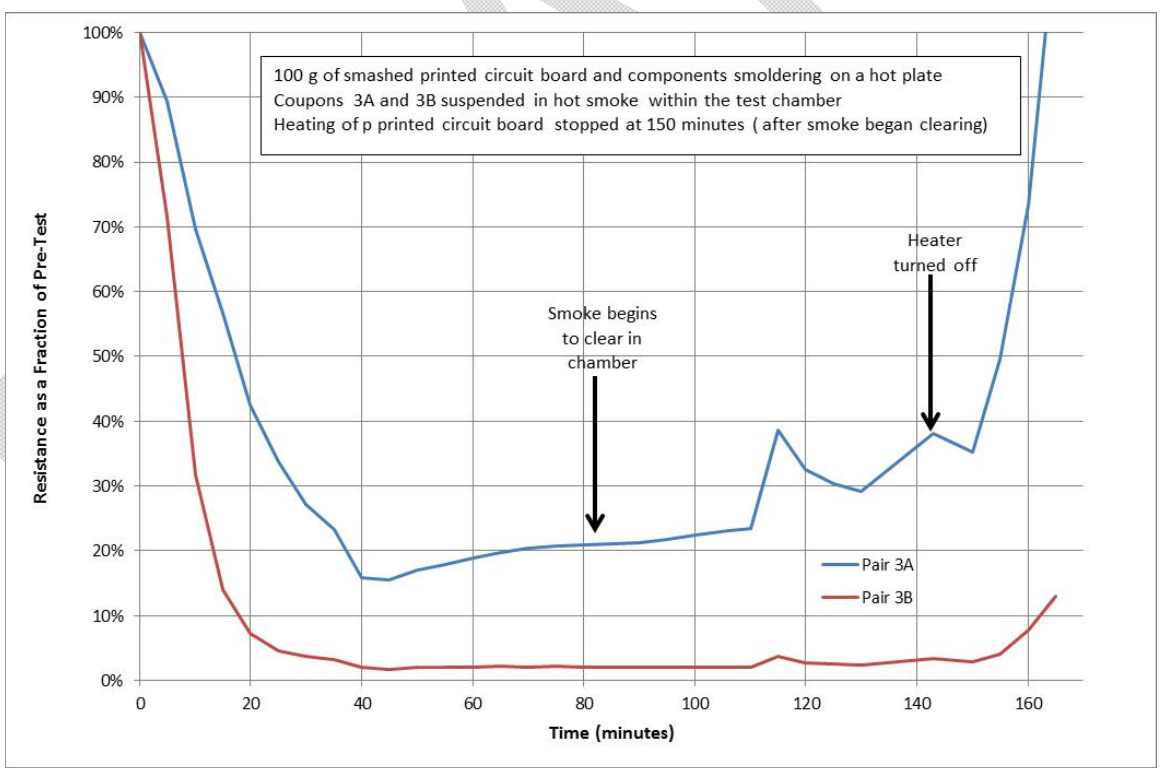

Figure 13 - Insulation resistance between cell pairs 3A and 3B when subjected to hot smoke from smoldering printed circuit board: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application, rebounds after smoke clears.

