Vehicle Sequential Testing after 5000 Mile Preconditioning

(Procedure and Report)

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

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Vehicle Sequential Testing Test Procedure and Test 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.

The battery cells and other components of a RESS are subject to aging mechanisms that can affect their performance, including safety performance. The intent of Vehicle Sequential Testing after 5000 Mile Preconditioning is to ensure that aging of RESS components, particularly the battery cells, has been adequately considered during the design process and that the RESS is sufficiently robust to aging to continue to meet typical safety performance requirements. The Preconditioning Sequence (Section 7.1) is intended to apply real world electrical, mechanical, thermal, and environmental loads to the RESS so that it undergoes realistic aging prior to being subjected to Sequential Testing. Then the Sequential Tests (Sections 7.2 through 7.9) are intended to validate the robustness of a RESS.

The tests included in Sequential Testing have been selected from a number of widely accepted battery pack test methods that represent commonly experienced single point failure modes. The RESS should be able to withstand the proscribed abuse and failure conditions without posing a hazard to the vehicle occupant or the surrounding environment. Tests have been placed in a sequence that not only reduces the number of required test articles, but is intended to reveal and exacerbate a range of RESS failure modes.

Following Sequential Testing, a destructive discharge procedure is to be demonstrated (Section7.10) that can be used to remove stranded energy from a damaged RESS. The destructive discharge mechanism should be designed to allow safe discharge of RESS that may become damaged in the field to the point that discharge using vehicle systems or external electrical means is not possible.

2. SCOPE

This test procedure is applicable to all RESS-equipped HEV, PHEV and EV vehicles. Specific guidance has been provided for application of the procedures to Li-ion based RESS systems as Li-ion cell chemistry is the dominant chemistry in RESS at the time of this writing, however, the general approach provided could be applied to a range of other cell chemistries.

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.
SAE J2841	Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data.

3.1.2 United States Department of Transportation - Code of Federal Regulations.

86 CFR Part 115-208; and Appendix 1.

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 IEC Publications

Available from the International Electrochemical Commission, 446 Main Street 16th Floor, Worcester, MA 01608, Tel: +1 508 755 5663, www.iec.ch.

CEI/IEC 61960	Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for portable applications.
CEI/IEC 62133	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.

3.2.2 IEEE Publications

Available from IEEE Operations Center, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE 1725	Standard for Rechargeable Batteries for Cellular Telephones.
IEEE 1625	Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices.

3.2.3 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 J2929	Electric and Hybrid Vehicle Propulsion System Safety Standard – Lithium-based Rechargeable Cells.

3.2.4 NFPA Publications

Available from the National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471 Tel: +1 617 770-3000, www.nfpa.org.

"Lithium-Ion Batteries Hazard and Use Assessment," Mikolajczak, C.J., et al. July 2011.

References included in 1.

SFPE Handbook of Fire Protection Engineering, 2008 Edition, "Chapter 2-6 Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat", Purser, David A.

3.2.5 NREL Publications

Available from http://www.nrel.gov/docs/fy13osti/54404.pdf .

D. H. Doughty, "Technical Report: Vehicle Battery Safety Roadmap Guidance", Subcontract Report NREL/SR-5400-54404, Oct. 2012, p. 24.

References included in 1.

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 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.

"Safety Issues for Lithium-Ion Batteries" http://www.ul.com/global/documents/newscience/whitepapers/firesafety/FS_Safety%20Issues%20for%20Lithium-Ion%20Batteries_10-12.pdf.

"UN Transportation Tests and UL Lithium Battery Program" www.prba.org/wp-content/uploads/UL_Presentation.ppt.

3.2.8 United States Department of Transportation- Code of Federal Regulations.

49 CFR Part 173.185 “Lithium cells and batteries.”

4. DEFINITIONS

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

5000 Mile Preconditioning

A preconditioning procedure for the RESS intended to be consistent with the expected in-vehicle usage of the RESS. The preconditioning procedure is conducted within the vehicle for which the RESS is intended.

Active device

A device which has an operating state and a non-operating state, or contains, or is connected to, a component which has such properties, such as an electric pump, or resistive heater governed by a switching element.

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.

Charge Sustaining Mode:

An operating mode in which the energy storage SOC may fluctuate but on-average is maintained at a certain level while driving. For example, in an HEV, the internal combustion engine and associated generator may provide power to generally maintain the state of charge of the RESS during vehicle operation.

Charge Depletion Mode:

An operating mode in which the energy storage SOC may fluctuate but on-average decreases while driving. Energy may also flow to the RESS during this mode (for example, as the result of power produced by an internal combustion engine and associated generator), however, the RESS is generally discharged during this mode.

Charge Mode:

A mode in which the RESS is able to accept charging power but it is not being driven. Charge power may come from a properly attached power cable, a generator associated with an internal combustion engine, or other onboard or off-board energy storage device.

Curb Weight

Vehicle weight with driver only (no cargo, no additional passengers).

DC Link:

An electrical connection to a high voltage bus on the vehicle or RESS for the sole purpose of conducting testing described in this standard. The DC Link will allow specific fault conditions to be applied to the RESS. If vehicle is equipped with an automatic disconnect physically contained within the RESS, the direct current bus, or DC Link shall be connected to the electrical bus on the traction side of the automatic disconnect. If the vehicle utilizes an automatic disconnect that is not physically contained within the RESS, the DC Link shall be connected to the electrical bus on the battery side of the automatic disconnect.

Design Weight

Vehicle weight with a typical expected complement of passengers and cargo.

Discharge or Drive Mode:

A mode in which the vehicle is able to draw power from the RESS and deliver motive power to the wheels.

Dynamometer:

A chassis dynamometer; a device consisting of rollers on which a vehicle is placed allowing it to drive while remaining stationary.

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 (for more than approximately 1 second). Sparks are not flames.

GVW (GVWR)

Gross vehicle weight: weight of vehicle with full complement of passengers and cargo.

HEV: Hybrid Electric Vehicle (HEV)

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

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.

Passive device

A device which performs its role simply due to its presence and material properties, such as a heat radiating fin.

OEM

Original Equipment Manufacturer.

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.

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.

RR

Rough road driving test pattern that includes vertical and torsional input events.

Sequential Tests:

A series of tests to be performed on a single RESS, in a specified order.

State of Charge (SOC)

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

Stranded Energy

Energy contained within a RESS that cannot be removed through normal discharge of the battery pack. For example, damage to a RESS can prevent normal discharge of the RESS and result in stranded energy.

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

Maximum Use Voltage.

UF or Utility Factor

The UF is a ratio of the number of miles driven under charge-depleting mode to the total number of miles driven. UF takes into account vehicle range and driving habits of the US light-duty vehicle fleet. For PHEVs, the assumption is that operation starts in battery charge-depleting mode and eventually changes to battery charge-sustaining mode. Total distance between charge events determines how much of the driving is performed in each of the two fundamental modes. An equation describing the portion of driving in each mode is defined in SAE J2841. Driving statistics from the National Highway Transportation Survey are used as inputs to the equation to provide an aggregate "Utility Factor" (UF).

UDDS

An urban operation simulating discharge cycle described in Appendix 1 to part 86 of the CFR, whose required operational precision is specified in 86.115-78. For the purpose of this document only the speed and time requirements of this cycle will be applied.

US06:

A high acceleration and high speed simulated discharge cycle described in Appendix 1 to part 86 of the CFR, whose required operational precision is specified in 86.159-08. For the purpose of this document only the speed and time requirements of this cycle will be applied.

Venting

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.

WOT

Wide open throttle driving test pattern.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting tests on any vehicle is potentially hazardous. Prior to conducting testing, the individuals conducting testing should become familiar with vehicle operation and the potential hazards associated with the vehicle being tested, including its various fuel systems and RESS. A Material Safety Data Sheet (MSDS) or Emergency Response Guide (ERG) may provide relevant information.

5.1.2 RESS are heavy and will need to be removed and remounted in a vehicle during the Preconditioning Sequence, and possibly in preparation for Sequential Testing. Removal after testing may pose additional difficulties. The testing agency should request guidance from the Manufacturer regarding safe removal and re-installation of a RESS.

5.1.3 Working with a RESS to prepare it for Sequential Testing, or to examine it after testing is potentially hazardous.

5.1.3.1 Installation of a DC Link can result in exposure to high voltage systems. Individuals attempting to install a DC Link should be thoroughly familiar with the vehicle's high voltage electrical system and use appropriate PPE.

5.1.3.2 A vehicle with an installed DC Link should be handled carefully at all times.

5.1.3.3 Opening a battery pack can expose personnel to high voltages and arc flash hazards.

5.1.4 When performing Sequential Tests, the testing agency should be prepared for the vehicle to emit flammable gases, or to completely burn.

5.1.4.1 Sequential Testing should be conducted at least 12 feet away from any extraneous flammable material (such as plastic, wood, or cloth) other than that required to instrument the vehicle or to provide power to the vehicle.

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

5.1.4.3 The testing facility should be prepared to detect and mitigate the hazards of a vehicle ignition or fire. Potential methods of mitigation include the presence of smoke or fire detectors and the capability to remotely activate appropriate fire suppression systems.

5.1.4.4 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 burn permits.

5.1.4.5 A vehicle fire can result in ejection of debris. Personnel conducting testing should be separated from contact with ejected debris. This may include use of a test chamber, a testing enclosure, or designation of a minimum safe distance to the test article.

5.1.4.6 If a RESS becomes involved in a vehicle fire, it should be remotely monitored until all visible signs of the event have ceased for at least 6 hours.

5.1.5 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.

5.1.6 After testing has concluded, test articles may be damaged and may pose a hazard during test cleanup. The testing agency should develop a plan for handling and disposing of damaged test articles.

5.2 Test Specific Precautions

5.2.1 Dynamometer Testing: during dynamometer operation the vehicle has the potential to detach from its anchors and become mobile. Proper precautions should be taken when anchoring the vehicle.

5.2.2 Overcharge and Short Circuit Testing

5.2.2.1 During overcharge and short circuit testing the potential exists for dangerous electric shock. Electrical monitoring equipment such as voltmeters and electrical safety PPE such as high voltage gloves should be used if high voltage connections are to be handled.

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

5.2.3 Destructive Discharge:

5.2.3.1 A destructive discharge of a RESS can release considerable energy. When conducting a destructive discharge of a RESS, the testing agency should be prepared for the RESS undergoing discharge to burn completely.

5.2.3.2 Preparing a RESS for destructive discharge can involve exposure to high voltage systems. PPE and engineering controls appropriate for mitigation of high voltage hazards should be used.

5.2.3.3 Should a Salt Bath method for destructive discharge be selected, the testing agency should follow the guidance in Section 7.11, and be prepared for the hazards described.

5.3 Safety Requirements

The testing agency must develop a test specific safety plan for each vehicle test, including a list of required PPE for personnel. This safety plan should be based upon information provided by the manufacturer regarding vehicle architecture, RESS chemistry and RESS architecture, as well as precautions typically associated with burn tests and high voltage systems. See discussion in Sections 5.1 and 5.2.

5.4 Test Facility/ Equipment Requirements

Pre-conditioning facility and equipment requirements.

5.4.1.1 Test track facility allowing wide open throttle operation.

5.4.1.2 Test track facility allowing rough road test cycles for mechanical vibration loading that includes both vertical and torsional input events.

5.4.1.3 Dynamometer for high speed testing.

5.4.1.4 A Mountain driving route(s) must be identified that includes elements such as steep ascents and descents and mountain road corners (Table 19). Route(s) is to include multiple ascents/descents greater than 500 m (more than 1,600 ft), and additional extended ascents of more than 1,000 m (more than 3,200ft). The mountain route must include at least 2,000 corners. The Mountain driving route should be on public roads.

Table 19 - Required Mountain Route Drive Elements.

Mountain Route Driving Element	Minimum Test Plan
Mountain Road Mileage	300 miles
Ascents/descents > 500m	8 ascents / 8 descents
Ascents/descents > 1,000m	4 ascents / 4 descents
Mountain road corners	2,000 corners

5.4.1.5 A Gravel Road Route must be identified. Driving a test vehicle on this route must produce appreciable dust throughout the drive. The Gravel Road Route must be at least 10 miles long.

5.4.1.6 A City Route must be identified. The City Route should be located within a high density urban area, and consist primarily of surface streets with stop signs and traffic lights that result in repeated stops and starts. The City Route must be at least 90 miles long.

5.4.1.7 Chargers that encompass both low rate charging (typically Level I charges), and the highest possible rate charging compatible with the vehicle under tests (for example a Level III charger).

5.4.1.8 Thermal chamber for high temperature / high humidity charging of the vehicle capable of producing a 45°C / 95% RH environment.

5.4.1.9 Thermal chamber for low temperature charging of the vehicle capable of producing a −30°C environment.

5.4.1.10 Rain booth for simulating heavy rain conditions. The booth should be capable of applying at least 500GPM of water divided into at least 125GPM

5.4.1.11 Drizzle booth for vehicle charging under drizzle conditions. The booth should be capable of applying at least 10GPM of water.

5.4.1.12 Salt spray applicator.

5.4.1.13 Car wash booth.

5.4.1.14 Vehicle hoist or lift with equipment to remove and re-install the RESS.

5.4.1.15 Workshop tools for servicing the test vehicle.

5.4.1.16 Vehicle weigh scales.

5.4.1.17 Wheel alignment and steering angle measurement tools.

5.4.1.18 Vehicle posture measurement tools.

5.4.1.19 Tire pressure and tread depth gauges.

5.4.2 Sequential Testing facility and equipment requirements.

5.4.2.1 Charging facilities, capable of delivering the maximum charge rate for which the vehicle is rated (for example, a Level 3 charger), as well as a Level 1 charging system.

5.4.2.2 Dynamometer facility with temperature control chamber or chambers capable of maintaining temperatures between -20 and 40°C for long periods.

5.4.2.3 A test area or chamber with sufficient clearance from surrounding structures, insulation, or fire suppression properties to tolerate complete failure of a vehicle under test.

5.4.2.4 Personal Protective Equipment such as respirators, safety glasses, and high voltage gloves. See discussion in Sections 5.1 and 5.2.

5.4.2.5 Test monitoring equipment and data logging equipment required to log data. This may include:

Table 20 - Sequential Test Monitoring Equipment.

Sequential Test Monitoring Equipment
Voltage probes
Current probe
Thermocouples
Interface for vehicle CAN Bus (optional)
Stopwatch

Smoke detector with a photoelectric sensor (opacity based detection)
Gas sensor (optional)
Video cameras

5.4.2.6 Cables and equipment for connection to and testing via the DC Link as described in Section 7.3.

Over-discharge resistor or load to be attached to the DC Link.

An Over-Current Source for applying an over-current overcharge to the RESS through the DC Link. The Over-Current Source should be a power supply capable of producing a maximum current consistent with regenerative braking or a faulting charger, at near full charge (max voltage) conditions of the RESS under test. The power supply should allow voltage and current limited operation, and ramping of applied current over approximately 1000 seconds. The specification of this power supply will be dependent on the vehicle under test.

An Overvoltage Source for applying an over-voltage overcharge to the RESS through the DC Link. The Overvoltage Source should be a power supply capable of producing a maximum voltage consistent with regenerative braking or a faulting charge. The power supply should allow voltage and current limited operation, and be capable of providing Level 1 charging power for 24 hours. The specification of this power supply will be dependent on the vehicle under test.

Short circuit device to be attached to the DC Link.

5.4.2.7 Capability to remove a RESS from a vehicle after testing.

5.4.3 Equipment specified by the manufacturer for conducting a destructive discharge of a RESS.

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

5.5 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 Sequential Testing is a potentially destructive full scale in-vehicle sequence of tests designed to confirm that after significant pre-conditioning (Preconditioning Sequence), the vehicle RESS and a number of fundamental RESS safety systems continue to function and do not pose a significant hazard to the vehicle's occupants or the surrounding environment.

6.1.2 At the end of Sequential Testing, the RESS is subjected to a destructive discharge per the Manufacturer's instructions to ensure that a reliable method for destructive discharge of heavily damaged RESS has been developed.

6.2 Device Under Test

6.2.1 The device under test (DUT) will be a full vehicle with an installed RESS. The vehicle and RESS should be new: less than one year old, with less than five charge discharge cycles applied to the RESS.

6.3 DUT Pre Conditioning (Preconditioning Sequence)

6.3.1 Full vehicle and RESS Preconditioning (Preconditioning Sequence) occurs during preparation for Sequential Testing.

6.3.2 Vehicle Preparation

6.3.2.1 Vehicle Components: record vehicle model and trim type.

6.3.2.2 Vehicle Mass: the vehicle manufacturer should provide a vehicle design weight and ballasting diagram for the vehicle, with a recommendation for the ratio of % of test distance that should be applied for each ballasting level and configuration, based on manufacture's expected vehicle usage profile. Should this data not be available, test weights are to be divided as per Table 3.

Prepare ballast for testing, and ensure that ballast can be distributed and secured as intended.

Weigh the test vehicle as received.

Table 3 - Vehicle Weight Conditions for Preconditioning Testing.

Vehicle Weight Condition	% of Test Distance	Relative Weight
Curb weight	5%	Curb weight
Design weight	90%	Curb weight + ½ (GVWR−Curb Weight)
GVWR	5%	GVWR

6.3.2.3 Tire Pressure: set vehicle tire pressure (cold) to specification.

6.3.2.4 Vehicle Posture: ensure that the vehicle posture is ±3mm of design intent at the test weight.

6.3.2.5 Wheel Alignment: check wheel alignment prior to test to ensure it is within specifications as outlined in the vehicle specification (ensure that alignment is performed at the design intent curb weight). If wheel alignment is out of specification, adjust to the mean level and record data.

6.3.2.6 Safety Inspection: perform a pre-test safety inspection.

6.3.3 Facility Preparation

6.3.3.1 The test track surfaces should be free from damage and debris that could affect the drive and road input loads.

6.3.3.2 Conduct a trial run (shakedown) using the test vehicle on the test track to ensure that each test can be run safely and properly.

6.3.4 Preconditioning Sequence

6.3.4.1 A variety of preconditioning events should be applied to the test vehicle. Minimum requirements for each pre-conditioning event are summarized in Table 4.

6.3.4.2 Pre-conditioning events can be applied in a variety of orders. A recommended precondition sequence is shown in

6.3.4.4 Table 5. A discussion of each preconditioning event and considerations for its sequencing can be found below and in Section 7.1.

6.3.4.5 Maintain a record of preconditioning events. Record the type of event, the vehicle weight used, event start time, and finish time, odometer reading at the beginning and end of the event, and either RESS SOC or vehicle projected range at the beginning and end of the event.

6.3.4.6 Should the vehicle suffer a mechanical problem unrelated to the RESS during preconditioning (for example, a flat tire), the vehicle should be repaired and preconditioning of the RESS should continue.

Table 4 - Summary of Vehicle Preconditioning Event Minimum Requirements.

Preconditioning Event	Minimum Required
Wide Open Throttle (WOT) + Rough Road (RR) mileage	2,500 miles
High Speed mileage	2,000 miles
Mountain Route mileage	400 miles
City Route mileage	90 miles
Gravel road mileage	10 miles
Mountain Route corners	2,000 corners
Mountain Route assents > 500 m	8
Mountain Route descents > 500 m	8
Mountain Route ascents > 1000 m	4
Mountain Route descents > 1000 m	4
Cold Charge	20 hrs
Hot Charge	20 hrs
Drizzle Charge	20 hrs
Car Wash	2
Salt Spray	1
Rain Booth hours	0.5 hrs
HV Pack Removal & Reinstall	1
Typical charging level hours (ambient temperature)	Less than 50% of ambient charge time
Highest charging level hours (ambient temperature)	More than 50% of ambient temperature charge time
Minimum Total Test Distance	5,000
Maximum Total Test Distance	10,000

Table 5 - Sequencing of Preconditioning Events.

Phase	Driving Profile	Charging
1	WOT + RR (1/2 of WOT + RR cycles)	Mix of highest level and low level ambient temperature charging
2	High Speed Driving Cycles (1/2 of HS cycles)	
3	Salt Spray Exposure	Mix of highest level and low level ambient temperature charging Cold Chamber Charging Hot Chamber Charging Drizzle Chamber Charging
	WOT + RR	
	Mountain Route	
	Gravel Road Route	
	Car Wash	
	WOT + RR	
	City Route	
	Rain Exposure	
4	High Speed Driving Cycles (1/2 of HS cycles)	
5	Car Wash	
	RESS Removal and Installation	
	WOT + RR (1/4 of WOT + RR cycles)	

6.3.4.7 WOT + RR Driving Pattern

The WOT+ RR driving pattern contains a mixture of wide open throttle (WOT) accelerations, decelerations that engage the vehicle regenerative braking system, and traverse of vertical and torsional input test roads for applying vibrational and torsional loads. The elements of the WOT + RR pattern used are described in

Table WOT accelerations are to be conducted to V, where V is the lower of 80% of vehicle maximum speed or 80 mph. If 80% of vehicle maximum speed is less than 60 mph, then the WOT acceleration is to be conducted to 60 mph. WOT + RR patterns are to be conducted in rapid succession, with periodic pauses for charging on an as needed basis. Approximately half of the planned WOT + RR drives are to be conducted in rapid succession as the first phase of preconditioning. Additional WOT + RR drives are to be sequenced in Phase 3 and Phase 5 of preconditioning.

For an EV, the vehicle should be recharged when SOC reaches 20% ±10%.

For an HEV, the vehicle should be refueled as needed.

For a PHEV, the vehicle should be subjected to electrical charging at sufficient intervals to match the Utility Factor (UF) for the vehicle: the number of miles to be driven in charge depleting mode are to be at least the UF multiplied by the planned WOT + RR miles. SAE J2841 defines Utility Factors for vehicles in the US fleet.

Table 6 - WOT + RR Elements Used for Manufacturer A Preconditioning

WOT + RR pattern elements	Number per pattern
Pattern length maximum: 1.5 miles	
0 − V wide open throttle operation (WOT)	1
V − 40 mph full regenerative braking and light brake application	1
40mph − V WOT	1
V − 20 mph full regenerative braking and medium brake application	1
Vertical input test event such as a rope road (0.05 mile)	1
Torsional input test event such as a wave road (0.05 mile)	1

V is either 80% of vehicle max speed or 80 mph, whichever is lower. V must be at least 60 mph.

6.3.4.8 High Speed Driving

The high speed driving pattern involves extended high speed operation and a mixture mid-range accelerations and decelerations that engage the vehicle regenerative braking system. The pattern is intended to be consistent with expressway driving. The maximum speed used should be 85% of the vehicle maximum speed point, or at least 80mph. The driving pattern is defined as 100 miles of driving per the requirements in Table 7. An example of one possible high speed pattern is shown in Figure 135. High speed driving patterns are to be conducted in rapid succession, with periodic pauses for charging and/or refueling on an as needed basis.

- An EV should be recharged as needed, in planned pauses within the test pattern.
- An HEV should be fueled at the beginning of the test pattern.
- A PHEV should be charged to 100% SOC at the beginning of every test pattern.

Approximately half of the planned high speed drives are to be conducted in rapid succession as the second phase of preconditioning. Additional high speed drives are to be sequenced in Phase 4 of preconditioning.

Table 7 - High Speed Driving Pattern Elements.

Event	Per 100 miles
Test Distance (miles)	100 miles
60% of max speed point (miles)	20 miles
70% of max speed point (miles)	15 miles
80% of max speed point (miles)	15 miles
85% of max speed point (miles), but not less than 80 mph	50 miles
Throttle accelerations between speed points	15
Throttle position during acceleration	Approximately 1/2
Full regenerative braking decelerations	14 minimum

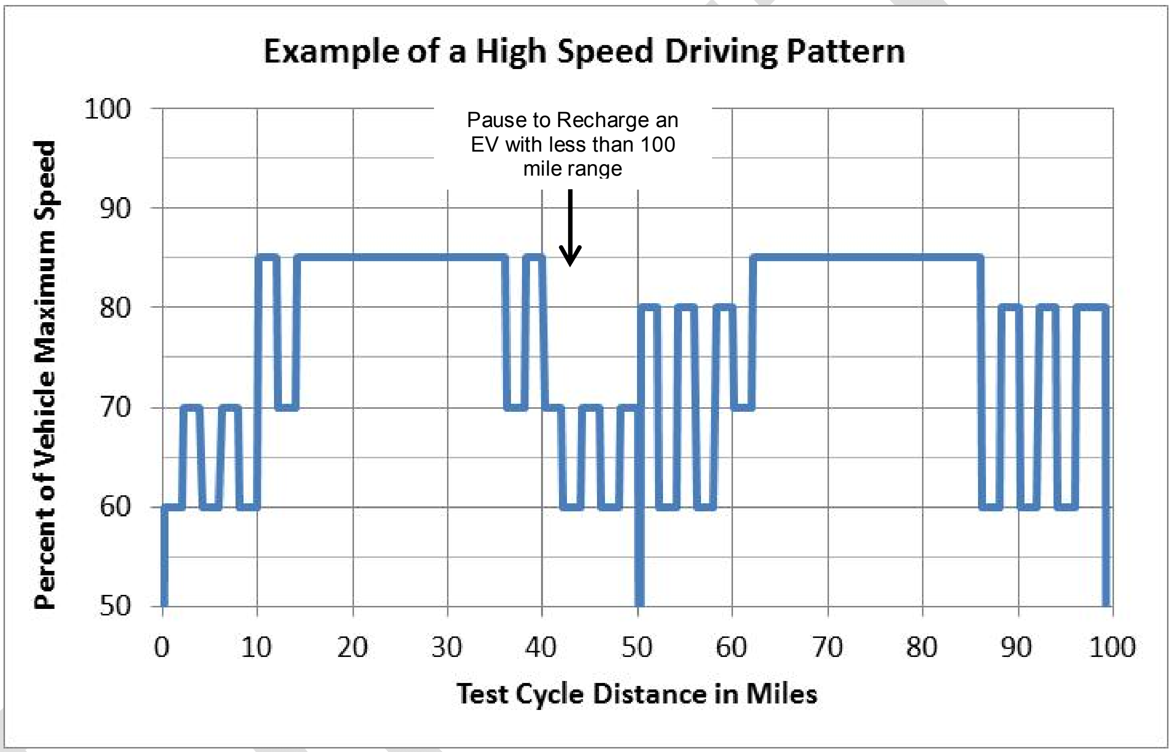

Figure 135 - Example of a High Speed Driving Pattern for an EV with less than 100 mile range.