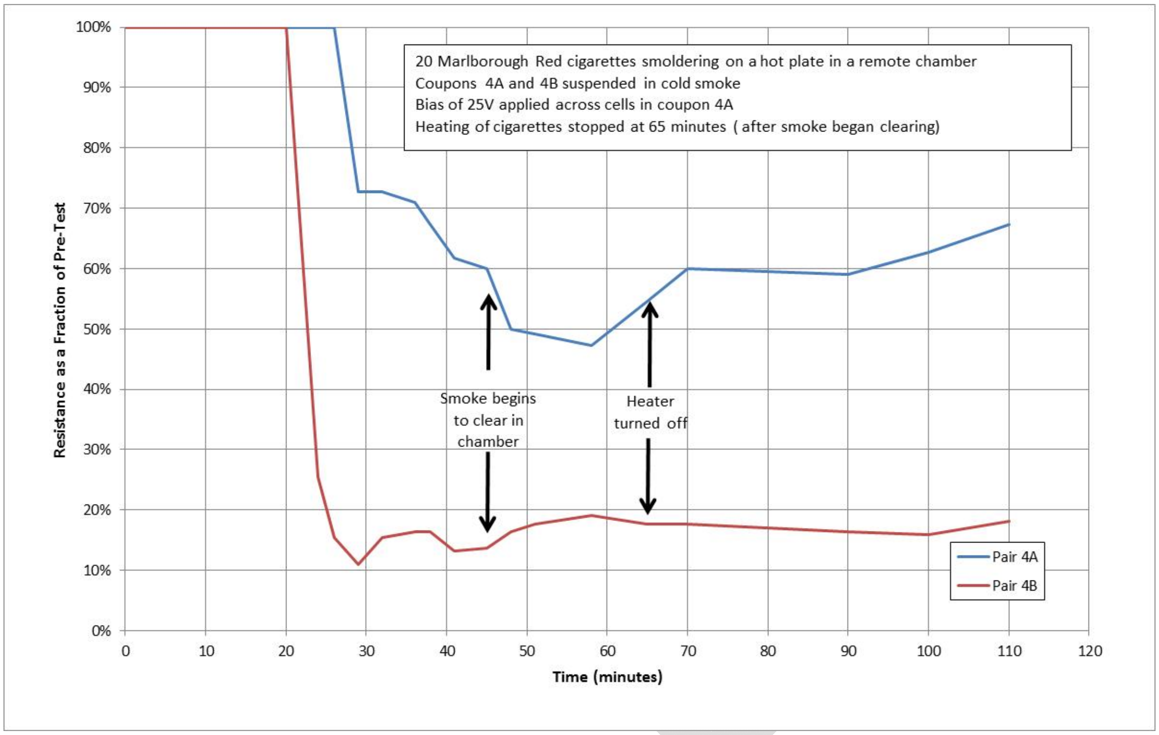

Figure 14 - Insulation resistance between cell pairs 4A and 4B when subjected to cold smoke from smoldering cigarettes: insulation resistance drops to an approximately steady state limit within 40 minutes of smoke application (smoke entered chamber at approximately 20 minutes after start of test), rebounds after smoke clears. Application of a bias across cells does not force an increased loss of isolation.

7.3.6 Leakage of Cells (Cell Electrolyte Exposure)

Introduction of lithium-ion cell electrolyte as a pollutant was considered as a test method. Electrolyte vapor will readily spread throughout the RESS. Electrolyte can be conductive and can deposit conductive debris or residue on surfaces. It could be present within a RESS due to leakage of cells, and can cause corrosion of additional cell cases, leading additional cell leakage. At the time of this writing there are no standards for examining the effect of leaked electrolyte on a RESS.

Electrolyte is an important component of all cell designs: it provides an ion path for charge to move between the electrodes of the cell during charging and discharging, completing the circuit inside the cell. For lithium-ion cell chemistries, electrolytes are composed of lithium salts in hydrocarbon based solvents. Typical components include:

- Dimethyl carbonate
- Ethyl methyl carbonate
- Ethylene carbonate
- Propylene carbonate
- Lithium hexafluorophosphate (salt)

Although the hydrocarbon based solvents are generally volatile and may only cause limited degradation of insulation prior to evaporating, dissolved lithium salts can react with water (or water vapor) to produce corrosive compounds. For example, lithium hexafluorophosphate can react with water to form hydrofluoric acid and lithium hydroxide, both of which are corrosive compounds.

A series of tests were conducted with cell coupons and typical printed circuit boards to assess the effect of lithium-ion cell electrolyte exposure on loss of isolation.

Electrolyte exposure coupons were constructed of small cylindrical cells that were not electrically connected, but were placed in close proximity of each other: cells were placed within millimeters or each other, consistent with the architecture in Manufacture A RESS (see SCTRI Procedure for further discussion). The coupons were placed in a 500 ml chamber heated to 25 C. Li-ion electrolyte was introduced into the chamber in one of two ways: 1) by puncturing a single cell or 2) by adding approximately 1.0 g of Mitsubishi Solrite electrolyte to the base of the chamber (sufficient to saturate the internal air with volatile gases). Figure 15 shows a cylindrical cell test setup.

A similar test setup was used to conduct testing on a coupon constructed of large format hard case prismatic cells. The coupon contained four cells, of which two cells were left connected and the other two were isolated. Figure 16 shows a hard case prismatic cell test setup.

Chamber electrolyte exposure tests were also conducted with a typical printed circuit board.

An insulation resistance tester capable of evaluating resistances up to 11 GΩ at 1000V.was used to test cell isolation periodically during testing. For some tests, a voltage bias up to 528 V was applied to cells within a coupon. When a voltage bias was applied, it was only removed when the insulation tester was used to test cell isolation. The power source used to apply the voltage bias was capable of measuring current flow greater than 1 mA, which would have indicated development of a current path.

Figure 15 - An electrolyte exposure chamber containing 4 18650 cells after 20 days of exposure. Cloudiness can be seen on the cell walls due to the electrolyte vapor.

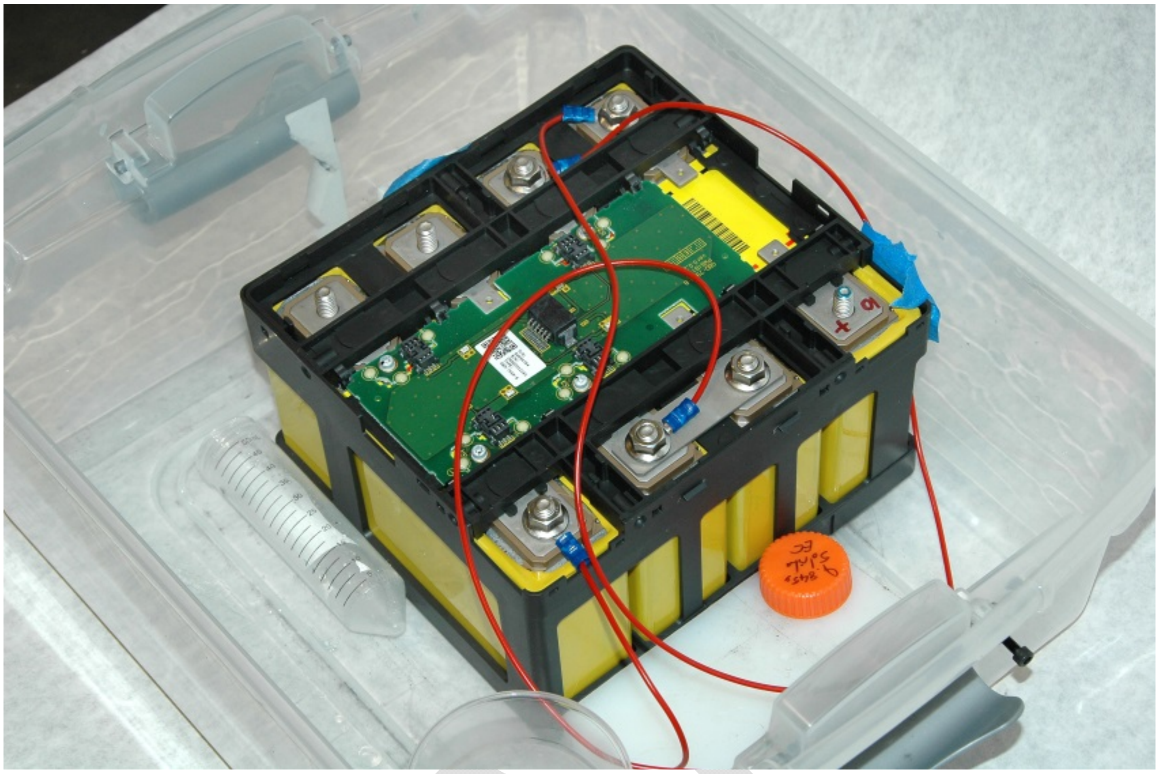

Figure 16 - An electrolyte exposure chamber containing 4 Prismatic Cells, their support structure and BMB. The isolation between the circled terminals fell significantly during the test.

Data from electrolyte exposure tests is presented below (Table 3 and Figure 17). A low concentration of electrolyte vapor from a punctured cell was not sufficient to produce measurable changes in isolation. However, air saturated with electrolyte vapor temporarily lowered insulation resistance between cells up to two orders of magnitude; comparable to the effect of water vapor condensation. When electrolyte vapor was evacuated from the chamber, insulation resistance rebounded to pre-test levels. Application of a voltage bias did not increase isolation loss between cells. Exposure to electrolyte vapor did not cause measureable loss of isolation on a typical printed circuit board.