6.3.4.9 Mountain Route driving is to be sequenced in Phase 3 of preconditioning. The Mountain Route drive must be conducted on a public roadway, driven in a manner consistent with other drivers on that roadway. The Mountain Route must include the minimum number of assents, descents, and corners described in Table 1. A minimum of 400 miles of Mountain Route driving must be accomplished. Mountain Route driving may occur in multiple sessions.

6.3.4.10 Gravel Route driving is to be sequenced in Phase 3 of Preconditioning. Driving a test vehicle on this route must produce appreciable dust throughout the drive. A minimum of 10 miles of Gravel Route driving must be accomplished. Gravel Route driving may occur in multiple sessions.

6.3.4.11 City Route driving is to be sequenced in Phase 3, 4, or 5 of Preconditioning. The City Route must be conducted on a public roadway within a high density urban environment, driven in a manner consistent with other drivers on that roadway. A minimum of 90 miles of City Route driving must be accomplished. City Route driving may occur in multiple sessions.

6.3.4.12 Salt Spray exposure is to be sequenced in Phase3 of Preconditioning. Approximately 1 L of 3% NaCl solution, or equivalent, is to be applied to a vehicle, evenly onto all external surfaces. The salt spray solution is to remain on the vehicle for at least 2 days before a car wash, rain exposure, or drizzle chamber charge is initiated.

6.3.4.13 Rain Exposure is to be sequenced in Phase 3, 4, or 5 of Preconditioning. Rain Exposure is to be conducted within a rain booth that applies at least 500GPM of water, divided into at least 125 GPM per vehicle side (top, bottom, right, left). A minimum of 0.5 hours of Rain Exposure must be accomplished. This may occur over multiple sessions.

6.3.4.14 Ambient temperature charging may be conducted with a range of charging systems. More than 50% of charging time must be accomplished with the highest level charging allowed for the Vehicle. The balance of charging may be accomplished with any level charging system. Publically available chargers may be used for charging.

6.3.4.15 Cold Chamber Charging is to be sequenced in Phase 3, 4, or 5 of Preconditioning. Cold Chamber Charging is to be conducted within a thermal chamber set at −30°C. The vehicle should be placed into the chamber and allow the RESS cells to cool to at least −10°C, or for a maximum of 6 hours before charging is initiated. A total of 20 hours of Cold Chamber Charging must be accomplished. This may occur over multiple charging sessions.

For an EV or PHEV, Cold Chamber Charging of the RESS must begin with the RESS at no more than 50% SOC. Charging must continue until normally terminated by the vehicle when it reaches a full state of charge. If charging does not initiate in the cold chamber, then the chamber temperature should be raised by 10°C, the vehicle should be allowed to thermalize to the new temperature for up to 6 hours, and charging should be attempted again. Repeat this procedure until charging initiates. If charging has not terminated within 24 hours of charge initiation, charging should be terminated, the vehicle should be removed from the chamber and charging should be completed at ambient temperatures.

For an HEV, the vehicle is to be cold soaked for 5 hours (rather than charged). Four cold soak events are sufficient for HEV testing.

6.3.4.16 Hot Chamber Charging is to be sequenced in Phase 3, 4, or 5 of Preconditioning. Hot Chamber Charging is to be conducted within a thermal chamber set at 45°C / 95% RH. The vehicle should be placed into the chamber and allowed to warm to at least 40°C, or for a maximum of 6 hours before charging is initiated. A minimum of 20 hours of Hot Chamber Charging must be accomplished. This may occur over multiple charging sessions.

For an EV of PHEV, charging of the RESS is to begin with the RESS at no more than 50% SOC. Charging must continue until normally terminated by the vehicle when it reaches a full state of charge. If charging does not initiate in the hot chamber, then the chamber temperature should be reduced by 10°C, the vehicle should be allowed to thermalize to the new temperature for up to 6 hours, and charging should be attempted again. Repeat this procedure until charging initiates. If charging has not terminated within 24 hours of charge initiation, charging should be terminated, the vehicle should be removed from the chamber and charging should be completed at ambient temperatures.

For an HEV, the vehicle is to be hot soaked for 5 hours (rather than charged). Four hot soak events are sufficient for HEV testing.

6.3.4.17 Drizzle Chamber Charging is to be sequenced in Phase 3, 4, or 5 of Preconditioning. Drizzle Chamber Charging is to be conducted within a drizzle chamber that applies at least 12GPM of water to the top of the vehicle. A minimum of 20 hours of Drizzle Chamber Charging must be accomplished. This may occur over multiple charging sessions. For an EV of PHEV, charging of the RESS is to begin with the RESS at no more than 50% SOC. Charging is to continue until normally terminated by the vehicle when it reaches a full state of charge.

For an HEV, the vehicle is to be subjected to the drizzle chamber without charging for a total of 20 hours.

6.3.5 Sequential Testing Preparation Procedure

Broadly, preparation of the vehicle and RESS for Sequential Testing will include: documentation and characterization of the vehicle and its installed RESS, determining method of DC Link connection to vehicle, and installation and documentation of monitoring sensors.

6.3.5.1 The vehicle and its RESS shall be photographed. Any anomalies shall be noted.

6.3.5.2 DC Link equipment shall be prepared per Section 7.3.

6.3.5.3 If the RESS must be opened to install any experimental equipment, it shall be photographed after opening and prior to the installation of any experimental equipment. An internal electrical isolation measurement should be performed prior to the installation of any experimental equipment. It is most convenient to obtain an isolation measurement while the RESS is installed in a vehicle. This will require the cooperation of the vehicle manufacturer. If a vehicle based measurement is not possible, then battery terminals inside the contactors must be accessed, likely by removing the pack cover. Isolation should then be measured between the battery negative terminal and the battery enclosure using an isolation resistance meter. A testing agency may also choose to conduct a Dielectric Withstand Test using a Hipot tester. The RESS shall be closed according to the manufacturer's specifications. Replacing a cover may require additional materials such as sealants or gaskets. The exterior of the RESS shall be photographed. 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.

6.3.5.4 Provision shall be made to monitor and record RESS temperature and SOC. A data link may be established with the vehicle CAN bus to allow logging of RESS temperature and SOC. RESS Voltage and current may also be monitored and logged through the CAN bus or through alternative sensors. Depending upon RESS architecture, thermocouples may be placed on the RESS exterior to monitor RESS temperature.

6.3.5.5 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.

6.3.5.6 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.

6.3.5.7 The vehicle cabin shall be physically isolated during testing: doors and windows shall be closed (with provision for experimental equipment leads to exit the vehicle cabin). The vehicle cabin heating, ventilation and air conditioning (HVAC) system shall be off or set at its lowest fan setting.

6.3.5.8 The vehicle as prepared for testing shall be photographed.

6.4 Test Methodology

6.4.1 General Testing Procedures

6.4.1.1 At least one video camera shall be used to record emission of smoke from the vehicle, any sounds associated with cell thermal runaway, and activation of the vehicle interior smoke detector.

6.4.1.2 The camera should be located at a safe distance from the vehicle to allow test personnel to approach it and change recording media (tapes) if necessary during testing, assuming that a vehicle fire occurs.

6.4.1.3 Sensors should be installed to monitor and record RESS temperature, voltage, current, and SOC. A data link may be established with the vehicle CAN bus to allow logging of this data.

6.4.1.4 Non-CAN bus based temperature, voltage, current, and SOC measurement logging devices should be configured to collect at least one measurement per second.

6.4.1.5 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.

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

6.4.1.7 The initiation of temperature logging and video recording should be synchronized: for example all systems could be started within a documented time of each other. At least five stable temperature measurements should be recorded per temperature logging channel prior to proceeding with testing.

6.4.2 Vehicle Charge and Discharge During Low Temperature Conditions: Failed Heating System Simulation

6.4.2.1 If a RESS is thermally coupled to an active heater, define a method to induce or simulate a failure which would cause that heater to become inoperable. See Section 7.4.4 for further discussion. If the pack does not rely on heaters, or uses only passive heating, no method development is required.

6.4.2.2 For a vehicle with only a charge depleting operational mode (EV), determine the RESS maximum sustained discharge power load. This information may be obtained from the vehicle manufacturer. Define a speed and grade combination that can be applied on a dynamometer to produce the maximum sustained discharge power load on the vehicle RESS.

6.4.2.3 For an EV or PHEV, bring the vehicle RESS to the midpoint of its charge depleting operational SOC (e.g. 50% ± 5% SOC). For an HEV, complete a single UDDS discharge cycle at an ambient temperature of 25°C.

6.4.2.4 For a vehicle with charge sustaining operations modes (for example an HEV or PHEV), add sufficient fuel to fill the fuel tank to 50% of its total volume.

6.4.2.5 Place the vehicle with installed RESS on a dynamometer in a temperature controlled chamber at −20±2°C (See Section 7.4.3 for further discussion). The vehicle shall be placed in the chamber for a sufficient time to equalize to ambient temperature: at least 6 hours. Chamber temperature shall be logged during testing.

6.4.2.6 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.2.7 If an EV or PHEV is being tested, connect the vehicle to a charging system capable of supplying the maximum allowable charge rate for that vehicle, and attempt to charge the vehicle. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a "steady state": either a battery temperature remaining within ±2°C for 30 minutes and an SOC remaining within ±1% for 60 minutes, or a rate of change of SOC over the previous hour indicating that charging will require more than 10 hours to complete (See Section 7.4.5 for further discussion). If an HEV is being tested move to Step 6.4.2.8.

6.4.2.8 Immediately after charging is completed (within 10 minutes), disconnect the vehicle from the charging system, place the vehicle into drive and begin a discharge cycle.

For a vehicle with only a charge depleting operational mode (EV), adjust the vehicle speed and the dynamometer rolling resistance to induce the maximum sustained discharge power load for the vehicle RESS. Continue the discharge until the vehicle will no longer provide motive power or for one hour after the vehicle has reached a steady state: either a battery temperature remaining within ±2°C for 30 minutes and an SOC remaining within ±1% for 60 minutes, or a rate of change of SOC over the previous hour indicating that discharge will require more than 10 hours to complete.

For a vehicle with charge sustaining operational modes (HEV or PHEV), apply one UDDS discharge cycle, followed by one US06 discharge cycle. Repeat the alternating UDDS and US06 discharge cycles. Discharge cycles should be initiated in rapid succession, with no more than 5 minutes elapsed between the end of one discharge cycle and the beginning of the next cycle. Continue to discharge until the vehicle will no longer provide motive power from either the RESS or the alternate fuel source. If the vehicle is not capable of operation at the requested speeds at the described temperature, maintain the achieved speed of the vehicle for sufficient time to cover the distance which would have been covered during the described test cycle before continuing to the next required speed.

6.4.2.9 For an HEV, this test will terminate when discharge is complete, continue to Section 6.4.2.12.

6.4.2.10 For an EV or PHEV, immediately after discharge terminates (within 10 minutes), connect the vehicle to a charging system capable of supplying the maximum allowable charge rate for that vehicle, and attempt to charge the vehicle. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a “steady state”.

6.4.2.11 Regardless of the point of testing which has been reached, terminate the test after 24 hours have elapsed since the start of the step 6.4.2.7.

6.4.2.12 Return the vehicle to ambient temperature and restore heating system functionality.

6.4.3 Vehicle Charge and Discharge During High Temperature Conditions: Failed Cooling System Simulation

6.4.3.1 If a RESS is thermally coupled to an active cooling system, define a method to induce or simulate a failure which would cause that cooling system to become inoperable. See Section 7.5.4 for further discussion. If the pack does not rely on an active cooling system, no method development is required.

6.4.3.2 For an EV or PHEV, fully charge the RESS at 25°C, until normal charge termination occurs and the vehicle RESS is at 100% ± 5% SOC. For an HEV, complete a single UDDS discharge cycle at an ambient temperature of 25°C.

6.4.3.3 For a vehicle with charge sustaining operations modes (for example an HEV or PHEV), add sufficient fuel to fill the fuel tank to 100% of its total volume.

6.4.3.4 Place the vehicle with installed RESS on a dynamometer in a temperature controlled chamber at the manufacturer’s specified maximum operating ambient air temperature and no less than 40°C (See Section 7.5.3 for further discussion). Chamber temperature shall be controlled to ±2°C of the target temperature. The vehicle shall be placed in the chamber for a sufficient time to equalize to ambient temperature: at least 6 hours. Chamber temperature shall be logged during testing.

6.4.3.5 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.3.6 Place the vehicle into drive and begin a discharge cycle.

For a vehicle with only a charge depleting operational mode (EV), adjust the vehicle speed and the dynamometer rolling resistance to induce the maximum sustained discharge power load for the vehicle RESS as determined in Section 6.4.2.2. Continue the discharge until the vehicle, reaches 5% SOC, the vehicle will no longer provide motive power, or for one hour after the vehicle has reached a steady state: either the RESS temperature remains within ±2°C for 30 minutes and the RESS SOC remains within ±1% for 60 minutes, or a rate of discharge of SOC over the previous hour indicates that discharge will require more than 10 hours to complete. (See Section 0 for further discussion).

For a vehicle with charge sustaining operational modes (HEV or PHEV), apply one UDDS discharge cycle, followed by one US06 discharge cycle. Repeat the alternating UDDS and US06 discharge cycles. Discharge cycles should be initiated in rapid succession, with no more than 5 minutes elapsed between the end of one discharge cycle and the beginning of the next cycle. Continue to discharge until the vehicle will no longer provide motive power from either the RESS or the alternate fuel source. If the vehicle is not capable of operation at the requested speeds at the described temperature, maintain the achieved speed of the vehicle for sufficient time to cover the distance which would have been covered during the described test cycle before continuing to the next required speed.

6.4.3.7 If an EV or PHEV is being tested, immediately after the discharge cycle is completed (within 10 minutes) connect the vehicle to a charging system capable of supplying the maximum allowable charge rate for that vehicle, and attempt to charge the vehicle. Allow normal charge termination, or terminate charging one hour after the vehicle reaches a "steady state": either a battery temperature remaining within ±2°C for 30 minutes and an SOC remaining within ±1% for 60 minutes, or a rate of change of SOC over the previous hour indicating that charging will require more than 10 hours to complete (See Section 0 for further discussion).

6.4.3.8 If an HEV or PHEV is being tested, refuel the vehicle (fill the fuel tank to 100% capacity).

6.4.3.9 Immediately after charging is completed (within 10 minutes), or after the vehicle has been refueled, disconnect the vehicle from the charging system, place the vehicle into drive and begin a discharge cycle.

For a vehicle with only a charge depleting operational mode (EV), adjust the vehicle speed and the dynamometer rolling resistance to induce the maximum sustained discharge power load for the vehicle RESS. Continue the discharge until the vehicle, reaches 5% SOC, the vehicle will no longer provide motive power, or for one hour after the vehicle has reached a steady state: either the RESS temperature remains within ±2°C for 30 minutes and the RESS SOC remains within ±1% for 60 minutes, or a rate of discharge of SOC over the previous hour indicates that discharge will require more than 10 hours to complete.

For a vehicle with charge sustaining operational modes (HEV or PHEV), apply one UDDS discharge cycle, followed by one US06 discharge cycle. Repeat the alternating UDDS and US06 discharge cycles. Discharge cycles should be initiated in rapid succession, with no more than 5 minutes elapsed between the end of one discharge cycle and the beginning of the next cycle. Continue to discharge until the vehicle will no longer provide motive power from either the RESS or the alternate fuel source. If the vehicle is not capable of operation at the requested speeds at the described temperature, maintain the achieved speed of the vehicle for sufficient time to cover the distance which would have been covered during the described test cycle before continuing to the next required speed.

6.4.3.10 Regardless of the point in testing which has been reached terminate the test after 24 hours have elapsed since the start of step 6.4.3.6.

6.4.3.11 Return the vehicle to ambient temperature and restore cooling system functionality.

6.4.4 Vehicle RESS Over-Discharge

6.4.4.1 Make the connection to the DC Link. See Section 7.3 for further discussion of DC Link installation. Installation may require that the RESS be removed from the vehicle, and subsequently re-installed.

6.4.4.2 Discharge the vehicle RESS to approximately 10% SOC. For an HEV or PHEV, remove fuel from the fuel tank so that the tank is less than 5% full.

6.4.4.3 Chock the vehicle to prevent rolling or creep.

6.4.4.4 Testing can occur at ambient temperatures, so long as the vehicle allows discharge of the RESS at the ambient temperature.

6.4.4.5 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.4.6 Drive Mode Over-Discharge Attempt

Place the vehicle into drive mode but do not request any acceleration.

Install the ‘over-discharge resistor’ into the terminals of the DC Link connection box, and close the positive and negative terminal switches to create a circuit across the DC Link with a resistive load. Allow the RESS to discharge at a power load of less than 1kW.

Continue to discharge the RESS via this method until one of the following happens: either the DC Link Voltage reaches 0V (this may occur if the RESS terminates discharge) or 8 hours elapse.

Isolate the discharge resistor in the DC Link (open the discharge circuit).

6.4.4.7 Should the vehicle not have separated driving and charging modes (e.g. an HEV), continue to Section 6.4.4.9.

6.4.4.8 Charge Mode Over-Discharge Attempt

For a vehicle with separate driving and charging modes (an EV or PHEV), connect the Vehicle to a Level 1 charger[28] and recharge the RESS to the lowest operational SOC at which vehicle will enter Drive Mode using energy from the RESS only.

Disconnect the charger at the AC supply side, but allow the cable to remain connected to the vehicle.

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[28] A Level 1 charger is specified in this test for experimental convenience. Using a Level 1 charger will most easily limit the charging of the vehicle between over-discharge attempts.

Install the 'over-discharge resistor' into the terminals of the DC Link connection box, and close the positive and negative terminal switches to create a circuit across the DC Link with a resistive load. Allow the RESS to discharge at a power load of less than 1kW.

Continue to discharge the RESS via this method until one of the following happens: either the DC Link Voltage reaches 0V (this may occur if the RESS terminates discharge) or 5 hours elapse.

6.4.4.9 Isolate the discharge resistor in the DC Link (open the discharge circuit).

6.4.5 Vehicle RESS Over-Current Overcharge

6.4.5.1 Charge the RESS until it is at 95% ± 2% SOC. This may be accomplished by connecting the vehicle to a charger (EV or PHEV) and allowing it to charge the vehicle normally to 100% SOC and then discharging the vehicle slightly by using the vehicle cabin heater, AC system, or through driving.

6.4.5.2 For an HEV, the RESS should be charged fully using a driving pattern recommended by the manufacturer.

6.4.5.3 For an HEV or PHEV, fill the fuel tank to 100% of capacity.

6.4.5.4 Confirm the DC Link connection is properly installed and that all switches are open within the switchboard.

6.4.5.5 Determine the maximum over-current that will be applied to the RESS. This value will be based upon the maximum current that can be supplied by regenerative braking or a faulting charger. The vehicle Manufacturer may provide guidance.

6.4.5.6 Determine the maximum theoretical voltage that can be applied to the RESS by the on-board charger or a faulting compatible charger. The vehicle Manufacturer may provide guidance. Multiply the maximum theoretical voltage by the maximum over-current to obtain the maximum charging power for power supply selection.

6.4.5.7 Connect the Over-Current Supply as described in Section 7.3 to the DC Link. Set the current limit and voltage limit on the Overcurrent Supply based on Sections 6.4.5.5 and 6.4.5.6.

6.4.5.8 Testing can occur at ambient temperatures, so long as the vehicle allows charge of the RESS at the ambient temperature.

6.4.5.9 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.5.10 Place the vehicle into charging mode. For an EV or PHEV, connect a Level 1 charger[29] to the vehicle and initiate charging. If the vehicle is a HEV with no separate charging and

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[29] A Level 1 charger is specified to allow establishment of steady charging and to provide the longest time window during which to introduce the charging fault which comes from an external supply. The recommended fault current in Section 6.4.5.5 is based on having only Level 1 charging in addition to the fault current.

discharging mode, place the vehicle into an operational mode. Allow charging currents to stabilize.

6.4.5.11 Turn on the Overcurrent Supply connected to the DC Link and linearly increase the attempted charging current over 1000 seconds from zero current until it reaches the maximum charging current determined in Section 6.4.5.5 or until the RESS isolates itself from the power supply.

6.4.5.12 Continue to attempt to charge at the final charging current reached in Section 6.4.5.11 until one of the following occurs; and automatic disconnect in the RESS opens and remains open for at least 2 hours, 24 hours elapse; or a failure occurs (smoke, fire, or explosion).

6.4.6 Vehicle RESS Over-Voltage Overcharge

6.4.6.1 Discharge the RESS, until it is at 95% ± 2% SOC. This may be accomplished by using the vehicle cabin heater, AC system, or through driving.

6.4.6.2 For an HEV or PHEV, fill the fuel tank to 100% of capacity.

6.4.6.3 Confirm the DC Link connection is properly installed on the RESS and that all terminal switches are open within the DC Link.

6.4.6.4 Determine the maximum theoretical voltage that can be applied to the RESS by the on-board charger or a faulting compatible charger. The vehicle Manufacturer may provide guidance.

6.4.6.5 Determine the appropriate current limit: divide 1.4 kW (Level 1 charging power) by the maximum voltage determined in Section 6.4.6.4.

6.4.6.6 Connect an Overvoltage Supply as described in Section 0 to the DC Link. Set its voltage limit to the maximum voltage determined in Section 6.4.6.4. Set the current limit to the maximum current determined in Section 6.4.6.5. If the Overvoltage Supply is of the type which features both a current/voltage limit and a trip current/voltage setting, the trip values should be set 10% higher than the current/voltage limit.

6.4.6.7 Testing can occur at ambient temperatures, so long as the vehicle allows charge of the RESS at the ambient temperature.

6.4.6.8 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.6.9 Place the vehicle into charge mode. If the vehicle is a HEV with no separate charging and discharging mode, place the vehicle into its driving or operational mode.

6.4.6.10 For an EV or PHEV, attach a charging cable to the vehicle at its charge inlet and begin charging at Level 1 charging levels. In a HEV move to the next step without taking any action.

6.4.6.11 Once charging has begun, turn on the Overvoltage Supply connected to the DC Link. Close the positive and negative terminal switches on the DC Link and allow the Overvoltage Supply to begin charging the vehicle.

6.4.6.12 Continue to attempt to charge until one of the following occurs; and automatic disconnect in the RESS opens and remains open for at least 2 hours, 24 hours elapse; or a failure occurs (smoke, fire, or explosion).

6.4.6.13 Once the test has concluded, disconnect the overvoltage supply and the charging cable (if present).

6.4.7 RESS External Short Circuit

6.4.7.1 Confirm the DC Link connection is properly installed on the RESS and that all terminal switches are open within the DC Link.

6.4.7.2 Discharge the RESS, until it is at 95% ± 2% SOC. This may be accomplished by using the vehicle cabin heater, AC system, or through driving.

6.4.7.3 If an HEV or PHEV is being tested, fill the fuel tank to 100% capacity.

6.4.7.4 Chock the vehicle to prevent rolling or creep.

6.4.7.5 Testing can occur at ambient temperatures, so long as the vehicle allows discharge of the RESS at the ambient temperature.

6.4.7.6 Initiate data recording: begin the test timer, start the video recording, and begin logging RESS temperature, voltage, current, SOC, vehicle interior temperature, and test chamber temperature.

6.4.7.7 Place the vehicle into Drive Mode.

6.4.7.8 Connect the short circuit device to the DC Link (Section 7.3).

6.4.7.9 Create the short circuit across the DC Link, causing a short circuit of the RESS and vehicle high voltage system. The total impedance of the short circuit shall be between 2 and 5 mΩ. It shall not be greater than 5 mΩ. See Section 7.9 for a discussion of the selection of short circuit impedance.

6.4.7.10 Continue to monitor the RESS until RESS temperature has remained stable for 60 minutes (within ±2°C).

6.4.7.11 Check the continuity of the fuses within the short circuit device. If fuses have opened, the test shall be repeated with fuses rated for higher current flow and other necessary improvements.

6.4.7.12 Photograph the vehicle with installed RESS.

6.4.7.13 Remove the RESS from the Vehicle and photograph the RESS.

6.4.8 RESS Destructive Discharge

6.4.8.1 The RESS Manufacturer should provide a method for destructively discharging a RESS in the instance that electrical discharge of the RESS is not possible. That method is to be attempted by the testing agency and assessed for efficacy.

6.4.8.2 If no Manufacturer provided destructive discharge method is available, and the RESS is composed of lithium-ion cells, the testing agency may attempt a salt bath method for destructive discharge as described below. Safety precautions should be taken to mitigate the hazards discussed in Section 7.11.

6.4.8.3 Obtain overall RESS physical dimensions, design voltage, and design capacity.

6.4.8.4 Remove the RESS cover and examine the physical construction of the RESS. Removal of a RESS cover can expose high voltage components. High Voltage safety precautions and PPE should be used. Note the RESS electrical architecture including whether components are connected in series or parallel, and the location of various passive protection devices such as fuses. Note the mechanical architecture of the RESS including individual module or cell dimensions, and whether, if flooded, water will contact individual cells.

6.4.8.5 Use gathered information regarding RESS architecture to determine whether the RESS can be subjected a single salt bath as a unit, or whether it should be divided into subcomponents for destructive discharge. Single cell salt bath trials as described in Section 7.11 may be appropriate to conduct prior to attempting a module or RESS level salt bath destructive discharge.

6.4.8.6 Prepare one or more salt bath(s) per the discussion in Section 7.11.

6.4.8.7 Prepare the RESS or subcomponents of the RESS for Salt bath immersion: remove covers and eliminate tortuous water flow paths; connect the item to be discharged to a hoist or other device for allowing rapid submersion in the salt bath.

6.4.8.8 Immerse the RESS or RESS components in the salt bath.

6.4.8.9 Monitor the salt bath closely for 1-3 hours until the most severe bubbling has ended, to ensure that water levels remain sufficiently high. Continue to monitor the salt bath periodically for 1-3 days until the destructive discharge reaction has completed to ensure that water levels remain sufficiently high.

6.4.8.10 Remove the destructively discharged item from the salt bath and prepare it for recycling.

6.4.8.11 Remove the liquid waste from the salt bath and prepare it for proper disposal.

6.5 Measured Data

6.5.1 Test reports should include the following information:

6.5.1.1 A description of the preconditioning vehicle used, including elements listed in Table 8.

Table 8 - Test Report Material; Preconditioning Vehicle.

Test Report Material
Vehicle model
Vehicle trim type
Vehicle curb weight
Vehicle design weight
Vehicle tire pressure at start of test

6.5.1.2 A description of the preconditioning procedure used, including elements listed in Table 9.

Table 9 - Test Report Material; Preconditioning Procedure.

Test Report Material
Summary of preconditioning events relative to requirements
Summary of preconditioning sequence
Description of WOT + RR pattern
Description of High Speed Driving pattern
Description of Mountain Route
Description of Gravel Route
Description of City Route
Description of Salt Spray application
Description of Rain Exposure water application
Description of ambient charging levels
Description of Drizzle Charge water application

6.5.1.3 Preconditioning summary and driver logs, including the elements listed in Table 10.

Table 10 - Test Report Material; Preconditioning Drive.

Test Report Material	
Summary of preconditioning events completed relative to requirements	
Summary of preconditioning sequence completed	
Driver log describing each completed preconditioning element	
	Description of element completed
	Vehicle weight used
	Date
	Start time
	End time
	Start odometer reading
	End odometer reading

6.5.1.4 Location of all sensors installed for Sequential Testing, including the elements listed in Table 11.

Table 11 - Test Report Material; Sequential Testing Sensor Locations.

Test Report Material
RESS Temperature sensor location (may be from CAN bus)
RESS SOC sensor location(may be from CAN bus)
RESS Voltage sensor location(may be from CAN bus)
RESS current sensor location(may be from CAN bus)
Opacity –based smoke alarm location
Gas sensor or gas sampling equipment location (optional)
Temperature sensor location(s) within vehicle cabin
DC Link installation description

6.5.1.5 For each sequential test conducted, the test report should include the materials listed in Table 12.

Table 12 - Test Report Material; Sequential Test Results.

Test Report Material
Photographs of vehicle and RESS prior to Sequential Testing
If RESS was opened for test preparation, then photographs of RESS before and after equipment installation
If RESS was opened for test preparation, then results of internal electrical isolation measurements before and after equipment installation
Video of Sequential Testing
RESS temperature
RESS SOC
RESS voltage
RESS current
Elapsed time for each test
Times of any anomalous events such as thermal runaway reactions, ignitions, or smoke alarm activation
Gas sensor or gas sampling results (optional)
Vehicle cabin temperature
Photographs of the RESS after completion of Sequential Testing and before destructive discharge

6.5.1.6 A description of the destructive discharge method used and an assessment of its efficacy.

6.6 Post-Test Requirements

6.6.1 After Sequential Testing, the vehicle without the RESS, may be undamaged and used for other purposes.

6.6.2 After destructive discharge, the remains of a RESS may require special handling for disposal or recycling. The testing agency should refer to manufacturer specified destructive discharge instructions and ensure that RESS remains are disposed of or recycled in accordance with environmental regulations.

6.7 Acceptance Criteria

Acceptance criteria for Sequential Testing are divided into two categories: hazard to the occupant, and hazard to the surrounding environment.

6.7.1 Cabin Tenability Requirements

The cabin must remain tenable throughout Sequential Testing for sufficient time to allow safe egress of vehicle occupants after they have perceived that a serious failure has occurred, or for 1 hour after initiation of a failure that does not produce a condition that provides significant warning properties to occupants.

6.7.1.1 The cabin temperature must remain tenable, assuming vehicle windows are closed, and the HVAC system is off or at its lowest fan setting.

6.7.1.2 The cabin air must remain free of significant inhalation hazards, assuming vehicle windows are closed and the HVAC system is off or at its lowest fan setting.

6.7.2 Hazards to the Surrounding Environment

The vehicle throughout Sequential Testing must not pose an ignition or mechanical hazard to the surrounding environment.

1. The vehicle should not ignite as a result of Sequential Testing.
2. Vent gases emitted by the vehicle as a result of Sequential Testing should not ignite.
3. There should be no explosion as a result of Sequential Testing.

6.7.3 A Destructive Discharge method for the RESS must be demonstrated.

7. TEST PROCEDURE RATIONALE

7.1 5,000 Mile Preconditioning

A number of testing standards related to cells and batteries such as UL1642 Standard for Lithium Batteries, UL2054 Standard for Commercial and Household Batteries, and the UN Manual of Tests and Criteria T-tests for lithium-ion batteries require testing not only of new un-cycled cells or battery packs, but also of cycled (aged) cells or battery packs. This approach acknowledges that cells of any chemistry are subject to a variety of aging mechanisms that can affect their performance, including safety performance. Aging mechanisms of many cell chemistries, particularly of relatively novel chemistries are often poorly understood. However, the UL and UN standards apply a preconditioning strategy that is appropriate for cells and battery packs designed for the consumer electronics industry: cells are electrically cycled under relatively uniform, ambient temperature conditions. As most consumer electronics devices are used in fairly benign home or office environments, electrical cycling is a reasonable preconditioning methodology, as electrical cycling is the dominant aging mechanism for these cells and battery packs.

The cells and other components of a RESS are also subject to aging mechanisms that can affect their performance, including safety performance, particularly since RESS construction, sensing and control approaches continue to evolve, and extensive reliability data remains unavailable for many potential RESS components. Electrical cycling remains an important aging mechanism. However, a number of additional mechanical, thermal, and environmental aging mechanisms may also affect the safety performance of a RESS, and the simultaneous or intermingled application of these aging mechanisms may be important to safety performance. For example, electrical charging a RESS that exhibits a strong thermal gradient due to high speed operation may cause damage to some cell electrodes but not to others. Torsional or vibrational loads on a RESS can cause mechanical damage to cell electrodes that can be exacerbated by extended high rate charging from a regenerative braking system. Liquid ingress after seals have been compromised by vibration or high temperature operation can compromise sensors or other RESS components. Any of this damage may result in components that are no longer robust to expected high stress conditions such as high temperature charging, overcharge conditions, over-discharge conditions, or RESS external short circuit.

Preconditioning, in a laboratory setting, a full RESS by applying multiple, relevant, usage conditions specific to an actual vehicle presents many experimental challenges. Equipment requirements are significant: for example, large format battery charge and discharge equipment, and facilities capable of simultaneous charge or discharge and temperature control during vibration are rare. The appropriate preconditioning load levels for each RESS would have to be determined by measuring load levels on the RESS during drive tests, and then applying those measured load levels in a laboratory setting. Even if a full vehicle were to be subjected to specific laboratory based testing, applying appropriate loads only with traditional laboratory test equipment (dynamometer, 4-post vibration fixture, vehicle thermal chamber) will not capture all relevant load conditions. In addition, it is difficult to apply load conditions either simultaneously or in multiple repetitions in a laboratory environment without incurring substantial experimental costs. In comparison, installing a RESS in its associated prototype or production vehicle and subjecting the vehicle to a combination of actual driving conditions and high acceleration factor driving conditions is a convenient and appropriate method for applying repeated and intermingled electrical loads, vibrational loads, torsional loads, environmental loads, and thermal gradients that are representative of actual usage conditions and RESS degradation modes. As each vehicle design is unique, a vehicle drive sequence will apply unique loads to the installed RESS that are appropriate for that RESS/ vehicle combination.

A RESS Preconditioning Sequence should applying sufficient electrical, mechanical, thermal, and environmental loads to the RESS to assess its robustness while not degrading the capacity of the RESS to such a degree that subsequent Sequential Testing would no longer meaningfully evaluate the RESS safety performance. For consumer electronics battery packs, the UN and UL standards require that approximately 50 electrical cycles be applied to a battery pack. A typical consumer electronics device would be expected to complete on the order of 500 cycles in its lifetime. Thus the UN and UL requirement represents approximately 1/10 of the device expected cycle life. Subjecting a RESS to 5,000 miles of driving would represent a small but significant fraction of expected vehicle operation, and should not cause RESS capacity to approach an end-of-life level. By applying high acceleration factor driving patterns that concentrate potentially damaging electrical, mechanical, and thermal loads, a 5,000 mile drive sequence can apply greater loading than would be encountered by a vehicle in the hands of a typical user for 5,000 miles.

The Preconditioning Sequence has not been rigidly defined as the intent of this Sequence is to apply real world loads to a RESS and ensure that the RESS is robust to those loads and continues to meet safety performance requirements as it ages. Neither the Preconditioning Sequence, nor the following Sequential Tests are intended to be a stress test of a RESS, but rather they are intended to ensure that aging of RESS components has been adequately considered and executed during the design and manufacturing process. Thus, it is less important that a specific preconditioning sequence be applied than it is that a representative preconditioning sequence be applied to a RESS. As a result, the Preconditioning Sequence has been defined in such a manner that is relatively non-burdensome to a testing agency and will allow for variability between test facilities.

A Preconditioning Sequence has been defined that mixes a large number of high acceleration factor driving patterns that concentrate potentially damaging electrical, mechanical, and thermal loads with some low acceleration factor driving patterns that apply a greater variety of less common potentially damaging loads. A variety of charging conditions are applied throughout the sequence and some typical environmental loads are also specified, to supplement environmental loads that may be encountered during driving. The elements of the Preconditioning Sequence are described in Sections 7.1.1 through 7.1.12. Preconditioning Sequence segment miles are not rigidly defined to allow for variability between testing facilities.

The order of the Preconditioning Sequence has been loosely defined to allow convenient scheduling by a test agency. However, it requires that at least half of the high acceleration factor driving patterns be completed before application of the less typical low acceleration factor events, challenging charging conditions, and supplemental environmental loads. The Preconditioning Sequence also varies the order of application of the various aging loads on the RESS.

7.1.1 WOT + RR Driving

The WOT + RR Driving pattern is intended to apply a large number of electrical high rate discharges, and regenerative braking charges, intermingled with high vibrational loads and torsional loads that might result from typical driving, but in a compressed format. The WOT +RR pattern has a high acceleration factor for potential damage compared to typical consumer driving patterns. The WOT + RR driving pattern is intended to accelerate damage to RESS cells and other components that are susceptible to degradation under high current flows, mixed with vibrational and torsional loads. For example, if a lithium-ion cell within a RESS has a poorly designed or manufactured electrode, vibrational and torsional loads may cause flaking of that electrode, while high current charging can result in lithium plating on the electrode regions subject to flaking, ultimately reducing safety performance of the cell.

7.1.2 High Speed Driving

High Speed Driving is intended to apply a large number of electrical high rate discharges and regenerative braking charges, as well as thermal loads resulting from high speed motor operation to a RESS consistent with loads that might result from significant expressway driving, but in a compressed format. The High Speed Driving pattern has a high acceleration factor for damage compared to typical consumer driving patterns. The High Speed Driving pattern is intended to accelerate damage to RESS cells and other components that are susceptible to degradation under extended high current discharge and charge, or thermal loads from extended, high speed motor operation.

7.1.3 Mountain Route

A Mountain Route to be conducted on public roads was included as a preconditioning element to apply real world variability to the Preconditioning process: a drive on a public roadway will result in a broad range of simultaneous accelerations, decelerations, lateral loads, vibrations and environmental loads that are difficult to program into a closed track or dynamometer program but that might have unexpected effects on a RESS. These loads include:

- Extended hill climbs with variable accelerations that result in extended high but variable loads on the RESS.
- Extended hill descents with variable braking that result in extended but variable regenerative braking charging of the RESS.
- Extensive cornering and lateral loading of the vehicle that can apply a variety of torsional loads to the RESS.
- Shifts in environmental conditions as the vehicle moves up and down in elevation, such as changes in temperature and humidity and pressure.

The Mountain Route was sequenced into Phase 3 of preconditioning to apply a range of loads after the vehicle has already seen a significant portion of WOT, vibrational, and high speed loads. The Mountain Route Drive pattern has a low acceleration factor for damage compared to typical consumer driving patterns.

7.1.4 Gravel Road Route

The Gravel Road Route is intended to expose the RESS to a high concentration of dust and road debris while simultaneously applying high vibrational loads. The Gravel Road Route is sequenced into Phase 3 of Preconditioning so that the RESS will already have experienced some vibrational loads that can compromise seals that might allow entry of dust and debris. The Gravel Road Route has a high acceleration factor for damage compared to typical consumer driving patterns.

7.1.5 City Route

A City Route to be conducted on public roads in a high density urban environment was included as a preconditioning element to apply real world variability to the Preconditioning process: a drive on a public roadway will result in a broad range of simultaneous accelerations, decelerations, lateral loads, vibrations and environmental loads that are difficult to program into a closed track or dynamometer program but that might have unexpected effects on a RESS. These loads include:

- Extended stop and go due to city traffic.
- Vibrational and shock loads due to uneven pavement and features such as potholes.

The City Route was sequenced into Phase 3 of preconditioning to apply a range of loads after the RESS has already seen a significant portion of WOT, vibrational, and high speed loads. The City Route Drive pattern has a low acceleration factor for damage compared to typical consumer driving patterns.

7.1.6 Salt Spray

A salt spray element has been included in preconditioning to simulate the presence of road salts that may work their way into a RESS and cause loss of internal isolation, corrosion, or compromise various RESS components. The salt spray is sequenced into Phase 3 of Preconditioning so that the RESS will have already experienced some vibrational loads that can compromise seals that might allow entry of salts, and so that any salt that enters a RESS will have some time to induce corrosion before Sequential Testing begins.

7.1.7 Rain Booth

Rain booth exposure had been included in preconditioning to simulate heavy rain exposure that may result in moisture penetration of RESS seals and ultimately causing a loss of internal isolation, or compromise various components of the RESS. The rain booth exposure has been sequenced into Phase 3, 4, or 5 of Preconditioning so that the RESS will have already experienced some vibrational loads that might have compromised seals, prior to rain exposure. The rain booth exposure is intended to ensure that Preconditioning includes some rain exposure even if no rain occurs during test track or public road operation.

7.1.8 Cold Charge

Cold Charging (or cold soaking for an HEV) has been included in preconditioning because this provides a thermal cycle that can result in failure of a range of components. In particular, cold charging of lithium-ion cells can induce non-ideal reactions such as lithium plating that can ultimately affect cell safety performance. Non-ideal reactions are more likely to occur if cell electrodes have become damaged due to significant vibrational, torsional, or electrical loading. The cold temperature will create thermal stresses from differences in the coefficients of thermal expansion (CTE). The cold soak can also create condensation within a battery pack. Cold Charging is sequenced into Phase 3, 4, or 5 of Preconditioning so that the RESS will have already seen a significant portion of WOT, vibrational, and high speed loads that might compromise cells with poor electrode design or electrode defects, and other components with poor robustness.

7.1.9 Hot Charge

Hot Charging (or hot soaking for an HEV) has been included in preconditioning because this provides a thermal cycle that can result in failure of a range of components, particularly those exposed to high current loads. The hot temperature will create thermal stresses from differences in the coefficients of thermal expansion (CTE). Hot temperatures can also accelerate plastic creep. Hot Charging is sequenced into Phase 3, 4, or 5 of Preconditioning so that the RESS will have already seen a significant portion of WOT, vibrational, and high speed loads that might compromise components with poor robustness.

7.1.10 Drizzle Charge

Charging under drizzle conditions (or exposing an HEV to a drizzle chamber) is intended to ensure that Preconditioning includes some charging under wet conditions for EVs and PHEVs, and to ensure that HEVs are exposed to drizzle even if no drizzle occurs during test track or public road operation.

7.1.11 Car Wash

Application of car washes is intended to expose the RESS to typical detergents and surfactants that can enhance the transport of road salt or dirt into crevices in the RESS.

7.1.12 RESS Removal and Re-Install

A RESS removal and re-installation element was added to simulate maintenance that may occur on a vehicle.

7.2 Sequential Testing

The Vehicle Sequential Tests are intended to apply normal and expected streses to a RESS, in order to ensure that aging of RESS components has been adequately considered and executed during the design and manufacturing processes. Following appropriate preconditioning, a RESS should be able to withstand a variety of expected abuse and failure conditions without posing a hazard to the vehicle occupant or the surrounding environment. A series of tests have been selected from a number of widely accepted battery pack test methods that represent commonly experienced single point failure modes. These tests have been adapted for application to large format RESS installed in a production vehicle and are discussed further in Sections 7.4 through 7.9.

Selected tests have been placed in a sequence (Sequential Testing) that not only reduces the number of required test articles, but is intended to reveal and exacerbate a range of potential failure modes. The concept of sequential testing for cells and battery packs is derived from the approach used in the UN Manual of Tests and Criteria for testing lithium ion cells and battery packs. In the UN Manual, a series of 5 tests for lithium-ion systems (T1-T5) are conducted in a specified order so that conditions that may damage cells or battery packs but that may not provide clear indication of damage (altitude simulation, thermal cycling, vibration, and mechanical shock) are followed by an external short circuit test, that not only tests the article's robustness to external short circuit, but is likely to indicate whether the article accrued serious damage in previous tests. As with the UN Tests, the final test in Sequential Testing is an external short circuit test.

In direct comparison to many standard tests which are conducted on cells or small battery packs, the ambient conditions and loads described in Sequential Testing may seem relatively benign. A RESS which behaves as desired during these tests should, with the exception of the short circuit test, remain unaltered by each test's electrical and environmental boundary conditions. However, this will only be true if the RESS properly operates whatever safety architecture has been built into its design, and that the safety architecture has not been compromised by RESS aging (preconditioning) or tests conducted previously in the sequence.

7.3 DC Link Function and Installation

A DC Link is required for the RESS over-discharge, over current overcharge, over voltage overcharge, and external short circuit tests. A variety of devices can be connected to the DC Link to achieve the required electrical conditions for the test. One possible configuration of electrical test equipment is diagramed in Figure 2 to Figure 5 with images of example equipment in Figure 6 and Figure 7.

Figure 2 shows the connection method of the DC Link to the RESS via a junction box that exists in Manufacturer A's vehicle. Requirements for a DC Link include:

- The Vehicle OEM should provide the testing agency with documentation detailing how a DC Link can be installed with minimum disruption to the vehicle systems. Generally, vehicle high voltage cables should be accessible adjacent to the RESS-to-vehicle high voltage connection.

- The DC Link should be electrically connected as close as possible to the outside of the RESS enclosure. There should be no active or passive protection components between the DC Link connection and the RESS unless they are contained within the RESS. This includes devices such as fuses, thermally activated switches, or relays. Examples of DC Link installation points in a variety of vehicles are shown in Section 8.1.

- The Vehicle OEM should provide information regarding expected short circuit current, maximum operational pack voltage, and a pack charge capacity vs. voltage curve to allow construction of an appropriate DC Link including cable gauge.

- The DC Link shall be sufficiently isolated from all other parts of the vehicle. This isolation shall be capable of withstanding a voltage difference equal to U + 1695V.

- Joints or terminals shall be of a design capable of secure and low resistance connection such as a bolt secured lug.

- Cables used in the DC Link shall be rated to safely conduct the currents levels expected in all test procedures such that they do not become a failure point.

- Exposed high voltage should be minimized as part of the DC Link.

- Many functionally equivalent circuits are possible, but care should be taken to select components which are rated for the appropriate currents and voltages.

- Vehicle shall be able to charge and discharge normally with the DC Link connection installed.

An example of the electrical equipment used for Sequential Testing is shown in Figure 6 and Figure 7. It is composed of three key components: a switchboard, a discharge resistor unit, and a power supply. As shown in Figure 3, the switchboard contains a short circuit box to allow for shorting of the pack, as well as two Tap boxes. The Tap boxes allow for a switched connection to the positive and negative terminal of the DC Link. All switches are rated for voltages up to 600 V and the entire switchboard is touch-safe.

To perform the Short Circuit Test, only the switchboard is required and the Tap boxes are open circuit with nothing connected.

- Appropriate information regarding sizing of the fuses in the vehicle and RESS should be provided by the Vehicle OEM.

- The switch shall be capable of withstanding the short circuit discharge current of the RESS.

- The short circuit box shall be fused to protect the DC link cables, connections and shorting switch. The short circuit device should be sized such that it does not interrupt the test. After the short circuit test, the fuses should be checked and if still intact then the test is valid. Otherwise, the short circuit device needs to be scaled up such that the vehicle or RESS interrupts the short circuit test.

The example shown in Figure 7 contains two 630A fuses in parallel and at least 2/0 AWG cable or equivalent bus bar size.

Figure 4 illustrates an example configuration for performing the Over-Discharge Test. For this test, the short circuit box shall remain open circuit and a discharge resistor is connected to the Tap boxes.

- The over-discharge resistor may represent a significant hazard during operation, and should be physically isolated from other circuit components and flammable material.

- This unit should be sufficiently cooled, for example, with air blowing fans, to allow it to maintain a safe operating temperature.

The example shown in Figure 6 is constructed from ten separate 20 Ω resistors. The discharge resistor unit construction allows for resistors to be placed in parallel or in series, so that the discharge resistor unit can be configured to produce a 1 kW discharge for RESS of a variety of operational voltages.

Figure 5 shows an example configuration of the setup for both the Over-Current Overcharge and Over-Voltage Overcharge Tests. The short circuit box is open circuit and both Tap boxes are used to make a connection to a power supply (Figure 40).

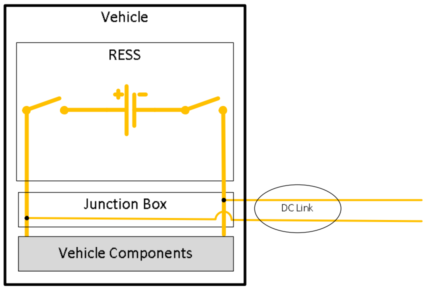

Figure 2 - Diagram of DC link for as tested for Manufacturer A.

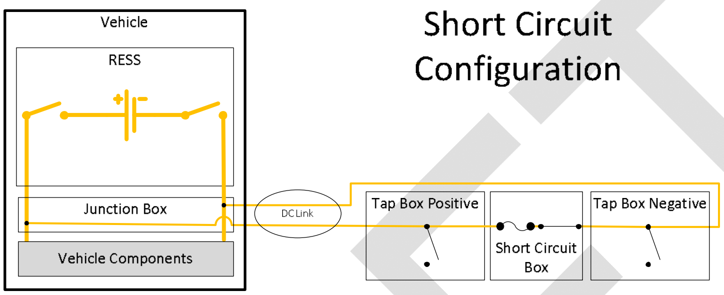

Figure 3 - Diagram of DC Link with switchboard configured for the Short Circuit Test.