Testing with li-ion cell electrolyte vapor showed that electrolyte vapor is a viable pollutant for isolation stress testing. It can provide a loss of isolation comparable with that observed during condensation of water vapor. For application to RESS testing, use of electrolyte vapor as a pollutant would require defining an appropriate source of electrolyte, as well as a total volume, and the duration of exposure. However, since proper handling of pure liquid electrolyte presents elevated hazards to personnel conducting testing, direct introduction of liquid electrolyte to a RESS to produce an electrolyte vapor is not recommended.

Table 3 - Summary of Electrolyte Exposure Tests

Test ID	Test Article	Experiment Type	Pre-test resistance at 1000 V	Minimum resistance at 1000 V	Resistance at 1000 V post-test
1	Cylindrical Cell Coupon (3cell)	Punctured cell to expose cells to vapor	>11000 MΩ	>11000 MΩ	>11000 MΩ
1	Cylindrical Cell Coupon (3cell)	Punctured cell to expose cells to vapor, 400V bias applied	>11000 MΩ	>11000 MΩ	>11000 MΩ
2	Cell Coupon	Pure electrolyte vapor from liquid source	>11000 MΩ	103 MΩ	>11000 MΩ
2	Cell Coupon	Pure electrolyte vapor from liquid source, voltage bias applied		150 MΩ	>11000 MΩ
3	iMiev half module	Pure electrolyte vapor from liquid source	>11000 MΩ	140 MΩ	
4	Printed Circuit Board	Pure electrolyte vapor from liquid source	>11000 MΩ	>11000 MΩ	>11000 MΩ
4	Printed Circuit Board	Pure electrolyte vapor from liquid source, 400V bias applied	>11000 MΩ	>11000 MΩ	>11000 MΩ

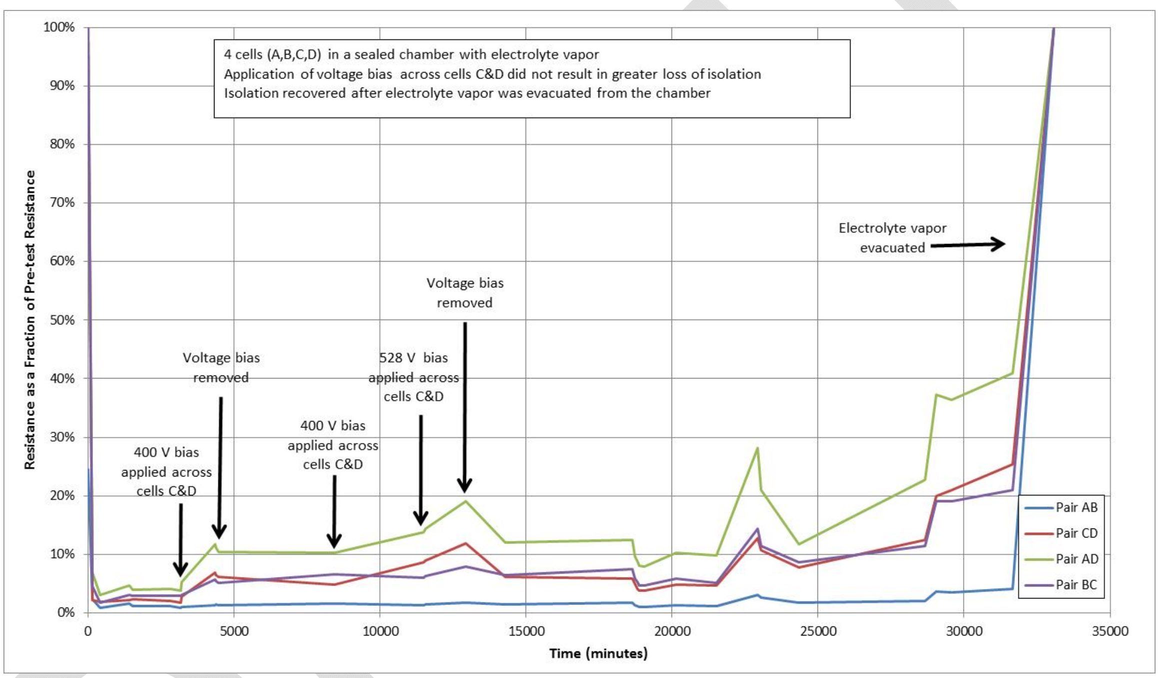

Figure 17 - Graph showing the changing isolation between cells A through D in coupon during exposure to electrolyte vapor.