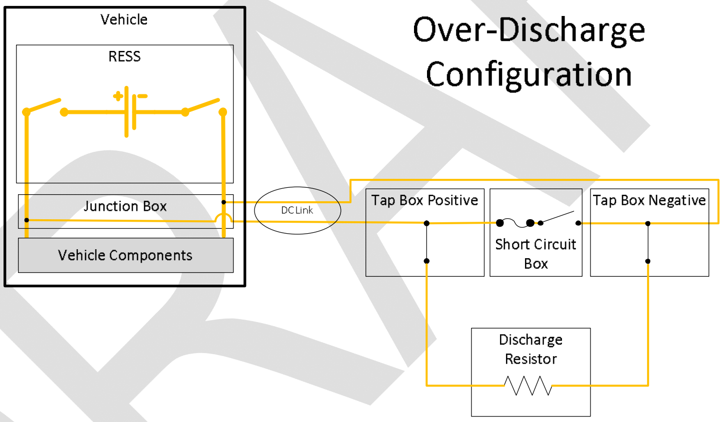

Figure 4 - Diagram of DC Link with switchboard and discharge resistor configured for the Over-Discharge Test.

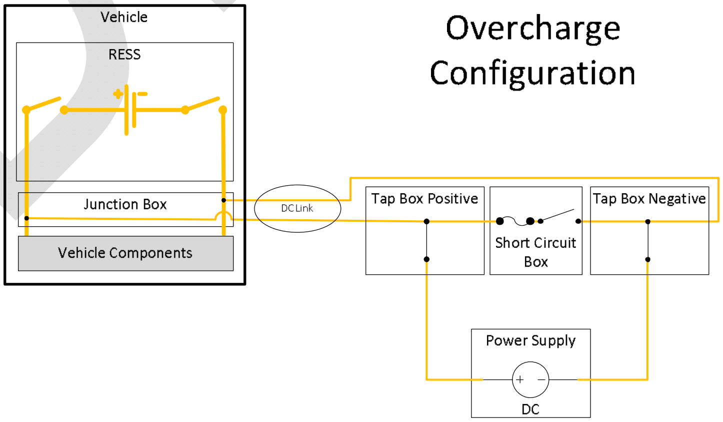

Figure 5 - Diagram of DC Link with switchboard and power supply configured for the Overcharge Tests.

Figure 6 - The switchboard (left) and discharge resistor (right). The discharge resistor is protected beneath a mesh cage to prevent inadvertent contact by an operator. During use a fan provided cooling air across the resistors to maintain their temperature.

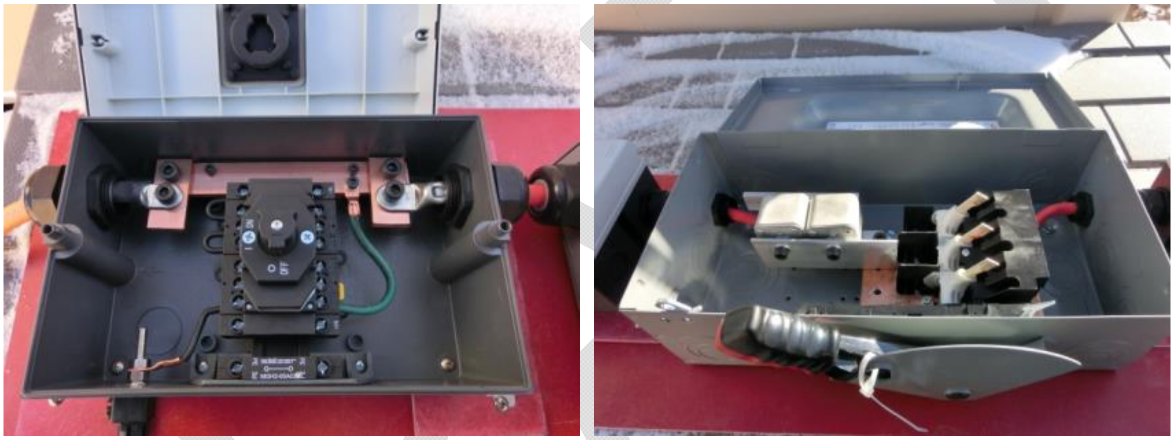

Figure 7 - The interior of a Tap box (left) and the fused short circuit box (right). The fused shorting switch connects directly to the copper bus-bar seen inside the Tap box and to the same component on the other Tap box.

7.4 Low Temperature, Failed Heating System Simulation

7.4.1 Many RESS employ a heating system to ensure that the cells of the RESS are maintained in an optimal temperature range during cold weather. Some battery cell chemistries can be significantly negatively affected if operation is attempted at low temperatures, or if aggressive operation is attempted at low temperatures (high rate charging or discharging). For example, lithium-ion cells are prone to lithium metal plating when charged at high rates at low temperatures, which can degrade the safety characteristics of the cells. In addition, variability in impedance between lithium-ion cells can be enhanced at low temperatures leading to temperature imbalance or voltage imbalance during operation at low temperatures. A properly designed RESS will limit or prevent operation at temperatures below cell capabilities, even if a heating system for the RESS fails.

7.4.2 Low temperature storage or thermal shock testing is common in cell and battery pack standard tests. For example:

- IEEE 1625 requires that an article be exposed to 75°C for 4 hours, followed by 20°C for 2 hours, followed by −20 °C for 4 hours, followed by 20°C for 2 hours.
- UL 1642 requires that an article be exposed to 70°C for 4 hours, followed by 20°C for 2 hours, followed by −40 °C for 4 hours, followed by 20°C for 2 hours.
- SAE J 2464 requires that an article be exposed to 70°C for at least 1 hour, followed by −40°C for at least 1 hour.

Low temperature operational tests are not specified. However, a RESS installed in a vehicle will likely implement temperature monitoring and control systems to prevent undesirable operation. Thus, an under-temperature, failed heating system simulation is a logical complement to high temperature failed cooling tests which are common in industry standards, such as UL 2580.

7.4.3 A low temperature condition of −20°C, regardless of the OEM specified minimum ambient operating temperature, has been selected for this test procedure. −20°C is considered a realistic low ambient temperature that a user is likely to encounter, that is likely to affect cell operation, but that is unlikely to prevent cell operation by freezing electrolyte. −20°C is a typical low temperature limit for many lithium-ion cell chemistries.

7.4.4 A vehicle manufacturer may provide guidance as to how a RESS heating system within its vehicle may be disabled in a minimally invasive fashion to simulate a non-operating condition. The manufacturer’s guidelines for disabling the RESS heating system should not result in the vehicle becoming inoperable or un-drivable. For example, the manufacturer should not provide a firmware patch which would both shut down an internal heater and cause the RESS to refuse to charge or discharge under all conditions. However if the RESS would always forbid charge or discharge on any detected failure of that heater, then a software patch to shut down a heater which resulted in an inoperable RESS would be acceptable.

7.4.5 A ‘steady state’ guideline has been implemented in this test to allow the testing agency to proceed to the next step for expediency in testing time. Many vehicles will respond to abnormal temperature regimes by entering a mode in which only very low power is allowed to be delivered, and as such fully charging or discharging a RESS in such a mode might require more time than would be scheduled for testing. The ‘steady state’ guideline places the requisite amount of stress on the vehicles systems while allowing the test agency to plan test time appropriately.

7.5 High Temperature, Failed Cooling System Simulation

7.5.1 Many RESS employ a cooling system to ensure that the cells of the RESS are maintained in an optimal temperature range during hot weather or under extended operation. Some battery cell chemistries can be significantly negatively affected if operation is attempted at high temperatures or if aggressive operation is attempted at high temperatures (high rate charging or discharging). For example, a failed cooling system can lead to higher RESS temperature during operation, and may also allow ‘hot spots’ to develop within the RESS, particularly if pockets of high impedance cells exist within the RESS (a potential effect of aging). A temperature imbalance may grow during operation, and if appropriate steps are not taken by the vehicle control systems, may lead to thermal runaway of cells. A properly designed RESS will limit or prevent operation at temperatures above cell capabilities, even if a cooling system for the RESS fails.

7.5.2 High temperature storage and operation tests are common in cell and battery pack standard tests. For example:

- IEEE 1625 and UL1642 require that a fully charged article be heated to 130°C and held at that temperature for 10 minutes.
- IEEE 1625 further requires that a battery pack shall contain at least one thermal protection device beyond those internal to the cells. The battery pack must shutdown, or take other protective action, when temperature and time limitations are exceeded.
- SAE J 2464 and SAE J2929 require that a RESS, with all active thermal controls disabled be exposed to 20 charge discharge cycles without rest in a static air volume.
- UL2580 requires that battery packs that rely upon integral cooling systems be designed to shut down upon failure of the cooling system unless it can be demonstrated through analysis and test that the cooling system failure does not result in a hazardous situation. The standard goes on to specify a failed cooling system test that tests both charge and discharge processes with the cooling system disabled and the RESS at maximum specified operating ambient conditions.

7.5.3 An ambient temperature condition of at least 40°C, regardless of the OEMs specified maximum ambient operating temperature, has been selected as this is an ambient temperature that a user is likely to encounter.

7.5.4 A vehicle manufacturer may provide guidance as to how the battery pack cooling system within its vehicle may be disabled in a minimally invasive fashion to simulate a non-operating condition. The manufacturer’s guidelines for disabling the battery cooling system should not result in the vehicle becoming completely inoperable or un-drivable. For example, the manufacturer should not provide a firmware patch which would both shut down an internal cooling system and cause the entire pack to refuse to charge or discharge under all conditions. However, if the pack would always shut down on any detected failure of that cooling system due to code or hardware in the production product, then a patch to shut down a cooling system which resulted in pack shut down would be acceptable.

7.5.5 A ‘steady state’ guideline has been implemented in this test to allow the testing agency to proceed to the next step for expediency in testing time. Many vehicles will respond to abnormal temperature regimes by entering a mode in which only very low power is allowed to be delivered, and as such fully charging or discharging a RESS in such a mode might require more time than would be scheduled for testing. The ‘steady state’ guideline places the requisite amount of stress on the vehicles systems while allowing the test agency to plan test time appropriately.

7.6 Over-Discharge

7.6.1 Many battery chemistries, can experience undesirable aging, electrolyte leakage, swelling or even violent failure if over-discharged. Even though over-discharge of lithium-ion cells generally appears benign, it can cause damage to cell electrodes that can compromise cell stability and safety on subsequent recharge. Cell aging and development of capacity imbalance can increase susceptibility to over-discharge, particularly if voltage sensing is not robust. A properly designed RESS will prevent cell over-discharge.

7.6.2 Over discharge tests are common in industry standards for cells and battery packs. For example:

- IEEE 1625 requires that a battery pack have at least one under voltage protection circuit that disables battery discharge to the external system. It further requires single cell forced over-discharge testing.
- IEEE 1725 requires that a single cell be discharged to 0V and recharged to 100% SOC at least 5 times.
- UL 1642 requires single cell forced over-discharge testing.
- UL 2580 requires that the battery pack prevent over-discharge (a full discharge of the RESS is tested).
- UL 2271 requires that a protective circuit shut down discharge of cells if they exceed their normal operating region. Full discharge of the RESS is tested.
- SAE J2929 requires a full discharge of the RESS.

7.6.3 A load of 1kW was selected for over-discharge testing as this is comparable to many 12V system loads in a vehicle, and likely to be allowed by the battery management system of the RESS.

7.7 Over-Current Overcharge

7.7.1 Overcharge is generally considered one of the most hazardous failure modes for lithium-ion cells. A significant overcharge can result in lithium-ion cell thermal runaway, while a minor overcharge can result in lithium plating that compromises cell safety characteristics. Most lithium-ion cell battery systems involve multiple, overlapping safety systems to prevent significant overcharge of the cells, however, minor overcharge is sometimes allowed under certain fault conditions. Overcharge of a RESS can occur as a result of a failure of a charging system such as a fault in an external charger, or in a regenerative braking charging system. It may also occur as a result of sensor failure or voltage reference drift. During an over-current overcharge, charge voltage remains proper, but excessive current is delivered. This excessive current can cause plating of lithium on lithium-ion anodes, particularly in localized regions after cell aging, and may cause de-lithiation and exothermic heating in localized regions of cathode. These degradation modes can reduce cell stability and affect safety performance.

7.7.2 Over-current overcharge tests are common in industry standards for cells and battery packs. For example:

- UL 1624 and 2054 require that a battery be charged for 7 hours at a charging current of 3 times the manufacturer's specified charging current.
- UL 2271 requires that the pack isolate itself if it exceeds its normal operating region for charging or discharging.
- UN T.7 Test requires that the battery be subjected to a constant charging current of twice the manufacturer's recommended charge current, using a minimum supply voltage of at least twice the maximum charge voltage of the battery if that recommended voltage is less than 18V. Otherwise the minimum charge voltage will be 1.2 times the maximum charge voltage. The test continues for 24 hours.

However, many of these standard tests are designed for smaller battery packs, and require overcurrent regimes which are effectively unachievable using any method to which a user might have access for large battery packs. For example, two times the manufacturers specified charging current as described in the UN T.7 test would be more than 200 kW for some vehicles on the market. For a RESS, it is reasonable to limit over-current to that which can be provided by the braking system or a compatible charger. The voltage limit can be set to the maximum voltage of a compatible charger in a failure state.

7.7.3 Typically, a RESS will refuse to accept a charging current if it does not first successfully communicate with a charger and request such a current. As such, simply applying a voltage to an isolated RESS, or to a RESS at 100% SOC will not be of relevance. For this testing, the RESS begins at 95% SOC. Normal charging is initiated prior to simulation of a charger fault that applies an over-current to the RESS. The over-current is ramped slowly towards the maximum charging current in a manner possible from a failing charging device and likely to produce the most overcharged battery.

7.8 Over-Voltage Overcharge

7.8.1 Overcharge is generally considered one of the most hazardous failure modes for lithium-ion cells. A significant overcharge can result in lithium-ion cell thermal runaway, while a minor overcharge can result in lithium plating that compromises cell safety performance. Most lithium-ion cell battery systems involve multiple, overlapping safety systems to prevent significant overcharge of the cells, however, minor overcharge is sometimes allowed under certain fault conditions. Overcharge of a RESS can occur as a result of a failure of a charging system such as a fault in an external charger, or in a regenerative braking charging system. It may also occur as a result of sensor failure or voltage reference drift. During an over-voltage overcharge, charge voltage exceeds proper limits, but charge current remains within proper bounds. Overvoltage can cause plating of lithium on lithium-ion anodes, particularly in localized regions after cell aging, and may cause de-lithiation and exothermic heating in localized regions of cathode. These degradation modes can reduce cell stability and affect safety performance.

7.8.2 Over-voltage overcharge tests are common in industry standards for cells and battery packs. For example:

- UL 2054 require that a battery be charged using a voltage source that will apply 10 times the C5 amp rate.
- UL 2271 and UL 1973 attempt to charge the battery with 110% of the maximum charge voltage.
- UN Test T.7 requires that the battery be subjected to a constant charging current of twice the manufacturer's recommended charge current, using a minimum supply voltage of at least twice the maximum charge voltage of the battery if that recommended voltage is less than 18V. Otherwise the minimum charge voltage will be 1.2 times the maximum charge voltage. The test continues for 24 hours.
- J 2464- Modules and Packs are subjected to a constant charging current of 1C until at least 200% SOC has been reached or the sample is terminated by a destructive factor.

7.8.3 For a RESS it is generally not practical to, for example, apply 800 V continuously across a battery system rated to 400 V as damage to capacitors or other sensing circuits may occur and it is difficult to imagine where a user might encounter such voltages. Application of a mild overvoltage condition, consistent with a faulting charger is sufficient.

7.8.4 Typically, a RESS will refuse to accept a charging current if it does not first successfully communicate with a charger and request such a current. As such, simply applying a voltage to an isolated RESS, or to a RESS at 100% SOC will not be of relevance. For this testing, the RESS begins at 95% SOC. Normal charging is initiated prior to simulation of a charger fault that applies an over-voltage to the RESS.

7.9 External Short Circuit

7.9.1 For a RESS, external short circuit testing is intended to ensure that intended current flow pathways are sufficiently robust or well protected even after aging to prevent a dangerous condition (either overheating or arcing) under foreseeable abnormal current flows.

7.9.2 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 UL 2054 specify short circuit tests through a maximum resistance load of 100 mΩ.
- UL 1973 and UL 2580 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.

- UL 2271 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.

7.9.3 A shorting resistance of 3-5 mΩ, consistent with SAE J2464 and J2929 test methods has been selected. This shorting resistance is relatively straightforward to achieve with fuses, high voltage rated switches, heavy gauge cable, and firmly bolted connections.

7.10 Destructive Discharge of a RESS

The destructive discharge requirement of Sequential Testing is not a stress test of the RESS. It is intended to ensure that a method exists to remove "stranded energy" from a RESS that cannot be removed either through normal electrical discharge of the RESS, or even through electrical discharge of individual RESS components.

Energy can become stranded in a RESS due to a variety of mechanisms:

- A RESS will not typically allow over-discharge of cells to 0 V (less than 0% SOC), and thus, if over-discharge to approximately 0 V is required, individual RESS components may need to be accessed and electrically discharged individually.

- A RESS may become damaged in such a way that normal electrical discharge to low SOC is not allowed: for example, a fuse may break the circuit. To allow discharge under these conditions, individual RESS components may need to be accessed and electrically discharged individually.

- Individual cells within a RESS may become damaged in such a way that electrical discharge is not possible: for example, cell separator may shut-down due to heating and prevent transfer of ions between cell anode and cathode. Although a cell in this condition cannot deliver current to an external circuit, it can remain hazardous if subjected to another mechanism that can release energy such as a severe crush, or external heating.

An effective destructive discharge method will discharge all components of the RESS fully, such that no appreciable electrical energy remains stored in any RESS component, up to and including the cell level.

7.11 Salt Bath Method for Destructive Discharge of a RESS

If due to some damage mechanism, electrical discharge on the RESS level, or even on the component (module) level is not sufficient to fully discharge a RESS or its components, one destructive discharge method that can be effective for lithium-ion cell based RESS is the Salt Bath Method, where modules or small RESS are submerged in a salt water solution.

7.11.1 Salt Bath Discharge Mechanism

The Salt Bath Method destructively discharges cells or modules in two ways:

1. The salt solution will complete an electric circuit between elements at different potentials. Thus, for a cell that is capable of discharge (separator is not shut down) with intact terminals, when salt water flows around those terminals, the circuit is closed and the cell begins to slowly discharge. The higher the concentration of salt in the water, the faster the discharge.

2. Discharge in salt water is a corrosive process. As cells discharge, their terminals corrode and ion concentrations within the bath increase. Corrosion of the cell terminals ultimately results in breach of the cell case. At that point, water enters the cell and reacts with the anode, directly discharging it at a higher rate.

Testing with single cylindrical 18650 cells shows the effects of these two processes. Figure 8 shows the initial voltage decay of 18650 cells placed in salt baths of varying concentrations. When the cell enters the liquid, discharge begins, which is seen as a step change in voltage. As expected, discharge rate is higher for higher salt concentrations. The discharge process results in electrolysis of water, which is highly corrosive to the cell terminals. Ultimately the cell case is breached by corrosion and another step change in cell voltage and discharge rate occurs (Figure 9). Voltage measurements ultimately become noisy as voltage sense wires become detached from the cell due to continued corrosion. An example of an 18650 cell after salt bath exposure can be seen in Figure 10: the positive terminal has been entirely eroded by corrosion.

Accelerated Rate Calorimetery (ARC) testing and impact testing of cylindrical 18650 cells removed from a salt bath after destructive discharge show that the cells no longer contain appreciable stored energy. Figure 11 shows that salt bath discharged cells exhibit self-heating rates similar to cells that have been deeply discharged by normal electrical methods. Self-heating rate for salt bath destructively discharged cells and electrically deep discharged cells are significantly lower than cells at 20% SOC. Figure 12 shows that a salt bath discharged cell produces less heating after a severe impact than a cell discharged to 10% SOC.

Note that a salt bath destructive discharge is not complete until all cells have been breached. This process can require significant time to complete. Thus, a salt bath discharge should be allowed to occur for at least 24 hours, and potentially for many days depending on the state and design of the items immersed in the salt bath.

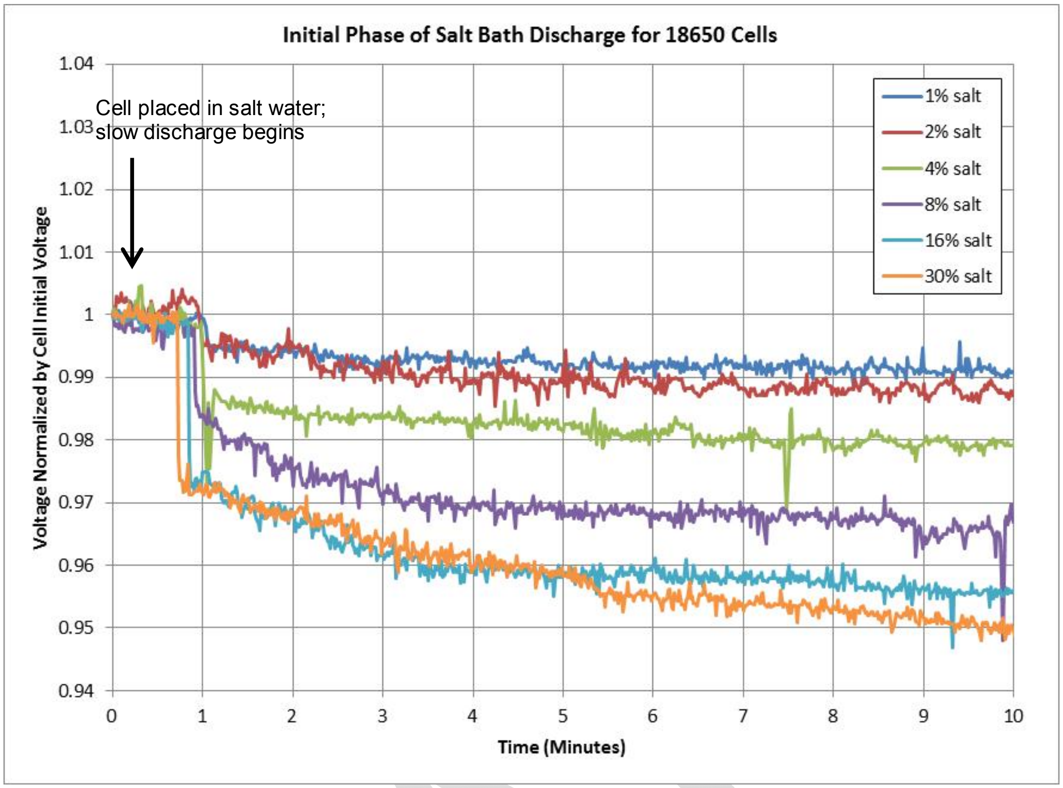

Figure 8 - Initial phase of salt bath discharge for single 18650 cell; discharge rate increased with increasing salt concentration.

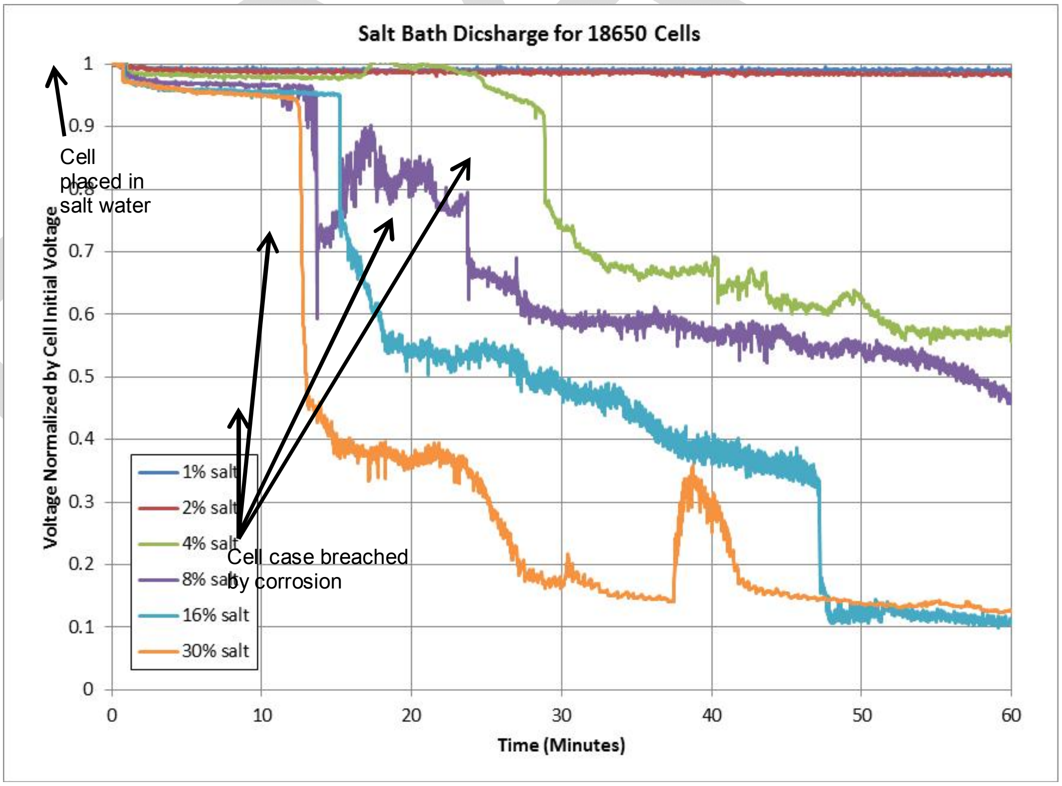

Figure 9 - Salt bath discharge for single 18650 cells in various concentrations of salt solution; discharge transitions to a higher rate as the cell case is breached by corrosion.

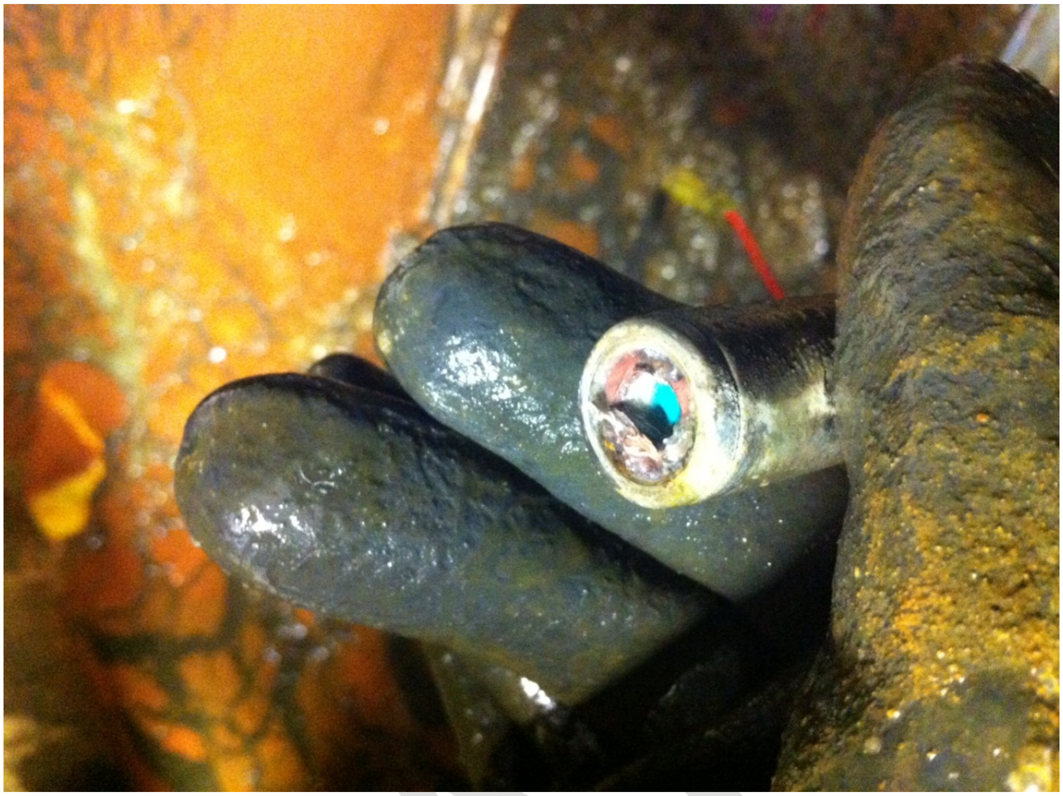

Figure 10 - Example of an 18650 cylindrical cell after salt bath destructive discharge: positive terminal has been removed by corrosion, exposing the cell interior.

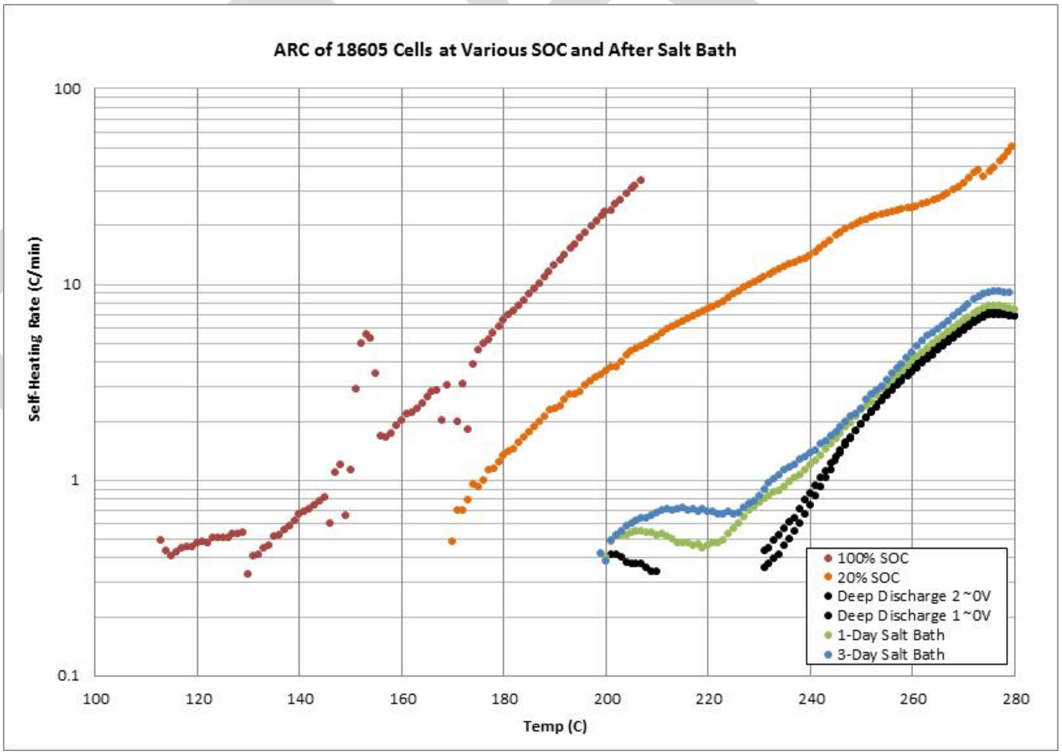

Figure 11: ARC Test results comparing self-heating rates of cells subjected to salt bath destructive discharge to cells subjected to deep discharge (~ 0V), and cells at either 20% or 100% SOC.

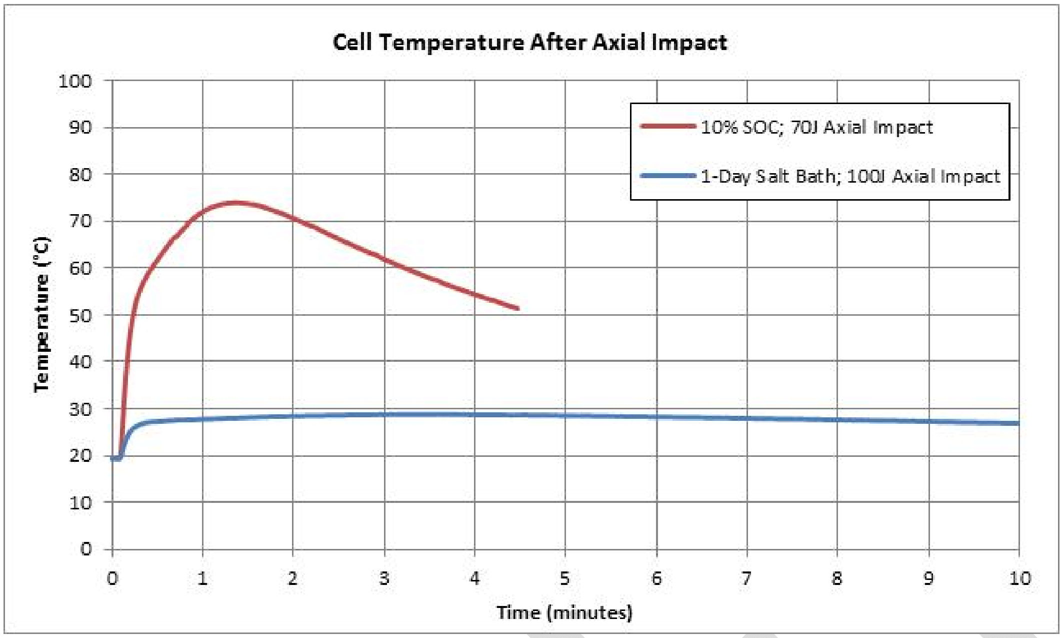

Figure 12 - Impact test results comparing post-impact heating of an 18650 cylindrical cell at 10% SOC subjected to a 70J axial impact to an 18650 cylindrical cell after one day of salt bath exposure subjected to a 100J axial impact.

7.11.2 Salt Bath Discharge Hazards

Discharge of cells, modules, or small packs can release appreciable energy, and thus, there are a number of associated hazards that must be mitigated.

7.11.2.1 Electrolysis of Water.

Immersion of cells will result in electrolysis of water. This results in production of hydrogen and oxygen gas. These gases bubble to the surface of the salt bath (Figure 13) and can produce a flammable atmosphere above the bath. Thus, salt bath destructive discharges should only be attempted in a well-ventilated area, preferably outdoors. The bubbling can be very intense, leading to splashing of liquid out of the salt bath. Finally, water is lost due to electrolysis. If the level of water drops below that of the materials being discharged, a fire can occur.

7.11.2.2 Potential for Arcing Between High Voltages

If a module or pack is submerged in a salt bath, currents develop between all of the different potentials in the pack. Depending on the electrical architecture of the pack, electrical arcs can become established between points of large potential differences. An established arc can ignite flammable gases produced during destructive discharge and result in a fire. In addition, an established arc can result in very rapid discharge of surrounding cells, to the point of forcing those cells into thermal runaway. Before submerging a unit (module or pack), a study of the unit architecture should be conducted to ensure that hazardous arcing will not occur.

7.11.2.3 Release of Heat

Much of the energy released during a destructive discharge will be converted to heat. Ideally, the dissipated heat will be absorbed by the water in the bath. If too little water is used, or if water is not able to readily flood heated components, boiling and generation of steam can occur and cause ejection of liquid from the salt bath. Components of the battery can become heated and potentially melt, or cause melting of the salt bath tank itself. Thus, obstructions such as battery or module covers that can prevent the flow of water around cells should be removed prior to submersion. The volume of water used should be at least three times the volume occupied by the item to be destructively discharged.

To best manage heat, an item should be submerged quickly into a low concentration salt bath. The item should be weighed down sufficiently to prevent it from floating on the surface of the salt bath. Placing an item into a bath and then adding salt water is not recommended as the fill process may not be sufficiently fast to manage the heat released in the discharge reaction. If a fill process will be used, the salt bath should be filled with pure water, and salt should be added to the tank only after the item is fully submerged.

7.11.2.4 Potential for Inducing Cell Thermal Runaway Reactions

If cell discharge reactions proceed too quickly, either due to too high of a concentration of salt or other ions in the water, due to the establishment of an electrical arc, or due to water entering the cell after corrosion occurs and oxidizing cell components, the cell may undergo a thermal runaway reaction. Testing with cylindrical 18650 cells has shown that as long as a cell is submerged at least 6 inches below the liquid surface, a thermal runaway reaction of that cell is unlikely to eject glowing sparks or flames from the bath. Larger hard case cells will likely require deeper submersion to prevent ejection of sparks or flames. Cells should be oriented in the bath to eject gases toward the sides and bottom of the salt bath, rather than the liquid surface. However, precautions should also be taken to ensure that submerged cell thermal runaway does not melt the sides of the salt bath.

7.11.2.5 Composition of Released Gases and Liquid Residue

Gases produced over a salt bath used for destructive discharge of lithium-ion cells and modules were sampled and analyzed for a range of chemical compounds including metals, acid gases and volatile organic compounds. The compounds detected (Table 13) were consistent with those present in the lithium-ion cells being destructively discharged: including current collectors (copper), electrode material (nickel, cobalt), and electrolyte constituents (lithium, and VOCs). No measured concentrations were above OSHA PEL levels. However, sufficient hydrogen gas is produced to be above the flammability limit of hydrogen.

The liquid from a salt bath must be disposed of as hazardous waste. The liquid residue will typically contain solids characterized as “dirt” and may contain reportable compounds such as nickel.

Table 13 - Results of gas sampling over a destructive discharge salt bath. (ND means not detected)

Compound	Analysis Method	Detected Over Salt Bath?
Chlorine gas	MOD NIOSH 6011	ND
Hydrogen Peroxide	MOD OSHA VI6, ACS AIHA# 102047	Yes
Lithium	NIOSH 7303/7300 Mod	Yes
Hydrochloric Acid	J6-010-03 - HCL	ND
Hydrogen Sulfide	J6-009 – H2S	ND
Aluminum	MOD OSHA ID 125	ND
Calcium	MOD OSHA ID 125	Yes
Cobalt	MOD OSHA ID 125	Yes
Copper	MOD OSHA ID 125	Yes
Iron	MOD OSHA ID 125	ND
Lead	MOD OSHA ID 125	ND
Nickel	MOD OSHA ID 125	Yes
Zinc	MOD OSHA ID 125	ND
VOC	EPA TO-15	Chloromethane Acetone Toluene Ethylbenzene

Figure 13 - Example of a salt bath with submerged modules: note bubbles of gas on surface produced by electrolysis.

7.11.3 Considerations for Planning a Salt Bath Discharge

A salt bath should be constructed in a well-ventilated or outdoor location. An appropriate location will be free of flammable materials, secured from access by the general public, and downwind of occupied structures within 50 feet. For example, a fenced, open yard may be an appropriate location for a salt bath.

Depending upon the architecture of the item being destructively discharged, and the type of damage that may have occurred, requiring the destructive discharge, the salt bath process may be complete within hours of initiation, or may require multiple days to complete. It is prudent to plan for multiple days of immersion. Thus the salt bath should be in a controlled area to prevent the public or animals from coming into contact with the salt bath while it is filled with liquid. The bath should be closely monitored for the first 1-3 hours of the reaction to ensure that water level has not dropped below the level of the submerged item. After 1-3 hours, periodic monitoring should be planned. A supply of extra water should be readily available at the salt bath, should bath levels drop below the level of the submerged item.

A 1% salt solution is sufficient to accomplish destructive discharge of a lithium-ion cell. Higher salt concentrations can increase the rate of reaction, but can also increase the rate of the reaction (hydrogen gas bubbling, etc.). Addition of extra salt should be conducted with caution. There is no need to monitor the salt concentration of the bath, once a reaction begins, the concentration of conductive ions in the bath will increase.

A hoist or similar device may be necessary to introduce items into the salt bath quickly, and subsequently remove them for disposal. The item to be submerged should be secured to the hoist with a non-conductive cable or rope.

When items are removed from a salt bath, they should be inspected to ensure that the case walls of 100% of cells have been breached by corrosion. If this has not occurred, the item should be returned to the salt bath. Until an inspection can be made of all cells, the item pulled from the salt bath should be handled as if it were a high voltage source.

7.11.4 Considerations for Construction of a Salt Bath

A salt bath should be constructed from non-conductive materials that are not susceptible to corrosion such as plastic, or other materials lined with plastic. The walls of the bath should be sufficiently sturdy to resist melting or puncture. A secondary containment system may be required surrounding the salt bath. The salt bath dimensions should be sufficiently large to easily encompass the item to be destructively discharged and sufficient water to absorb released heat, with sufficient depth to fully submerge the item, protect against ejection of flames or sparks, and to provide sufficient headspace to allow for bubbling of the liquid without overflowing. The salt bath should be provided with a loose lid that can be used to cover the bath after most reactions have terminated to prevent access by animals or people during a long dwell period, or before the salt bath is emptied.

The salt bath should either have a drain to allow convenient removal of the liquid for disposal, or provision should be made for pumping the liquid out of the bath after reactions have completed.

8. APPENDIX

8.1 DC Link Installation Examples

For demonstrative purposes a DC Link was installed and used to conduct testing on one EV vehicle (Manufacturer A). In addition, points for DC Link connection were identified on additional vehicles (Manufacturers B and C).

- The Manufacturer A vehicle contained a RESS built with small cylindrical cells.
- The Manufacturer B vehicle contained a RESS built with large, hard case prismatic cells.
- The Manufacturer C vehicle contained a RESS built with large pouch cells.

8.1.1 DC Link Connection: Manufacturer A Vehicle

The RESS from Manufacturer A consists of a large flat unit mounted to the floor of the vehicle. The high voltage leads exit the RESS and arrive at a DC junction box beneath the rear seat of the vehicle (Figure 14; red box). In this vehicle, the DC Link can be installed at the DC Junction box, and removal of the RESS from the vehicle is not required.

A DC Link was installed in this vehicle by:

- Ensuring that the RESS contactors remained open and all vehicle high voltage systems were de-energized by removing the first responder cut loop.
- Removing the DC Junction box cover
- Attaching the DC Link cable directly to the high voltage terminals using the same lugs which are used to secure the other high current cables (Figure 15Figure).
- Replacing the DC Junction box cover.
- Reinstalling the first responder cut loop.

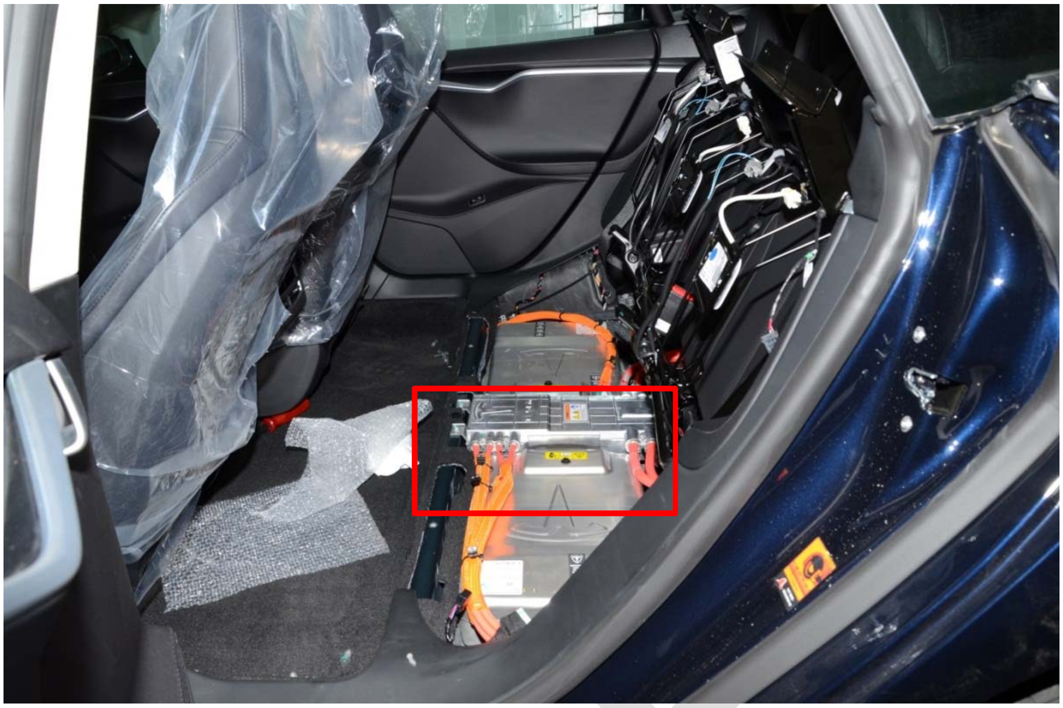

Figure 14 - Manufacturer A Vehicle; DC Junction Box beneath rear seat with orange high voltage cables.

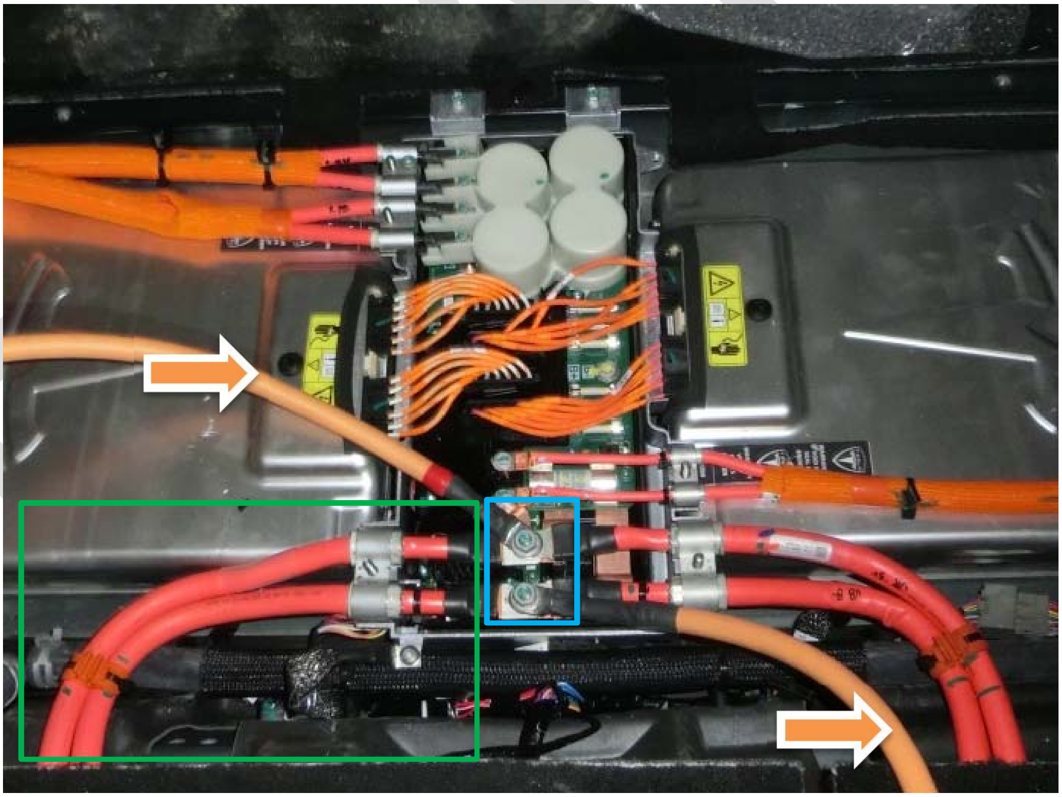

Figure 15 - Manufacturer A Vehicle; DC Junction Box with cover removed and DC Link installed. The RESS high voltage leads are to the lower left of the image (green box). The vehicle high voltage leads that connect to the vehicle powertrain are the same size and color as the RESS high voltage leads and connect to the RESS high voltage leads at a junction using lug nuts (blue box). DC Link

connection cables are light orange (orange arrows) and shown connected to the main DC junction using existing lug nuts.

8.1.2 DC Link Connection Points: Manufacturer B Vehicle

8.1.2.1 The RESS from Manufacturer B consisted of a unit that was mounted to the floor of the vehicle. A Manufacturer B vehicle that had previously undergone NHTSA New Car Assessment Program (NCAP) crash testing[30] was examined to determine whether a DC Link could be conveniently installed on the vehicle.

8.1.2.2 In the Manufacturer B vehicle, the high voltage leads enter the RESS through a pair of ports (Figure 16, red box). The orange high voltage leads attach at two threaded holes on the bus bars (Figure 17, blue box) using lugs (Figure 17, green box) behind a metal cover plate on the RESS. In this vehicle, removal of the RESS from the vehicle is not required to install a DC Link.

A DC Link could be installed in this vehicle by:

- Ensuring that the RESS contactors remained open and all vehicle high voltage systems were de-energized by removing the RESS Service Disconnect Plug (from inside the vehicle cabin).
- Either splicing cables into the pair of orange high voltage cables that enter the RESS, or connecting to the RESS internal contacts and modifying the RESS DC junction cover plate to allow a pass-through for the DC Link terminal cables.
- Reinstalling the Service Disconnect Plug.

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[30] Although the vehicle RESS appeared undamaged as a result of previous crash testing, vehicle structures were no longer entirely representative of production vehicles.

Figure 16 - Manufacturer B; high voltage cable pass through (red box) into RESS (high voltage cables have been disconnected and are hanging at left.

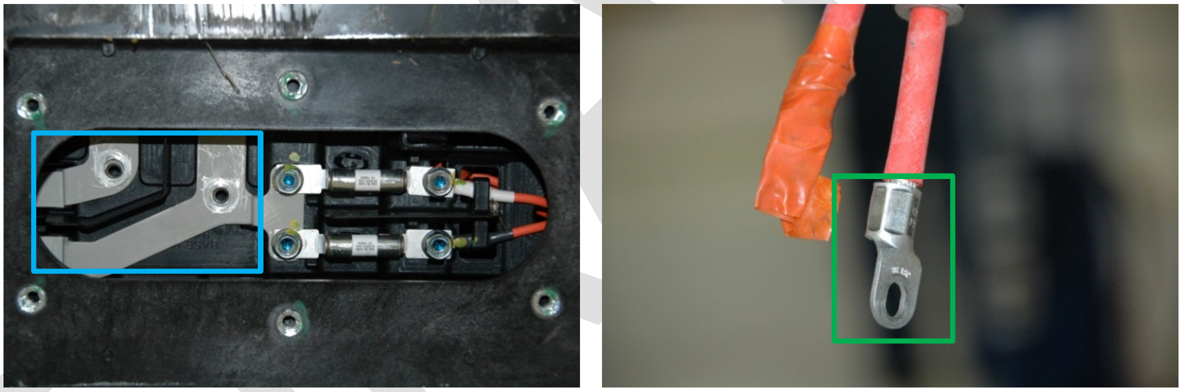

Figure 17 - Manufacturer B; high voltage cable connection point (blue box; left image) inside RESS (cover plate removed). High voltage cable connector end (green box, right image).