7.3.7 Cell Thermal Runaway Products

Introduction of cell thermal runaway reaction products as a pollutant was considered as a test method. Lithium-ion cell thermal runaway products can contain a mixture of conductive solid debris, smoke, and electrolyte (both solvent and salt components), and therefore, comprise a complex pollutant that could cause a loss of isolation failure through a variety of mechanisms as described previously. Introduction of thermal runaway reaction products from a single cell within a RESS ensures that pollutant quantities, composition, flow rate, and temperatures are appropriate to an expected field failure of each specific RESS (for a discussion of cell thermal runaway reactions, see Section 7.1 of the SCTRI Procedure).

By using a thermal runaway reaction as a source of pollutants, application and distribution of the pollutant material will be relatively fast, similar to smoke introduction, and thus appreciable losses in isolation should be apparent within 30-60 minutes of pollutant application (consistent with smoke testing results).

Ideally, RIS testing can be accomplished in conjunction with SCTRI testing, increasing testing efficiency. However, if necessary, RIS testing can be conducted independently by introducing thermal runaway reaction products collected remotely from a single cell into an adjacent RESS. RIS testing was demonstrated during full vehicle SCTRI testing. See Section 8 for a discussion of test results.

7.4 Methods for Measuring Loss of Isolation

Typical methods for attempting to assess the effect or to quantify a loss of isolation include:

- Isolation resistance measurements
- Dielectric withstand measurements
- Transient overvoltage stress tests (applying voltage stresses to a system)
- Extended observation of the RESS to ensure that a possible loss of isolation does not result in a fire or explosion.

7.4.1 Insulation Resistance Measurements

An insulation resistance test is a commonly used method employing a widely available handheld meter (such as a Fluke 1507) to test potentially high resistance connections at specified voltages. It can show how a connection will behave at high voltages (100s of volts) at which its resistive properties might be expected to change from what would be seen at low voltages (10s of volts). It will give the tester information about system properties; and allow them to predict whether subsequent stress tests are likely to be effective or result in a hazardous condition. An insulation resistance measurement will typically detect high impedance connections such as contact between conductors, but will not detect damage to insulators that has not resulted in physical contact between conductors (for example, a hole in insulation between two conductors). An insulation resistance test should not result in arcing within the system or appreciable current flows, and thus is unlikely to perturb the system being measured.

7.4.2 Dielectric Withstand Measurements

A dielectric withstand test provides information about changes to isolation which may not be apparent with insulation resistance measurements (for example a dielectric withstand test can be used to detect a hole in insulation). A dielectric withstand test is conducted with a Hipot tester capable of producing potential differences of up to 1000s of volts. When a Hipot test is applied between a pair of terminals, the voltage is ramped between the terminals to a specified limit or to the point at which dielectric breakdown occurs: an arc forms between the terminals. When the Hipot tester detects a current spike associated with the arc caused by a dielectric breakdown, it will remove the voltage bias. A dielectric withstand test serves as a minor stress test for the system, as an arc can form and can cause damage to surrounding materials. In addition, an arc is a competent ignition source for internal flammable gases.

A typical dielectric withstand test method has been selected for RESS loss of isolation evaluation. IEC 60664-1 5.3.3.2.3. specifies that the Hipot tester increase voltage linearly over 3 seconds to U + 1695V. It should maintain that voltage for 5 seconds. Subsequently, it should linearly decrease the voltage back to 0V over a period of 3 seconds.