8.1.3 DC Link Connection Points: Manufacturer C Vehicle

The RESS from Manufacturer C consisted of a unit that was mounted to the floor of the vehicle. A Manufacturer C vehicle that had previously undergone NHTSA New Car Assessment Program (NCAP) crash testing[30] was examined to determine whether a DC Link could be conveniently installed on the vehicle.

In the Manufacturer C vehicle, the vehicle high voltage cables are individually insulated and carried inside a single common insulating orange high voltage line. The high voltage line arrives at a plug at the RESS (Figure 18, green box and Figure 19). There is no convenient access port into the RESS to connect to the high voltage lines.

A DC Link could be installed in this vehicle by:

- Ensuring that the RESS contactors remained open and all vehicle high voltage systems were de-energized by removing the RESS Service Disconnect Plug (from inside the vehicle cabin).
- Splicing into the orange cable, exposing the individual wires and contacting the positive and negative terminals of the DC Link to them. Using the internal contacts would require removal and opening of the RESS.
- Reinstalling the Service Disconnect Plug

Alternatively, it may be possible to install a DC Link elsewhere in the vehicle. Input from the Manufacture could be used to select a more convenient installation point.

Figure 18: Manufacturer C RESS high voltage connection. High voltage cable from vehicle is shown within the green box. This cable connects to the RESS at a connector one face of the RESS (red box). Note that the RESS was removed from the vehicle for demonstrative purposes. The high voltage connection can be accessed without RESS removal.

Figure 19: Manufacturer C high voltage cable connector.

8.2 Example Sequential Testing Results: Manufacturer A Vehicle

8.2.1 Manufacturer A: Preconditioning

An 85kWh RESS produced by Manufacturer A was subjected to the 5,000 Mile Preconditioning Sequence while installed in a durability test vehicle (Durability Vehicle) also produced by Manufacturer A (Figure 20). At the beginning of preconditioning the RESS was of production quality and unused, other than those cycles which are required during assembly.

Vehicle weight was measured (Table 14). The Manufacturer provided a design weight and ballasting diagram for the vehicle. Per the Manufacturer recommendation, 5% of testing was conducted with no ballast (curb weight) and 95% of testing was conducted at the vehicle design weight (Table 15). Vehicle tire pressure was set to specification (Table 16).

The vehicle completed a shakedown drive on the test track and then was subjected to a series of test events summarized in Table 17. Sequencing of preconditioning tests is shown in Table 18. Preconditioning activities were recorded as in Table 20.

Preconditioning began with a series of wide open throttle and rough road drives (WOT + RR) conducted on a test track. The WOT + RR pattern used for this testing was 1.22 miles in length. It contained a mixture of wide open throttle accelerations, decelerations that engaged the vehicle regenerative braking system, and traverse of rope and wave roads for applying vibrational and torsional loads. The elements the WOT + RR pattern used are described in Table 19. WOT + RR patterns were conducted in rapid succession, with periodic pauses for charging on an as needed basis. Typically, the vehicle was recharged when SOC reached 20% ±10%. The vehicle was recharged using a mixture of Level II and Level III charging systems. Approximately half of the planned WOT + RR drives were conducted in rapid succession as the first phase of preconditioning.

For Phase 2 preconditioning, the vehicle was installed on a dynamometer and subjected to high speed driving. The dynamometer was equipped with a velocity matching fan. The high speed driving pattern used is shown in Figure 23. High speed drive patterns were conducted in rapid succession, with periodic pauses for charging. The vehicle was recharged as needed to complete full test patterns using a Level III charger. Approximately half of the planned high speed drives were conducted in rapid succession as the second phase of preconditioning.

In the 3rd phase of preconditioning, ¼ of planned WOT + RR drives were then conducted as in the first phase, with a number of additional events interspersed including: salt spray exposure (Figure 24), mountain driving (Figure 25), gravel road driving (Figure 26), hot chamber charging, cold chamber charging, rain booth exposure, and a car wash.

- Salt spray exposure was accomplished by manually applying approximately 1 Liter of a 3% NaCl solution over the exterior surfaces of the vehicle.

- Rain exposure was simulated using a rain booth (Figure 27) that applied a total water flow rate of 600 GPM divided into 150 GPM per side (top, left, right, bottom) for approximately 20 minutes.

- Hot chamber charging was conducted in a chamber set at 65°C. The vehicle was placed into a pre-heated chamber, and charging was immediately initiated. At the end of charging, the vehicle temperature approached that of the chamber. More ideally, a vehicle would be allowed 6 hours to thermalize at a lower temperature condition, such as 45°C, before charging would be initiated.

- Cold chamber charging was conducted in a chamber set at −30°C. The vehicle was placed into a pre-cooled chamber, and charging was immediately initiated. At the end of charging, the vehicle temperature approached that of the chamber. More ideally, a vehicle would be allowed 6 hours to thermalize before charging would be initiated.

- Ambient temperature charging was accomplished by using a mixture of Level II and Level III chargers.

For the 4th phase of preconditioning, the vehicle was installed on a dynamometer to complete the planned high speed drives. The drives were completed as in the 2nd phase of preconditioning. The vehicle was recharged as needed using a Level III charger.

For the 5th and final phase of preconditioning, the vehicle was again exposed to the rain booth and then the City Route drive. Recharging was accomplished at a public Level II charger. Then the planned WOT + RR drives were completed with a number of additional events interspersed including: hot chamber charging, cold chamber charging, drizzle booth charging, a car wash, and RESS removal and re-installation. Drizzle booth charging (Figure 27) was accomplished within a rain booth that applied a total water flow rate of 12 GPM to the top of the vehicle. Ambient temperature charging was accomplished by using a mixture of Level II and Level III chargers.

After Preconditioning was completed, the RESS was removed from the Durability Vehicle and installed in a Manufacturer A production vehicle for Sequential Testing (Test Vehicle) (Figure 29). The Test Vehicle was aligned and inspected by Manufacturer A and judged to be appropriate for the Sequential Testing sequence despite having suffered mechanical damage to body components.

Table 14 - Durability Vehicle Weight.

Vehicle Position	Total
Front (FR)	2202 lbs
Rear (RR)	2476 lbs
Total	4678 lbs

Table 15 - Vehicle Weight Conditions Used for Preconditioning Testing.

Vehicle Weight Condition	% of Test Distance
Curb weight	5%
Design weight	95%

Table 16 - Durability Vehicle Tire Pressures.

Vehicle Position	Left Hand Side (LH)	Right Hand Side (RH)	Specification
Front (FR)	38 psi	38 psi	38-42 psi
Rear (RR)	40 psi	40 psi	40-42 psi

Table 17 - Summary of Vehicle Preconditioning Events.

Preconditioning Event	Miles Driven	Other Events	Minimum Required
Wide Open Throttle (WOT) + Rough Road (RR) mileage	4,369		2,500
High Speed mileage	2,676		2,000
Mountain Route mileage	413		400
City Route mileage	148		90
Gravel road mileage	18		10
Vehicle repositioning mileage	494		0
Mountain Route corners		2,000	2,000
Mountain Route assents > 500 m		8	8
Mountain Route descents > 500 m		8	8
Mountain Route ascents > 1000 m		4	4
Mountain Route descents > 1000 m		4	4
Cold Charge (approximately 5 hrs/charge)		21 hrs	20 hrs
Hot Charge (approximately 5 hrs/charge)		23 hrs	20 hrs
Drizzle Charge (approximately 5 hrs/charge)		19 hrs	20 hrs
Car Wash		2	2
Salt Spray		1	1
Rain Booth hours		0.66 hrs	0.5 hrs
HV Pack Removal & Reinstall		1	1
Level II charging hours (ambient temperature)		128	
Level III charging hours (ambient temperature)		159	
Total Preconditioning Distance	**8,118**		5,000

Table 18 - Sequencing of Preconditioning Events.

Phase	Driving Profile	Driving Start Date	Charging	Charging Start Date
1	WOT + RR (2,388 miles)	10/11/2013	Mix of Level II and Level III charging	10/11/2013
2	High Speed (1,238 miles)	10/25/2013	Level III charging	10/25/2013
3	WOT+RR (532 miles)	10/27/13	Salt Spray Exposure	10/28/2013
			Hot chamber charging	10/31/2013
	Mountain Route 1 and Gravel Road (244 miles)	10/30/2013	Level II charging	10/30/2013
	Rain Booth	10/30/2013		
	Car Wash	10/30/2013		
	WOT + RR (246 miles)	10/30/2013	Hot chamber charging	10/31/2013
	Mountain Route 2 (187 miles)	11/1/2013	Level II charging	11/1/2013
	WOT + RR (385 miles)	11/1/2013	Cold chamber charging	11/1/2013
			Hot chamber charging	11/3/2013
4	High Speed (1,441 miles)	11/3/2013	Level III charging	11/3/2013
5	City Route (148 miles)	11/5/2013	Level II charging	11/5/2013
	Rain Booth	11/6/2013		
	WOT + RR (790 miles)	11/6/2013	Level III charging with other charging	11/6/2013
			Hot Chamber	11/7/2013
			Cold Chamber	11/8/2013
			Drizzle Chamber	11/9/2013
			Cold Chamber	11/10/2013
			Hot Chamber	11/12/2013
			Drizzle Chamber	11/12/2013
	Car Wash	11/12/2013		
	RESS Removal and Reinstall	11/12/2013		
	WOT + RR (323 miles)	11/12/2013	Mix of Level II and Level III charging with other charging	11/12/2013
			Cold Chamber	11/13/2013
			Cold Chamber	11/13/2013
			Drizzle Chamber	11/13/2013
		11/14/2013		

Table 19 - WOT + RR Elements Used for Manufacturer A Preconditioning.

WOT + RR pattern elements	Number per pattern
Pattern length was 1.22 miles	
0-80 mph wide open throttle operation (WOT)	1
80-40 mph full regenerative braking and light brake application	1
40-80 mph WOT	1
80-20 mph full regenerative braking and medium brake application	1
Vertical input test event road: rope road (0.07 mile)	1
Torsional input test event road: wave road (0.07 mile)	1

Figure 20 - The Durability Vehicle used to apply the Preconditioning Sequence.

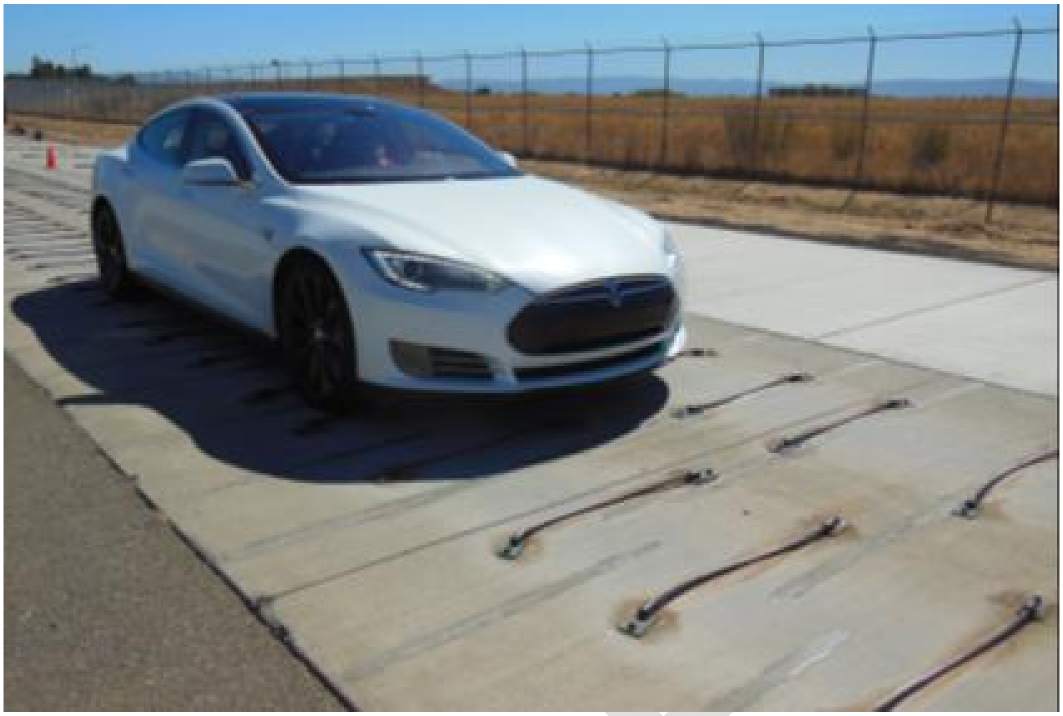

Figure 21 - Example of a vehicle on a rope road (rough road element).

Figure 22 - Example of a vehicle on a wave / sinusoidal road (rough road element).

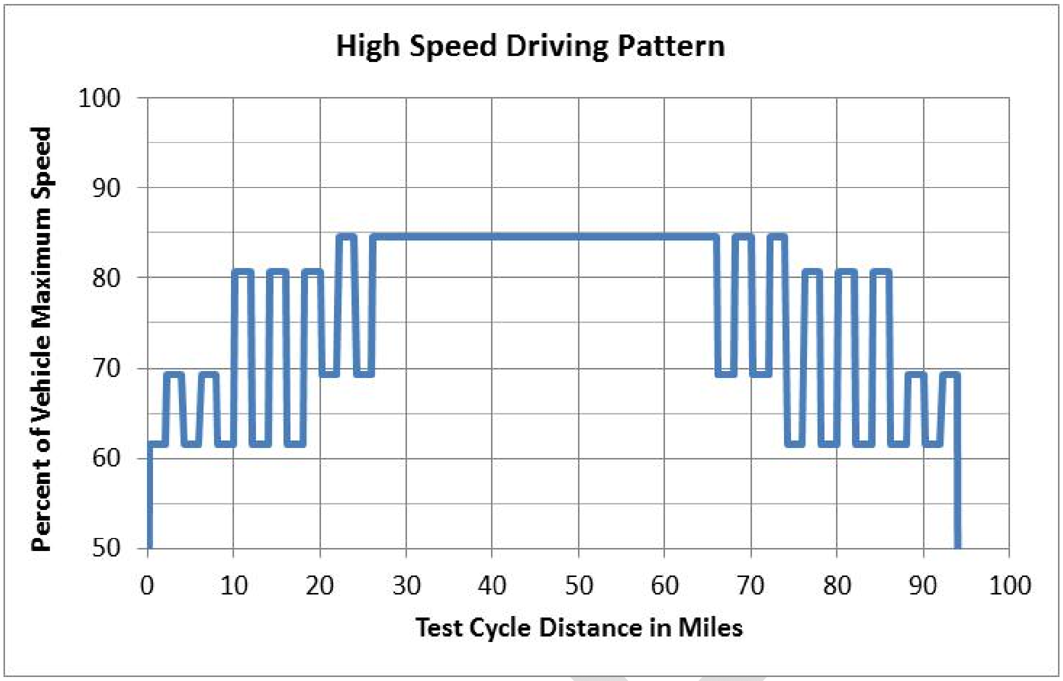

Figure 23 - High speed test pattern used for Manufacturer A vehicle preconditioning.

Figure 24 - Salt spray applicator and example of a vehicle after application of salt spray.

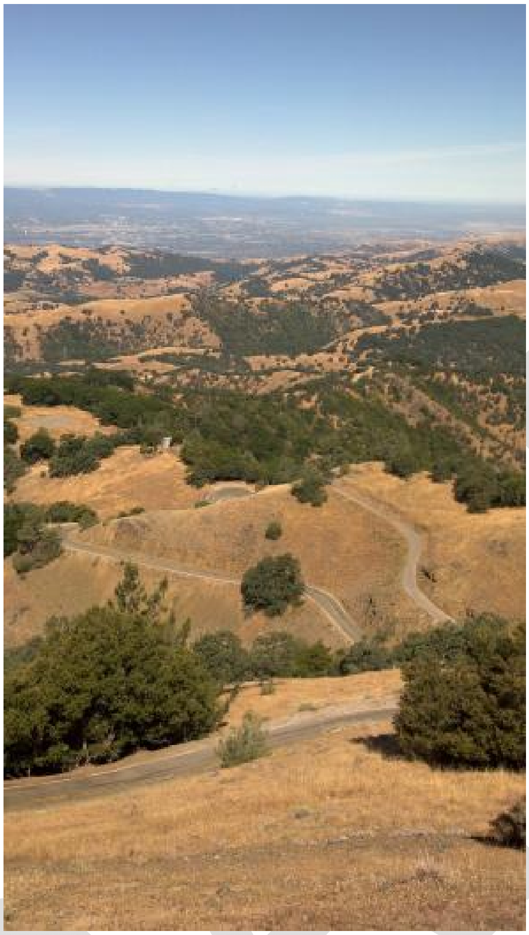

Figure 25 - Switchbacks on Mountain Route 2.

Figure 26 - Example of gravel road driving.

Figure 27 - Example of a vehicle installed in the booth used for rain and drizzle testing. Rain (monsoon) is simulated by applying a total water flow rate of 600 GPM divided into 150 GPM per side (top, left, right, bottom).

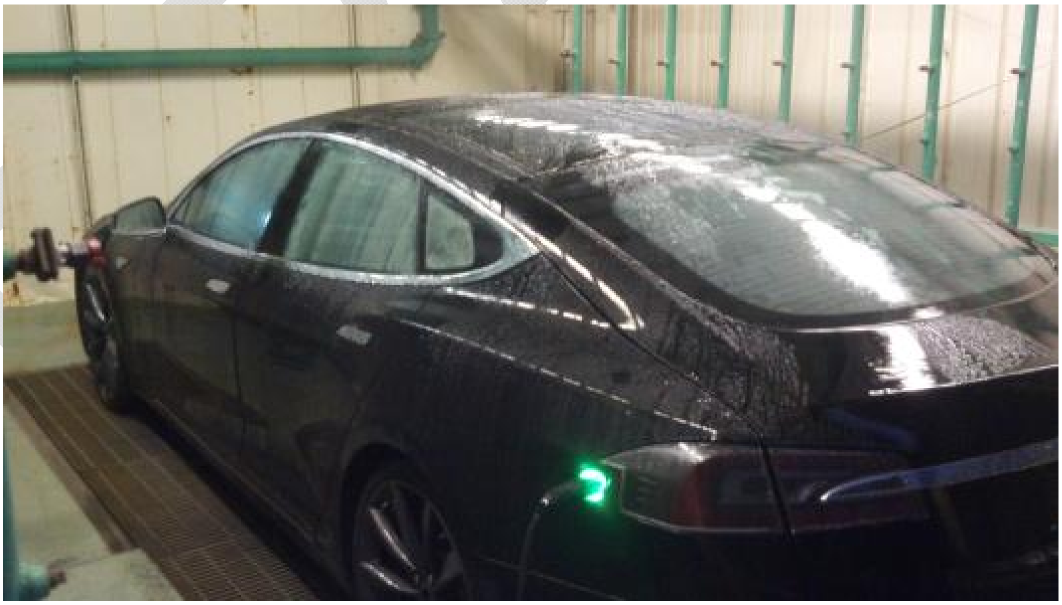

Figure 28 - Example of a vehicle subjected to drizzle chamber charging; drizzle is simulated by applying a total water flow rate of 12GPM from the top of the chamber only.

Figure 29 - The Test Vehicle before Sequential Testing was conducted.

Table 20 - Preconditioning Sequence Records.

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Drive	WOT + Rough Road	Curb + Driver	10/11/2013	5:05:00 PM	6:43:00 PM	1.6	9892.8	9929.8	36.6	70.8	26.6
Charge	Level II	N/A	10/11/2013	6:50:00 PM	8:36:00 AM	13.8	9930.9	9930.9	0	26	100
Drive	WOT + Rough Road	Curb + Driver	10/12/2013	9:15:00 AM	11:35:00 AM	2.3	9931.7	9993.7	61	98.8	28.2
Charge	Level II	N/A	10/12/2013	11:45:00 AM	4:25:00 AM	15.5	9994.8	9994.8	0	27.4	99
Drive	WOT + Rough Road	Curb + Driver	10/13/2013	4:25:00 AM	6:57:00 AM	2.5	9995.6	10064.9	68.32	98.6	17
Drive	WOT + Rough Road	Curb + Driver	10/13/2013	5:40:00 PM	7:40:00 PM	2	10067	10128.8	61	99.2	28.4
Charge	Level II		10/13/2013	7:34:00 AM	5:30:00 PM	9.9		10066		16.6	100
Charge	Level II	N/A	10/13/2013	8:24:00 PM	5:20:00 AM	8.9	10130	10130	0	28.2	99.6
Drive	WOT + Rough Road	Curb + Driver	10/14/2013	5:47:00 AM	6:00:00 AM	0.2	10130.9	10133.3	2.44	99.2	98.8
Drive	WOT + Rough Road	Curb + Driver	10/14/2013	8:03:00 AM	8:54:00 AM	0.8	10135.4	10159.3	23.18	96.6	69.6
Drive	WOT + Rough Road	Curb + Driver	10/14/2013	10:08:00 AM	11:46:00 AM	1.6	10161.1	10204.6	42.7	69.2	14.4
Charge	Level III	N/A	10/14/2013	11:56:00 AM	1:55:00 PM	2	10205.6	10205.6	0	13.6	99.4
Drive	WOT + Rough Road	Design	10/14/2013	4:04:00 PM	5:43:00 PM	1.6	10206	10250	42.7	98.4	43
Drive	WOT + Rough Road	Design	10/14/2013	5:51:00 PM	6:30:00 PM	0.7	10251.4	10270.1	18.3	42.8	16.4
Charge	Level III	N/A	10/14/2013	6:40:00 PM	8:08:00 PM	1.5		10271.2		15.4	87.2
Drive	WOT + Rough Road	Design	10/14/2013	8:13:00 PM	10:01:00 PM	1.8	10272.3	10321.9	48.8	86.6	22
Charge	Level II	N/A	10/14/2013	10:05:00 PM	5:11:00 AM	7.1	10323	10323	0	21.2	100
Drive	WOT + Rough Road	Design	10/15/2013	5:43:00 AM	8:03:00 AM	2.3	10323.8	10388.3	63.44	99.4	19.6
Charge	Level III	N/A	10/15/2013	8:12:00 AM	10:45:00 AM	2.5	10389.4	10389.4	0	19	100
Drive	WOT + Rough Road	Design	10/15/2013	11:05:00 AM	1:25:00 PM	2.3	10390.2	10452	61	99.6	19.8
Charge	Level III	N/A	10/15/2013	1:38:00 PM	3:22:00 PM	1.7		10453.2		19	96
Drive	WOT + Rough Road	Design	10/15/2013	3:27:00 PM	5:36:00 PM	2.1	10454.3	10516.3	61	96	18.6
Charge	Level III	N/A	10/15/2013	5:41:00 PM	8:02:00 PM	2.4		10517.4		18	99.8
Drive	WOT + Rough Road	Design	10/15/2013	8:08:00 PM	10:19:00 PM	2.2	10518.5	10580.5	61	99.2	23.2
Charge	Level II	N/A	10/15/2013	10:23:00 PM	4:02:00 AM	7.8	10581.5	10581.5	0	22.6	100
Charge	Level III	N/A	10/16/2013	6:40:00 AM	9:18:00 AM	2.6		10641.7		29	100
Drive	WOT + Rough Road	Design	10/16/2013	9:23:00 AM	10:38:00 AM	1.3	10642.8	10679.9	36.6	99.4	55.2
Drive	WOT + Rough Road	Design	10/16/2013	10:51:00 AM	11:46:00 AM	0.9	10680.7	10708	24.4	54.6	18.8
Charge	Level III	N/A	10/16/2013	11:50:00 AM	1:34:00 PM	1.7		10709		18.2	92.2
Drive	WOT + Rough Road	Design	10/16/2013	1:38:00 PM	2:51:00 PM	1.2	10710	10747.1	36.6	91.6	47
Charge	Level III		10/16/2013	2:56:00 PM	5:15:00 PM	2.3		10748.2		46.4	100
Drive	WOT + Rough Road	Design	10/16/2013	5:30:00 PM	6:10:00 PM	0.7	10749.5	10764.1	14.64	99.4	82.4
Drive	WOT + Rough Road	Design	10/17/2013	9:00:00 PM	10:23:00 PM	1.4	10766.4	10806	39.04	96.8	47.6
Charge	Level II		10/17/2013	10:28:00 PM	3:54:00 AM	5.5		10807		47.2	100
Charge	Level II		10/17/2013	12:50:00 AM	12:00:00 PM	11.2		10765.3		81.8	100
Drive	WOT + Rough Road	Design	10/18/2013	6:30:00 AM	8:52:00 AM	2.4	10808.4	10871.4	61	99	22.8
Drive	WOT + Rough Road	Design	10/18/2013	11:37:00 AM	1:45:00 PM	2.1	10875.9	10937.7	61	99.4	18.2
Charge	Level III		10/18/2013	8:59:00 AM	11:25:00 AM	2.4		10872.5		22.2	100
Charge	Level III	N/A	10/18/2013	1:53:00 PM	3:33:00 PM	1.7		10938.7		17.2	99.4
Drive	WOT + Rough Road	Design	10/18/2013	3:39:00 PM	5:55:00 PM	2.3	10939.8	11007.8	67.1	98.8	16.4