7.4.3 Transient Overvoltage Stress Testing

After pollutants have been introduced into a RESS, the system may have lost isolation such that current can pass from a terminal to vehicle ground when an elevated voltage is applied (high impedance current paths). Current paths created by pollutants may be fragile and relatively benign such that they quickly open if a current begins to flow through them. For example, small metallic debris may melt when current is applied. Alternatively, current paths created by pollutants may be sufficiently durable to extended flow of current to cause heating, corrosion or degradation of surrounding materials, and ultimately pose a hazard to the RESS. By applying an elevated voltage between an internal terminal and vehicle ground while limiting current flow (a transient overvoltage test), development of potentially hazardous current paths can be accelerated. Potentially hazardous current paths that develop will flow current, providing additional stress to RESS components.

A system in compliance with IEC 60664-1 5.3.3.2.3 at the time of manufacture should pass no current with an overvoltage of 353VDC applied between an internal battery terminal and vehicle ground.[8] After pollution is applied, a RESS may have developed current paths that are sufficiently durable to become hazardous when a 353V overvoltage is applied. Because those current paths could be fragile, a low current limit of 0.2 A has been adopted. A low current limit will prevent rapid fusing of potentially hazardous current paths. Any practical RESS will be capable of sourcing 0.2A.

7.4.4 Post-Test Observation

An extended observation time has not been included in the RIS test procedure. Coupon testing with pollutants such as smoke and electrolyte showed that the effect of these compounds on isolation is strongest shortly after application, and that isolation rebounds. Thus, a stress test has been selected to allow a more rapid assessment of the effect of a loss of internal isolation on the vehicle occupant or the surrounding environment. This stress test is the application of a high voltage potential to stimulate latent failure modes such as self-discharge heating within a RESS.

Full vehicle testing involving pollutants generated by cell thermal runaway reactions showed that isolation rebounded with time. The state of vehicles subjected to testing, did not change over an extended dwell period (Section 8).

7.5 Installation of Loss of Isolation Testing and Monitoring Leads

The loss of isolation testing and monitoring leads should consist of three cables, one attached to the most positive accessible surface through which current can flow inside the battery pack, one attached to the most negative accessible surface through which current can flow inside the battery pack, and one attached to vehicle ground either at the RESS or nearby on the vehicle. The installation of the cables should be done in such a way as to not diminish creepage and clearance distances in the pack.

[8] IEC 60664 describes the use of a transient test voltage of use + 250 V RMS. To convert from a 250 V RMS to a DC voltage with the same value as the peak value of AC Voltage the value shall be multiplied by√2. This results in a value of 353 V for longer term transient overvoltage application.

The cables which are attached to terminals through which current can flow inside the battery pack should be attached to surfaces which cannot be isolated from the potential of the majority of the cells by the battery pack protection electronics. For example, if the battery pack has no active isolation components of any kind (such as switches or contactors) which could open if the pack was expected to be idle or on fault detection the cables could be attached to the external terminals of the battery pack. However since most battery packs will have protection electronics these cables should be attached between these protection electronics and the cells themselves such that they cannot be isolated.

The cables should be attached securely with connectors which can handle up to 1A of current at 600 V without providing significant resistance, such as a firmly bolted ring terminal. The cables should be electrically insulated with a rating higher than 2000 V. 10 gauge wire or thicker should be used. The user interface end of each cable should terminate in a switch leading to a touch safe port, capable of accepting the cables leading from a power supply used for transient overvoltage stress testing, the Hi Pot tester, and the probes from the insulation tester. The switches should be rated for up to 1 A at 600 V. The switches should be physically and electrically isolated from each other. The switches should not be touched during the operation of the Hipot tester.

7.6 Vehicles and RESS Test Temperature

7.6.1 A RESS temperature of 25 °C at the start of thermal runaway initiation has been selected for RIS testing for two reasons

7.6.1.1 25 °C describes most likely conditions for a RESS in a vehicle not in use or with low charge or discharge rates. Many vehicle charge rates are low produce minimal heating during extended charge periods, for example, more than three hours.

7.6.1.2 25 °C is experimentally convenient. Testing is most likely to be conducted in an out-door environment with variable ambient temperatures. After exiting a conditioning chamber, a vehicle must be sited and data logging equipment connected. During that setup time, vehicle temperature is likely to drift toward the ambient temperature. 25 °C is a moderate temperature, and ambient is likely to be relatively close to 25 °C

7.6.2 Depending upon the heat transfer properties of various materials and ambient temperatures, vehicle temperatures may quickly become non-uniform. The RESS is likely to have a sealed enclosure and significant mass, such that it is likely to maintain a target temperature during test setup. Thus the temperature of the RESS and not the vehicle is specified for start of testing.

7.7 Electrical Preconditioning of Cells, Modules, and RESS

The test procedure specifies that cells, modules, and RESS used for testing be as new and uncycled as practical: being less than one year old and having accumulated less than five charge discharge cycles. Typically, cell capacity decreases with calendar aging and cell cycling; therefore a new test article should contain the maximum stored energy.

7.8 100% SOC Requirement

RIS testing is to be conducted on fully energized RESS (all cells at 100% SOC). This condition was selected because it will result in the highest voltages within the RESS, and because cells are most susceptible to thermal runaway when in a fully charged (100% SOC) condition.

8. APPENDIX

8.1 Example of Full Vehicle Testing: Manufacturer A Vehicle; RESS Containing Small Cylindrical Cells

An in-RESS cell thermal runaway reaction was initiated within a RESS from Manufacturer A. Full scale vehicle RIS testing was conducted in conjunction with SCTRI testing. A detailed discussion of that testing is found in Section 8 of the SCTRI Procedure. A summary of preparation specific to RIS testing and RIS specific results are provided here.

Preparation of the RESS included installation of loss of isolation test and monitoring leads. Electrical leads were connected to the battery side of the contactors and run into a touch-safe connector through grommets in the enclosure. This connector (Figure 18) was subjected to further insulation and protection, and was treated with great care as it represented an always-live connection to the 350V battery pack.

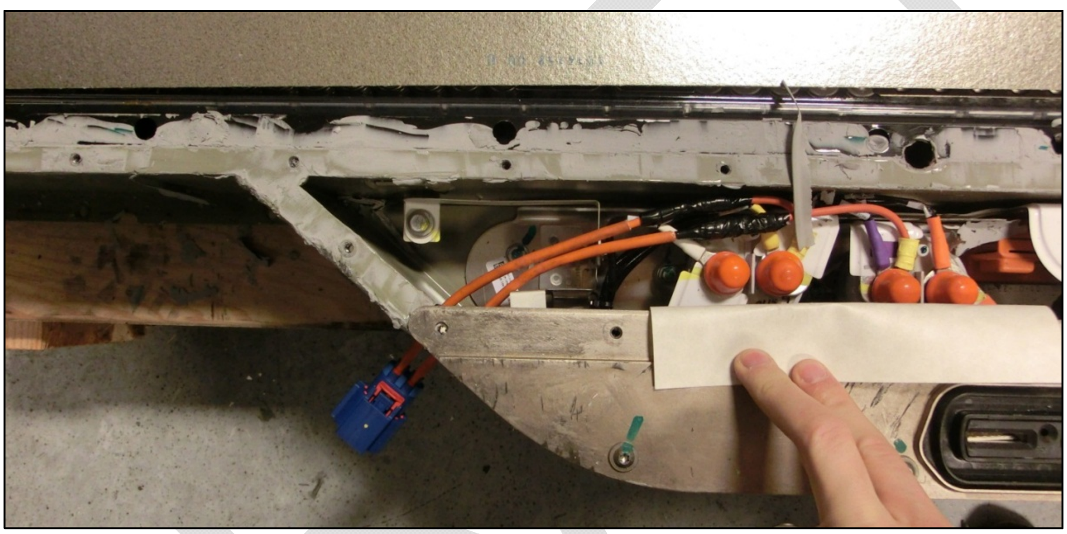

Figure 18 - The connector used for accessing the HV chain for isolation testing.

Isolation resistance and dielectric withstand voltage measurements before testing indicated that internal isolation of the RESS had not been significantly compromised by installation of test equipment. Isolation resistance and dielectric withstand voltage were reduced after the initial cell thermal runaway, but exposure to the transient overvoltage stress test did not cause any additional thermal events. After stress testing, dielectric withstand testing indicated that internal isolation was rebounding to pre-test levels.

The battery pack was allowed to sit for approximately one month after conclusion of the test. No additional cells underwent a thermal runaway reaction. Insulation resistance returned to levels comparable to pre-test levels.