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Charge	Level III	N/A	10/18/2013	5:59:00 PM	7:37:00 PM	1.6		1108.9		15.8	99
Drive	WOT + Rough Road	Design	10/18/2013	7:42:00 PM	9:20:00 PM	1.6	11010	11053.3	42.7	98.6	47
Drive	WOT + Rough Road	Design	10/18/2013	9:37:00 PM	10:27:00 PM	0.8	11055.5	11080.2	24.4	46.2	13.6
Charge	Level III	N/A	10/18/2013	10:32:00 PM	4:22:00 AM	5.9	11081.3	11081.3	0	13	100
Drive	WOT + Rough Road	Design	10/19/2013	5:00:00 AM	7:45:00 AM	2.8	11082.1	11144.8	61	99.4	17.8
Charge	Level III	N/A	10/19/2013	2:28:00 PM	3:25:00 PM	0.9		11178.8		53.6	98.6
Drive	WOT + Rough Road	Design	10/19/2013	3:30:00 PM	5:36:00 PM	2.1	11179.9	11241.8	61	98	16.2
Charge	Level III	N/A	10/19/2013	7:55:00 AM	9:45:00 AM	1.8		11145.9		17	30
Charge	Level III	N/A	10/19/2013	9:45:00 AM	10:47:00 AM	1		11145.9		30	94.8
Drive	WOT + Rough Road	Design	10/19/2013	1:15:00 PM	2:16:00 PM	1	11146.8	11177.8	30.5	95	55.2
Charge	Level III	N/A	10/19/2013	5:41:00 PM	7:10:00 PM	1.5		11242.9		15.2	99.2
Drive	WOT + Rough Road	Design	10/19/2013	7:15:00 PM	9:26:00 PM	2.2	11244	11305.9	61	98.6	20.8
Charge	Level II	N/A	10/19/2013	9:31:00 PM	4:02:00 AM	6.5	11307	11307	0	20	99.8
Drive	WOT + Rough Road	Design	10/20/2013	4:38:00 AM	6:50:00 AM	2.2	11307.8	11369.8	61	99.2	19.6
Charge	Level III	Design	10/20/2013	7:00:00 AM	8:40:00 AM	1.7	11370.9	11307.9	0	18.8	99.6
Drive	WOT + Rough Road	Design	10/20/2013	8:50:00 AM	10:52:00 AM	2	11371.7	11433.6	61	99.4	16.2
Charge	Level III	N/A	10/20/2013	11:00:00 AM	12:14:00 PM	0	11434.7	11434.7	0	15.6	95.8
Drive	WOT + Rough Road	Design	10/20/2013	12:25:00 PM	1:25:00 PM	1	11435.5	11466.6	30.5	95.6	55.2
Charge	Level III	N/A	10/20/2013	1:30:00 PM	2:27:00 PM	0.9		11467.6		54.4	96.2
Drive	WOT + Rough Road	Design	10/20/2013	2:31:00 PM	4:35:00 PM	2.1	11468.7	11528.2	58.56	95.8	16
Charge	Level III	N/A	10/20/2013	4:39:00 PM	6:15:00 PM	1.6		11529.2		15.2	99
Drive	WOT + Rough Road	Design	10/20/2013	6:20:00 PM	8:27:00 PM	2.1	11530.3	11594.7	63.44	98.4	10.6
Charge	Level III	N/A	10/20/2013	8:31:00 PM	4:18:00 AM	7.8	11595.8	11595.8	0	10	99.4
Drive	WOT + Rough Road	Design	10/21/2013	4:28:00 AM	6:40:00 AM	2.2	11596.6	11658.7	61	99	18.2
Charge	Level III	N/A	10/21/2013	6:50:00 AM	7:50:00 AM	1	11659.7	11659.7	0	17.6	92
Drive	WOT + Rough Road	Design	10/21/2013	7:56:00 AM	8:51:00 AM	0.9	11660.5	11687.9	26.84	91.6	55.6
Charge	Level III	N/A	10/21/2013	8:57:00 AM	9:21:00 AM	0.4	11689	11689	0	54.8	78.2
Drive	WOT + Rough Road	Design	10/21/2013	9:30:00 AM	10:58:00 AM	1.5	11689.8	11733.4	42.7	78	18.2
Charge	Level III	N/A	10/21/2013	11:10:00 AM	12:14:00 PM	1.1	11734.6	11734.6	0	17.4	85
Drive	WOT + Rough Road	Design	10/21/2013	12:20:00 PM	1:10:00 PM	0.8	11735.5	11760.4	24.4	84.6	51.4
Charge	Level II	N/A	10/21/2013	1:20:00 PM	1:40:00 PM	0.3	11761.5	11761.5	0	50.6	53.6
Drive	WOT + Rough Road	Design	10/21/2013	10:45:00 PM	12:35:00 AM	1.9	11765.9	11821.6	54.9	98	22.2
Charge	Level III		10/21/2013	6:35:00 PM	8:10:00 PM	1.6		11761.5		51.8	100
Charge	Level II	N/A	10/22/2013	1:15:00 AM	5:17:00 AM	4	11822.6	11822.6	0	21.2	92.8
Drive	WOT + Rough Road	Design	10/22/2013	5:24:00 AM	7:12:00 AM	1.8	11823.4	11875.3	51.24	92.4	17.8
Charge	Level III	N/A	10/22/2013	7:18:00 AM	9:45:00 AM	2.5	11876.4	11876.4	0	17.4	100
Drive	WOT + Rough Road	Design	10/22/2013	9:50:00 AM	11:47:00 AM	2	11877.2	11934.1	56.12	99.6	19.8
Charge	Level III	N/A	10/22/2013	11:54:00 AM	12:45:00 PM	0.8	11935.2	11935.2	0	19	67.8
Drive	WOT + Rough Road	Design	10/22/2013	12:51:00 PM	1:50:00 PM	1	11936	11963.3	26.84	67.6	30.2
Charge	Level III		10/22/2013	1:55:00 PM	2:49:00 PM	0.6		11964.4		29.2	76
Charge	Level III		10/23/2013	8:35:00 PM	10:30:00 PM	1.9		12013		44.8	99.4
Drive	WOT + Rough Road	Design	10/23/2013	10:33:00 PM	1:07:00 AM	1.7	12014	12079	64.66	99.2	33.6
Drive	WOT + Rough Road	Design	10/24/2013	6:10:00 AM	8:25:00 AM	2.3	12082.1	12143.8	61	99.4	18

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Charge	Level II		10/24/2013	1:22:00 AM	5:43:00 AM	4.3		12080		33.2	100
Charge	Level III		10/24/2013	8:30:00 AM	10:05:00 AM	1.6		12144.8		17.4	98.8
Drive	WOT + Rough Road	Design	10/24/2013	10:15:00 AM	11:55:00 AM	1.7	12146.1	12195.3	48.8	98.2	32.6
Charge	Level III		10/24/2013	12:05:00 PM	2:00:00 PM	1.9		12196.3		32.2	100
Drive	WOT + Rough Road	Design	10/24/2013	2:07:00 PM	2:57:00 PM	0.8	12197.6	12222.2	24.4	99.4	70.8
Charge	Level II		10/24/2013	4:27:00 PM	6:56:00 PM	2.5		12223.2		71.2	88.6
Drive	WOT + Rough Road	Design	10/24/2013	6:56:00 PM	9:08:00 PM	2.2	12224	12279	54.9	88.2	29.4
Charge	Level III		10/24/2013	9:18:00 PM	10:26:00 PM	1.1		12280		29	97.2
Drive	WOT + Rough Road	Design	10/24/2013	10:32:00 PM	1:12:00 AM	2.75	12281	12356	74.42	96.6	20.2
Drive	WOT + Rough Road	Design	10/25/2013	7:57:00 AM	9:05:00 AM	1.1	12363.2	12394.2	30.5	97.6	59.8
Charge	Level III		10/25/2013	9:10:00 AM	9:43:00 AM	0.6		12395.2		59.2	87.4
Charge	Level II		10/25/2013	1:23:00 AM	6:30:00 AM	5.1		12357		19.6	100
Drive	Dynamic Evaluation	Design	10/25/2013	10:45:00 AM	5:20:00 PM	6.6	12395.3	12551.9		88.2	77.2
Charge	Level III	N/A	10/25/2013	5:30:00 PM	6:10:00 PM	0.7	12551.9	12551.9	0	77.2	99
Drive	High Speed Cycle	N/A	10/25/2013	6:13:00 PM	7:29:00 PM	1.3	12551	12654	103	99	36.6
Charge	Level III	N/A	10/25/2013	7:31:00 PM	8:53:00 PM	1.4	12654	12654	0	36.6	99.4
Drive	High Speed Cycle	N/A	10/25/2013	8:55:00 PM	10:04:00 PM	1.1	12654	12757	103	99.4	37.2
Charge	Level III	N/A	10/25/2013	10:07:00 PM	11:10:00 PM	1.1	12757	12757	0	37.2	95.6
Drive	High Speed Cycle	N/A	10/26/2013	11:12:00 PM	12:17:00 AM	0.9	12757	12859	103	95.6	34.2
Charge	Level III	N/A	10/26/2013	12:20:00 AM	5:25:00 AM	5.1	12859.8	12859.8	0	34.2	100
Drive	High Speed Cycle	Design	10/26/2013	5:56:00 AM	7:01:00 AM	1.1	12862.1	12964.9	102.8	99	36.6
Charge	Level III	N/A	10/26/2013	7:03:00 AM	8:05:00 AM	1	12964.9	12694.9	0	36.6	95
Drive	High Speed Cycle	Design	10/26/2013	8:10:00 AM	9:15:00 AM	1.1	12694.9	13068.2	103.3	95	31.8
Charge	Level III	N/A	10/26/2013	9:17:00 AM	10:33:00 AM	1.3	13068.2	13068.2	0	31.8	97.8
Drive	High Speed Cycle	Design	10/26/2013	10:39:00 AM	11:43:00 AM	1.1	13068.2	13171.7	103.5	97.8	35.2
Charge	Level III	N/A	10/26/2013	11:45:00 AM	1:00:00 PM	1.3	13171.7	13171.7	0	35	97.8
Drive	High Speed Cycle	Design	10/26/2013	1:05:00 PM	2:10:00 PM	1.1	13171.7	13274.7	103	97.8	35.6
Charge	Level III	N/A	10/26/2013	2:11:00 PM	3:19:00 PM	1.1	13274.9	13274.9	0	35.6	96.4
Drive	High Speed Cycle	N/A	10/26/2013	3:21:00 PM	4:38:00 PM	1.3	13274	13378	103.2	96.4	34.4
Charge	Level III	N/A	10/26/2013	4:39:00 PM	5:29:00 PM	0.8	13378	13378	0	34.4	87
Drive	High Speed Cycle	N/A	10/26/2013	5:35:00 PM	6:34:00 PM	1	13378	13481	102.2	87	25.4
Charge	Level III	N/A	10/26/2013	6:45:00 PM	7:42:00 PM	0.9	13481	13481	0	25.4	87.8
Drive	High Speed Cycle	N/A	10/26/2013	7:56:00 PM	8:59:00 PM	1.1	13481	13583	102.3	87.8	26.6
Charge	Level III	N/A	10/26/2013	9:00:00 PM	9:51:00 PM	0.8	13583	13583	0	26.6	84
Drive	High Speed Cycle	N/A	10/26/2013	9:58:00 PM	11:03:00 PM	1.1	13583	13685	102.4	84.2	21.4
Charge	Level III	N/A	10/26/2013	11:08:00 PM	5:42:00 AM	6.6	13685	13685	0	21.4	100
Drive	High Speed Cycle	Design	10/27/2013	6:01:00 AM	7:07:00 AM	1.1	13686	13788.9	102.9	99.6	38.6
Charge	Level III	N/A	10/27/2013	3:48:00 PM	4:56:00 PM	1.1	13789	13789	0	36.8	95.8
Drive	WOT + Rough Road	Design	10/27/2013	5:01:00 PM	7:49:00 PM	2.8	13790	13863	71.98	95.6	19.8
Charge	Level III	N/A	10/27/2013	11:45:00 PM	12:25:00 AM	0.7	13929	13929	0	19	74.8
Charge	Level III	N/A	10/28/2013	7:55:00 PM	8:55:00 PM	1	13865	13865	0	19	90.4
Drive	WOT + Rough Road	Design	10/28/2013	9:01:00 PM	11:39:00 PM	2.6	13866	13928	62.22	89.8	19.8
Drive	WOT + Rough Road	N/A	10/28/2013	12:29:00 AM	12:58:00 AM	0.5	13931	13945	14.64	73.6	57.6

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Charge	Level II	N/A	10/28/2013	1:25:00 AM	5:36:00 AM	4.2	13946	13946	0	57	100
Drive	WOT + Rough Road	Design	10/28/2013	10:06:00 AM	12:02:00 PM	1.9	13947.5	14004.5	56.12	98.8	19
Charge	Level III	N/A	10/28/2013	12:08:00 PM	1:50:00 PM	1.7	14005.5	14005.5	0	18.4	99.6
Drive	WOT + Rough Road	Design	10/28/2013	1:57:00 PM	3:38:00 PM	1.7	14006.8	14055.8	48.8	99.2	31.8
Charge	Level III		10/28/2013	3:50:00 PM	5:46:00 PM	1.9		14056.9		31	100
Drive	WOT + Rough Road	Design	10/28/2013	7:15:00 PM	9:25:00 PM	2.2	14058.2	14119.8	61	259	27
Charge	Level III		10/28/2013	9:35:00 PM	11:25:00 PM	1.8		14120.8		24	267
Drive	WOT + Rough Road	Design	10/28/2013	11:35:00 PM	12:55:00 AM	1.2	14121.9	14159.1	36.6	265	125
Chamber Soak	Corrosion Drying Chamber	N/A	10/28/2013	12:55:00 AM	4:30:00 PM	40.5	14161.1	14161.1	0		
Charge	UMC (240V) - Hot Chamber	N/A	10/29/2013	1:31:00 AM	5:11:00 AM	3.7	14601.1	14601.1	0	52.4	82.6
Charge	Level III	N/A	10/29/2013	5:21:00 AM	5:51:00 AM	0.5	14160.2	14160.2	0	82.4	97.4
Drive	WOT + Rough Road	Design	10/29/2013	5:58:00 AM	8:09:00 AM	2.2	14161	14219.4	57.34	97	21.2
Charge	Level III	N/A	10/29/2013	8:20:00 AM	9:51:00 AM	1.5	14220.4	14220.4	0	20.6	99.4
Drive	WOT + Rough Road	Design	10/29/2013	10:00:00 AM	12:12:00 PM	2.2	14221.1	14283.1	61	99.8	18.6
Charge	Level III		10/29/2013	12:24:00 PM	2:28:00 PM	2.1		14284.2		17.8	100
Drive	WOT + Rough Road	Design	10/29/2013	11:40:00 PM	12:55:00 AM	1.25	14285.6	14322.4	36.6	98.4	52.8
Charge	Level III		10/30/2013	1:05:00 AM	1:20:00 AM	0.3		14323.5		52.2	71.4
Charge	Level II	N/A	10/30/2013	1:22:00 AM	4:58:00 AM	3.6	14323.5	14323.5	0	71.4	100
Drive	MTN1	Design	10/30/2013	5:25:00 AM	9:15:00 AM	3.8	14323.6	14441.9	118.3	100	47.2
Charge	Level III	N/A	10/30/2013	9:31:00 AM	10:30:00 AM	1	14442	14442	0	47	96.6
Drive	MTN1	Design	10/30/2013	10:35:00 AM	3:14:00 PM	4.7	14442	14567.9	125.9	96.6	47.4
Charge	Level III	Design	10/30/2013	3:15:00 PM	4:28:00 PM	1.2	14567.9	14567.9	0	47.4	99.4
Drive	WOT + Rough Road	Design	10/30/2013	9:44:00 PM	11:34:00 PM	1.8	14569	14620	51.24	98.4	45.2
Charge	Level III	Design	10/30/2013	11:47:00 PM	12:20:00 AM	0.7	14621	14621	0	44.2	80.6
Drive	WOT + Rough Road	Design	10/31/2013	6:00:00 AM	7:40:00 AM	1.7	14625.4	14674.7	48.8	99.2	26.8
Charge	Level III		10/31/2013	7:50:00 AM	9:40:00 AM	1.8		14675.7		26	98.2
Drive	Dynamic Evaluation		10/31/2013	10:10:00 AM	10:30:00 AM	0.3	14675.8	14681.1		98.2	94.4
Drive	WOT + Rough Road	Design	10/31/2013	10:47:00 AM	12:05:00 PM	1.3	14682.4	14703.6	18.3	93.8	68.6
Charge	UMC (240V) - Hot Chamber		10/31/2013	12:47:00 AM	3:46:00 AM	3		14623		81.4	100
Drive	WOT + Rough Road	Design	10/31/2013	5:59:00 PM	7:40:00 PM	1.7	14705	14748	42.7	68.4	21.8
Charge	Level III	Design	10/31/2013	7:48:00 PM	9:05:00 PM	1.3	14750	14750	0	21.4	91.8
Drive	WOT + Rough Road	Design	10/31/2013	9:14:00 PM	12:24:00 AM	1.2	14751	14815	61	91.6	26.4
Drive	WOT + Rough Road	Design	11/1/2013	4:30:00 PM	6:47:00 PM	2.3	15012	15057	42.7	67.2	18.2
Charge	Level III	Design	11/1/2013	6:55:00 PM	7:45:00 PM	0.8	15058	15058	0	17.8	81.8
Drive	WOT + Rough Road	Design	11/1/2013	7:55:00 PM	10:01:00 PM	2.1	15059	15109	48.8	81.8	30.4
Charge	UMC (240V) - Cold Chamber	N/A	11/1/2013	10:48:00 PM	5:15:00 AM	7.5	15110	15110	0	28	86
Charge	Level II	N/A	11/1/2013	12:37:00 AM	5:21:00 AM	4.7	14818	14818	0	25	100
Drive	MTN2	Design	11/1/2013	5:25:00 AM	1:55:00 PM	8.5	14818.5	15005.5	187	100	30.4
Charge	Level III	N/A	11/1/2013	2:00:00 PM	2:30:00 PM	0.5	15005.5	15005.5	0	30.4	70
Drive	WOT + Rough Road	Design	11/2/2013	6:38:00 AM	8:20:00 AM	1.7	15111.3	15154.9	42.7	80.6	19.4
Charge	Level III	N/A	11/2/2013	8:30:00 AM	9:56:00 AM	1.4	15155.4	15155.4	0	19.2	95.6
Drive	WOT + Rough Road	Design	11/2/2013	9:58:00 AM	12:14:00 PM	2.3	15155.8	15215.2	58.56	95.8	19.2

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Charge	Level III	N/A	11/2/2013	12:46:00 PM	1:50:00 PM	1.1	15217.4	15217.4	0	17.8	94.4
Drive	WOT + Rough Road	Design	11/2/2013	1:55:00 PM	2:50:00 PM	0.9	15217.8	15245.1	26.84	94	60
Drive	WOT + Rough Road	Design	11/2/2013	4:28:00 PM	7:09:00 PM	2.7	15246	15332	75.64	99	19.8
Charge	Level III	Design	11/2/2013	7:14:00 PM	7:57:00 PM	0.7	15323	15323	0	19.6	80.4
Drive	WOT + Rough Road	Design	11/2/2013	8:08:00 PM	9:57:00 PM	1.8	15323	15375	51.24	80.2	26
Charge	Level III	Design	11/2/2013	10:15:00 PM	10:36:00 PM	0.3	15376	15376	0	24.8	58
Drive	WOT + Rough Road	Design	11/2/2013	10:42:00 PM	11:31:00 PM	0.8	15378	15397	19.52	57.4	37.2
Charge	UMC (240V) - Hot Chamber	N/A	11/3/2013	12:19:00 AM	5:12:00 AM	4.9	15398.9	15398.9	0	36.6	86.6
Drive	High Speed Cycle	Design	11/3/2013	8:26:00 AM	9:32:00 AM	1.1	15399.1	15508.3	109.2	84.8	18.8
Charge	Level III	N/A	11/3/2013	9:34:00 AM	11:10:00 AM	1.6	15508.3	15508.3	0	18.8	100
Drive	High Speed Cycle	Design	11/3/2013	11:15:00 AM	12:19:00 PM	1.1	15508.3	15610.6	102.3	100	37
Charge	Level III	N/A	11/3/2013	12:21:00 PM	1:33:00 PM	1.2	15610.6	15610.6	0	37	98.4
Drive	High Speed Cycle	Design	11/3/2013	1:39:00 PM	2:43:00 PM	1.1	15610.6	15712.7	102.1	98.4	35.4
Drive	High Speed Cycle	Design	11/3/2013	3:48:00 PM	4:58:00 PM	1.2	15712	15812	103	93.2	28.6
Charge	Level III	Design	11/3/2013	4:59:00 PM	5:48:00 PM	0.8	15815	15815	0	28.6	83.6
Drive	High Speed Cycle	Design	11/3/2013	5:52:00 PM	7:00:00 PM	1.1	15812	15918	102.49	83.6	18.4
Charge	Level III	Design	11/3/2013	7:03:00 PM	8:02:00 PM	1	15918	15918	0	18.4	85.2
Drive	High Speed Cycle	Design	11/3/2013	8:06:00 PM	9:13:00 PM	1.1	15918	16021	102.84	85.2	20
Charge	Level III	Design	11/3/2013	2:46:00 PM	3:32:00 PM	0.8	15712.7	15712.2	0	35.4	93.2
Charge	Level III	Design	11/3/2013	9:14:00 PM	10:08:00 PM	0.9	16021	16123	0	20	83.4
Drive	High Speed Cycle	Design	11/3/2013	10:11:00 PM	11:18:00 PM	1.1	16021	16123	102.75	83.4	18.4
Charge	Level III	N/A	11/3/2013	11:20:00 PM	4:55:00 AM	5.6	16123.9	16123.9	0	18.4	100
Drive	High Speed Cycle	Design	11/4/2013	5:40:00 AM	6:46:00 AM	1.1	16123.9	16226.1	102.2	99.6	38
Charge	Level III	N/A	11/4/2013	6:48:00 AM	7:41:00 AM	0.9	16226.1	16226.1	0	38	91.4
Drive	High Speed Cycle	Design	11/4/2013	7:53:00 AM	8:58:00 AM	1.1	16226.1	16378.7	102.6	92.4	29.4
Charge	Level III	N/A	11/4/2013	9:00:00 AM	9:57:00 AM	0.9	16378.7	16378.7	0	293.4	90.2
Drive	High Speed Cycle	Design	11/4/2013	10:20:00 AM	11:25:00 AM	1.1	16328.7	16431	102.4	90.6	26.4
Charge	Level III	N/A	11/4/2013	11:27:00 AM	12:20:00 PM	0.9	16431	16431	0	26.4	86
Drive	High Speed Cycle	Design	11/4/2013	12:31:00 PM	1:37:00 PM	1.1	16431	16533.8	102.8	85.8	21.2
Charge	Level III	N/A	11/4/2013	1:40:00 PM	2:36:00 PM	0.9	16533.8	16533.8	0	21.2	86.2
Drive	High Speed Cycle	Design	11/4/2013	2:40:00 PM	3:45:00 PM	1.1	16533.8	16636.4	102.4	86.2	21.6
Charge	Level III		11/4/2013	3:47:00 PM	5:24:00 PM	1.6		16636.4		21.6	100
Drive	High Speed Cycle	Design	11/4/2013	5:30:00 PM	6:33:00 PM	1.1	16636.4	16738.4	102	100	38.4
Charge	Level III		11/4/2013	6:40:00 PM	8:00:00 PM	1.3		16738.4		38.4	99.8
Drive	High Speed Cycle	Design	11/4/2013	8:05:00 PM	9:08:00 PM	1.1	16738.4	16840.3	101.9	99.8	39.2
Charge	Level II		11/4/2013	9:20:00 PM	11:07:00 PM	1.8		16840.3		39	70.8
Charge	Level II	N/A	11/5/2013	1:35:00 AM	4:51:00 AM	3.3	16840.6	16840.6	0	71.4	100
Drive	CTY1	Design	11/5/2013	5:55:00 AM	6:46:00 AM	0.8	16840.6	16879.8	39.2	99.6	85.6
Charge	Level II	N/A	11/5/2013	6:46:00 AM	7:46:00 AM	1	16879.8	16879.8	0	85.6	92.2
Drive	CTY1	Design	11/5/2013	7:46:00 AM	4:46:00 PM	9	16879.8	16989	109.2	92.2	33
Charge	Level III	N/A	11/5/2013	4:54:00 PM	6:40:00 PM	1.8	16989	16989	0	33	100
Charge	UMC (240V) - Hot Chamber	N/A	11/6/2013	1:55:00 AM	8:20:00 AM	6.4	16989.1	16989.1	0	92.2	99.6
Drive	WOT + Rough Road	Design	11/6/2013	8:53:00 PM	10:57:00 PM	2.1	16993	17049	48.8	98	44.8