Table 4 - Summary of Manufacturer A RIS Testing Results

Pre-test pack voltage	350 V
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	5.6 MΩ between the negative battery terminal and enclosure 3.9 MΩ between the positive battery terminal and enclosure
Pre-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit exceeded at 1.67kV
Post-test pack voltage	350 V
Post-test isolation – 1000V Handheld Isolation Resistance Meter	0 MΩ between the negative battery terminal and enclosure
Post-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit was exceeded at 0.79kV
Transient Overvoltage Stress Test power supply maximum current @ maximum voltage	0.002A
Stress test power supply maximum voltage if current limited	n/a
Time to thermal runaway of additional cells	No additional thermal runaway reactions
Final isolation – 1000V Handheld Isolation Resistance Meter	0 MΩ between the negative battery terminal and enclosure
Final Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit exceeded at 1.59kV
Isolation – 1000V Handheld Isolation Resistance Meter After 6 Week Dwell	5.8 MΩ between the negative battery terminal and enclosure 4.2 MΩ between the positive battery terminal and enclosure

8.2 Example of Full Vehicle Testing: Manufacturer B Vehicle; RESS Containing Hard Case Prismatic Cells

An in-RESS cell thermal runaway reaction was initiated within a RESS from Manufacturer B. Full scale vehicle RIS testing was attempted in conjunction with SCTRI testing. A detailed discussion of that testing is found in Section 8 of the SCTRI Procedure. A summary of preparation specific to RIS testing and RIS specific results are provided here.

After the SCTRI test was complete, isolation stress testing was attempted. Because the RESS had been damaged due to cell thermal runaway reactions, the driver's seat was cut away to access the service disconnect, which was removed and disassembled. A wire was soldered to the disconnect's internal busbar, and this was used instead of the negative or positive high voltage terminal for the high voltage side of isolation testing. An exposed metal portion of the vehicle near the driver's seat was used for the "enclosure" side: a bolt was removed, a ring terminal was inserted, and the bolt was re-installed.

The handheld isolation meter indicated 0.0MOhm of isolation, and the voltmeter indicated that the service disconnect busbar was approximately 120V above the vehicle potential. A dielectric withstand test was attempted, but the 7.5mA maximum current was achieved at 0.0kV, indicating that no additional potential needed to be applied to allow for 7.5mA of current flow. The 1-hour power supply test was attempted, but upon making the connections, the voltage reading was slightly negative and the current value was at the saturation value: indicating that too much current was flowing even without the power supply providing additional voltage. The test was aborted to avoid damage to the power supply.

The battery pack was allowed to sit for approximately one month after conclusion of the test. No additional cells underwent a thermal runaway reaction.

Table 5 - Summary of Manufacturer B SCTRI Testing Results

Pre-test pack voltage	365V nominal[9]
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	Measurement not possible[9]
Pre-test Dielectric Withstand Voltage – Hipot Tester	Measurement not possible[9]
Post-test pack voltage	Accurate measurement was not possible due to burned string of cells
Post-test isolation – 1000V Handheld Isolation Resistance Meter	0.0 MΩ between the negative service disconnect terminal and enclosure
Post-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit was exceeded at 0.0 kV
Transient Overvoltage Stress Test power supply maximum current @ maximum voltage	Test aborted
Stress test power supply maximum voltage if current limited	n/a
Time to thermal runaway of additional cells	Test aborted
Final isolation – 1000V Handheld Isolation Resistance Meter	Test aborted
Final Dielectric Withstand Voltage – Hipot Tester	Test aborted
Isolation – 1000V Handheld Isolation Resistance Meter After 6 Week Dwell	0.1 MΩ between the service disconnect and enclosure

All test data is available on hard drive labeled “SAE-3257 RESS ISS Tests”, folder “Section 3 – Isolation”.

[9] The Manufacturer B vehicle was non-functional and thus could not be used to charge the RESS before testing, measure voltage, or self-check isolation resistance. To charge the RESS, groups of modules were removed from the RESS and charged independently, then reassembled into the RESS: voltages of bricks were measured during charge and pack preparation. The testing agency chose not to install voltage measurement leads into the battery pack to ensure that such leads could not be a source of arcing within the RESS during the SCTRI test. Thus, once the pack was closed, there was no straightforward way to measure pack voltage, isolation resistance, or perform dielectric withstand testing.

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