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Charge	UMC (240V) - Hot Chamber	N/A	11/7/2013	1:13:00 AM	6:30:00 AM	5.3	17044	17044	0	44.8	89
Chamber Soak		Design	11/7/2013	4:00:00 PM	4:15:00 PM	0.3	16993	16993	0	98	98
Drive	WOT + Rough Road	Design	11/7/2013	10:33:00 AM	11:39:00 AM	1.1	17045.8	17077	30.5	87.2	47.6
Charge	Level III	N/A	11/7/2013	11:47:00 AM	1:05:00 PM	1.3	17078	17078	0	47.2	99.4
Drive	WOT + Rough Road	Design	11/7/2013	11:22:00 PM	12:19:00 AM	0.9	17082	17106	24.4	96.6	72
Drive	WOT + Rough Road	Design	11/8/2013	6:54:00 AM	7:34:00 AM	0.7	17111.2	17129.9	18.3	98.4	75.2
Drive	WOT + Rough Road	Design	11/8/2013	7:48:00 AM	8:49:00 AM	1	17130.6	17161.6	30.5	74.8	36
Charge	Level III		11/8/2013	8:55:00 AM	10:02:00 AM	1.1		17162.7		35.4	97.2
Drive	WOT + Rough Road	Design	11/8/2013	10:10:00 AM	11:52:00 AM	1.7	17163.8	17214.3	48.8	96.8	32.6
Charge	Level III		11/8/2013	12:00:00 PM	1:33:00 PM	1.6		17215.4		32	100
Drive	WOT + Rough Road	Design	11/8/2013	2:00:00 PM	2:50:00 PM	0.8	17216.7	17241.2	24.4	99.4	70.4
Chamber Soak	UMC (240V) - Cold Chamber		11/8/2013	12:51:00 AM	4:59:00 AM	4.1		17109		70.8	100
Charge	Level II	Design	11/8/2013	3:00:00 PM	3:36:00 PM	0.6	17242.3	17242.3	0	70	80.2
Drive	Dynamic Evaluation	Design	11/8/2013	3:45:00 PM	4:05:00 PM	0.3	17242.3	17242.3	0	80.2	80
Drive	Dynamic Evaluation	Design	11/8/2013	4:28:00 PM	4:44:00 PM	0.3	17243	17250	0	80.4	75.2
Drive	WOT + Rough Road	Design	11/8/2013	5:19:00 PM	7:29:00 PM	2.2	17251	17303.8	51.24	74.4	19.8
Charge	Level III	Design	11/8/2013	7:50:00 PM	9:10:00 PM	1.3	17304.9	17304.9	0	19.2	86.8
Drive	WOT + Rough Road	Design	11/8/2013	9:19:00 PM	9:58:00 PM	0.7	17306	17322.1	15.86	86.6	70.2
Charge	UMC (240V) - Drizzle Chamber	N/A	11/9/2013	10:33:00 PM	7:28:00 AM	8.9	17323	17323		69.6	100
Drive	WOT + Rough Road	Design	11/9/2013	7:51:00 AM	9:58:00 AM	2.1	17324	17374	48.8	99	40.6
Charge	Level III	N/A	11/9/2013	10:03:00 AM	1:42:00 PM	3.6	17375	17375		40.2	100
Drive	WOT + Rough Road	Design	11/9/2013	1:47:00 PM	3:36:00 PM	1.8	17376	17421	42.7	99.4	47.6
Charge	Level III	Design	11/9/2013	3:43:00 PM	4:58:00 PM	1.3	17422	17422	0	47.2	98.6
Drive	WOT + Rough Road	Design	11/9/2013	5:03:00 PM	7:03:00 PM	2	17423.5	17455.1	30.5	98	69.4
Drive	WOT + Rough Road	Design	11/9/2013	8:37:00 PM	10:17:00 PM	1.7	17456.2	17499.3	42.7	67.6	22.4
Charge	Level III	Design	11/9/2013	10:26:00 PM	11:23:00 PM	0.9	17500.4	17500.4	0	22.2	92.4
Drive	WOT + Rough Road	Design	11/10/2013	11:27:00 PM	1:04:00 AM	0.6	17502.6	17544.5	42.7	90.8	46.8
Drive	WOT + Rough Road	Design	11/10/2013	6:55:00 AM	7:55:00 AM	1	17547.2	17578	30.5	89.2	47.4
Drive	WOT + Rough Road	Design	11/10/2013	8:05:00 AM	8:42:00 AM	0.6	17578	17597.3	18.3	46.8	20
Charge	Level III		11/10/2013	8:50:00 AM	10:50:00 AM	2		17598.2		19.4	100
Chamber Soak	UMC (240V) - Cold Chamber		11/10/2013	1:09:00 AM	6:38:00 AM	5.5		17545.6		45.6	90.6
Drive	WOT + Rough Road	Design	11/10/2013	1:45:00 PM	2:57:00 PM	1.2	17599.5	17637.6	36.6	99.2	52.2
Charge	Level III	Design	11/10/2013	3:05:00 PM	4:19:00 PM	1.2	17637.6	17637.6	0	51.8	99
Drive	WOT + Rough Road	Design	11/10/2013	4:23:00 PM	7:15:00 PM	2.9	17638.7	17712.8	73.2	98.4	27.4
Charge	Level III	Design	11/10/2013	7:18:00 PM	8:23:00 PM	1.1		17713.3	0	27.4	89.2
Drive	WOT + Rough Road	Design	11/10/2013	8:27:00 PM	10:46:00 PM	2.3	17714.2	17781.7	67.1	88.8	19
Charge	Level III	Design	11/10/2013	10:55:00 PM	12:04:00 AM	1.1		17782.7	0	18	94.6
Chamber Soak	UMC (240V) - Hot Chamber	N/A	11/12/2013	2:18:00 AM	5:45:00 AM	3.5	17782.9	17782.9	0	95	100

Event Type	Description	Weight Condition	Date	Start Time	End Time	Test Time [hr]	Start ODO [mi]	End ODO [mi]	Test Distance	Start SOC	End SOC
Drive	WOT + Rough Road	Design	11/12/2013	7:20:00 AM	8:43:00 AM	1.4	17783.8	17821.2	36.6	99.4	51.2
Charge	Level III	N/A	11/12/2013	8:54:00 AM	9:45:00 AM	0.8	17822.3	17822.3	0	50.4	94.2
Drive	WOT + Rough Road	Design	11/12/2013	10:18:00 AM	11:33:00 AM	1.3	17823.2	17860.5	36.6	94.2	47.2
Charge	UMC (240V) - Drizzle Chamber		11/12/2013	12:45:00 PM	5:50:00 PM	5.1		17861.7		46	61.6
Charge	Level III		11/12/2013	10:20:00 PM	10:50:00 PM	0.5		17862.4		61.4	86.8
Drive	WOT + Rough Road	Design	11/12/2013	11:00:00 PM	12:15:00 AM	1.25	17863.8	17900.8	36.6	86	37.4
Chamber Soak	UMC (240V) - Cold Chamber	Design	11/13/2013	1:15:00 AM	5:12:00 AM	4	17901.8	17901.8	0	35	71.2
Drive	WOT + Rough Road	Design	11/13/2013	5:50:00 AM	7:07:00 AM	1.3	17902.7	17938.8	36.6	68	17.2
Charge	Level III	N/A	11/13/2013	8:08:00 AM	10:15:00 AM	2.1	17940	17940	0	13.8	100
Charge	UMC (240V) - Cold Chamber	Design	11/13/2013	10:30:00 AM	3:37:00 PM	5.1	17940.1	17940.1	0	100	97.6
Drive	WOT + Rough Road	Design	11/13/2013	4:20:00 PM	6:52:00 PM	2.5	17942	18009.8	67.1	93	19.6
Charge	UMC (240V) - Drizzle Chamber	Design	11/13/2013	7:02:00 PM	12:02:00 AM	5		18010.9	0	18.8	48.2
Drive	WOT + Rough Road	Design	11/14/2013	12:33:00 AM	1:15:00 AM	0.7	18013.2	18031.5	18.3	48.4	26.6
Charge	Level III	Design	11/14/2013	2:25:00 PM	3:30:00 PM	1.1		18032.6	0	24.8	93.8
Drive	WOT + Rough Road	Design	11/14/2013	3:37:00 PM	6:34:00 PM	3	18033.7	18105.9	67.1	93.4	16
Charge	Level II	Design	11/14/2013	6:39:00 PM	12:11:00 AM	5.8	18106.9	18106.9	0	15.4	94

8.2.2 Manufacturer A: General Test Procedures.

The vehicle internal CAN data was logged on a regular basis. For the Manufacturer A Vehicle the CAN bus provided RESS voltage, current, SOC, maximum module temperature, and minimum module temperature. Measured SOC was used as a minimum estimate of the battery power remaining. Additional data, such as chamber ambient temperatures, was recorded manually as required. Had smoke, fire, or another anomalous condition occurred, it would have been manually recorded.

All discharge cycles were conducted using a dynamometer. The vehicle discharge operation target for Sequential Testing discharge cycles was continual maximum operational power. For a Manufacturer A vehicle, this target is achieved at 70 mph on a steep simulated grade. The power request was controlled using a manual pedal. This manual operation required periodic adjustment of pedal position as the vehicle temperature changed and the vehicle operating system adjusted the amount of power delivered for a constant pedal position. The effect of periodic adjustments can be seen in the 'sawtooth' pattern of the pack current traces in the initial part of some of the discharge curves.

8.2.3 Manufacturer A Vehicle: Charge and Discharge During Low Temperature Conditions

Manufacturer A provided a firmware patch that, once installed, disabled the RESS heating system. The firmware patch prevented the vehicle logic from activating RESS coolant heaters but had no other effect on the vehicle operating system. After testing was completed, the firmware patch was removed and the heating system functioned normally.

The Test Vehicle RESS was brought to 40% SOC, and the Test Vehicle was then installed on a dynamometer inside a thermally controlled chamber set at −20°C (Figure 30). The vehicle was allowed to thermalize for 18 hours, after which time minimum and maximum module temperatures were between −15.5 and −17.5°C.

A summary of test results is provided in Table 21 and Figure 31 through Figure33.

For Charge #1 the vehicle was connected to a Level 3 Charger. During Charge #1 the RESS did not allow charging to occur: a normal vehicle response to low RESS temperature with heating disabled. There was no change in RESS SOC or temperature during this charge attempt. The RESS was at a steady state after one hour, and Charge #1 was ended one hour later (Figure 31).

Figure 32 shows the data collected during Discharge #1. Discharge current increased with decreasing RESS voltage (power remained approximately constant 70kW) until a low SOC was reached, and the vehicle responded by limiting output power; a normal response. The vehicle normally terminated the discharge process when RESS SOC dropped to approximately 0%. RESS internal temperatures increased steadily throughout the discharge process to 32°C.

Figure 33 shows the result of Charge #2. The vehicle was connected to a Level 3 Charger while the RESS remained above 20 C despite the −20 C ambient. Charging initiated under these conditions. Until RESS SOC exceeded 2.6% charge current was limited to approximately 18A:

a normal vehicle response. Once SOC exceeded 2.6%, charging current rose to approximately 270A (typical of Level 3 charging). Charging proceeded normally: charging current decreased with increasing SOC, once the target voltage was reached, charge current tapered until full charge was achieved. Charging was normally terminated by the vehicle. During the charging cycle, the RESS reached a maximum temperature of 47°C.

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 21 - Summary of Charge and Discharge During Low Temperature Test Results.

Operation	Charge #1	Discharge #1	Charge #2
Time (hours)	2	0.6	2.2
Initial SOC	40%	40%	0%
Final SOC	40%	0%	100%
SOC change	0%	40%	100%
Maximum RESS Temperature (C)	−17.5°C	32°C	47°C
Evidence of Smoke	No	No	No
Compromised Cabin Tenability	No	No	No
Evidence of Fire	No	No	No
Evidence of Explosion	No	No	No

Figure 30 - The Test Vehicle as installed on the dynamometer. Solar load lights are used to provide illumination for the image, but were not used during testing. The Level 3 charge cable can be seen, coiled, at the left of the image.

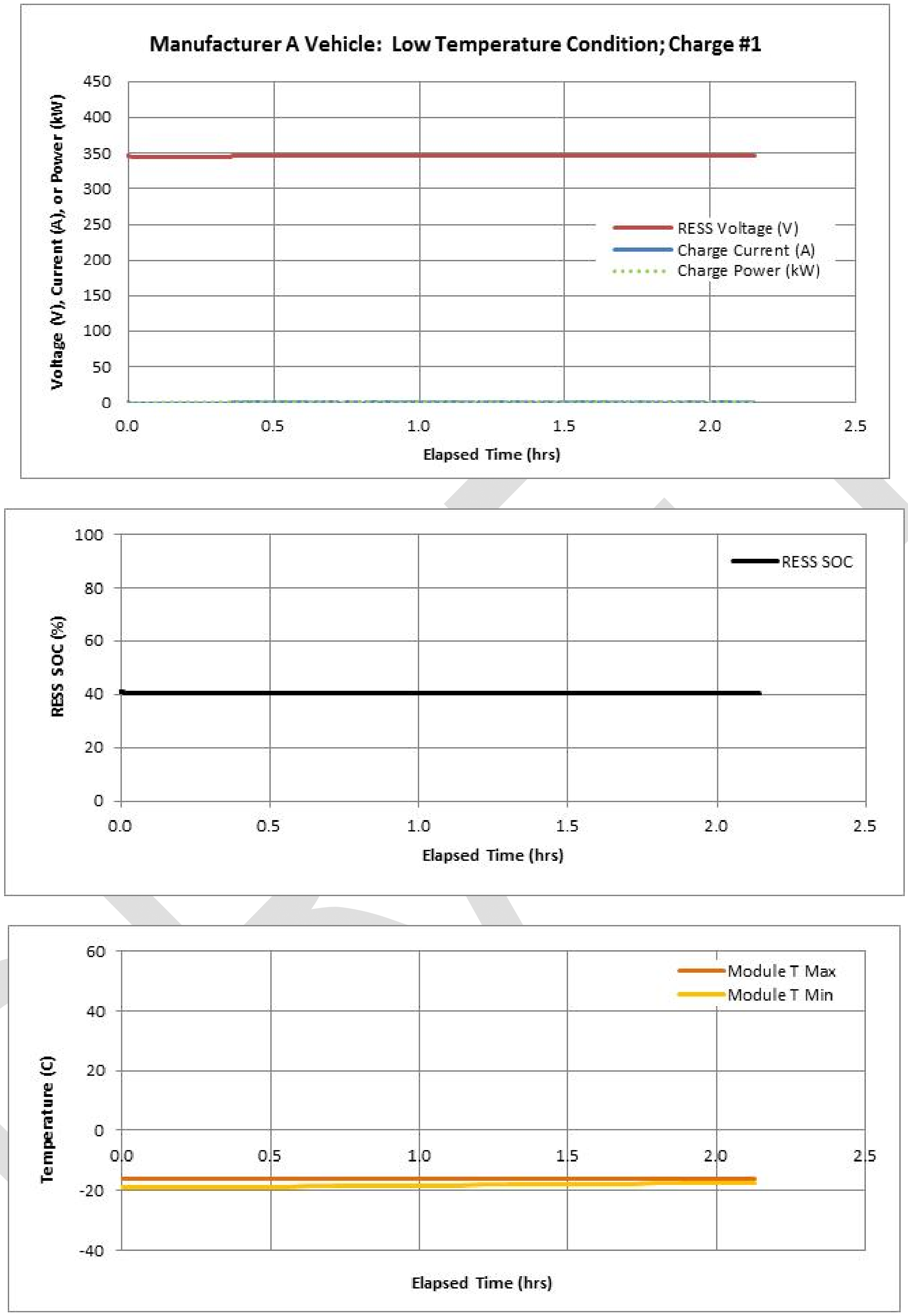

Figure 31 - Measured voltage, current, SOC, and temperature during Charge #1 at −20°C after 18 hour soak. The vehicle did not allow charging, thus RESS voltage and SOC remained constant.

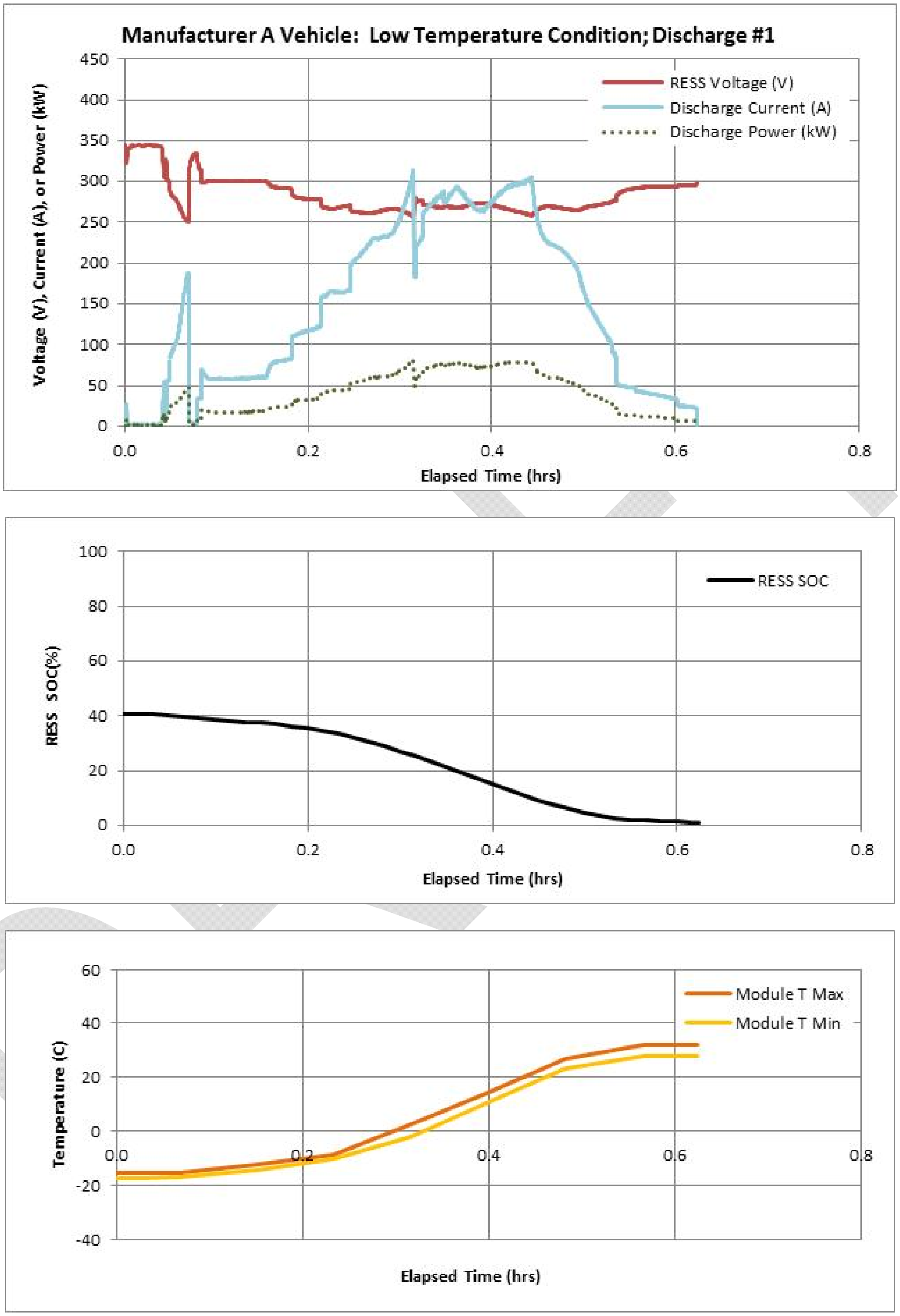

Figure 32 - Measured 4voltage, current, SOC, and temperature during Discharge #1 at −20°C.

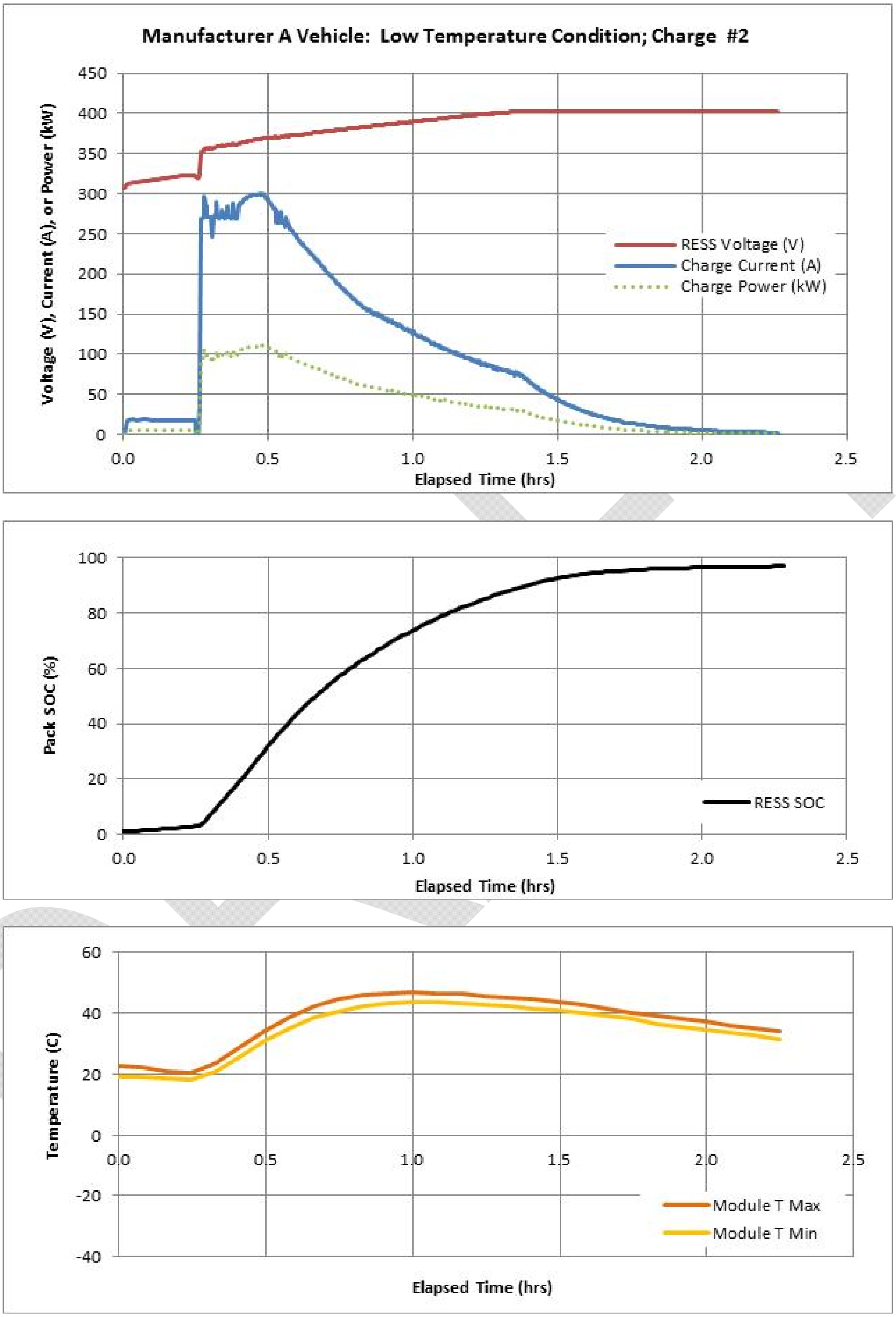

Figure 33 - Measured voltage, current, SOC, and temperature during Charge #2 at −20°C.

8.2.4 Manufacturer A Vehicle: Charge and Discharge During High Temperature Conditions

Manufacturer A provided a firmware patch that, once installed, disabled the RESS cooling system. The firmware patch prevented the vehicle logic from activating RESS coolant compressors in the coolant chiller and activating valves directing coolant flow to the radiators. The firmware patch had no other effect on the vehicle operating system. After testing was completed, the firmware patch was removed and the cooling system functioned normally.

The Test Vehicle RESS was brought to 100% SOC, and the Test Vehicle was installed on a dynamometer inside a thermally controlled chamber set at 40°C. The vehicle was allowed to thermalize until both the maximum and minimum RESS temperatures were within 2°C of 40°C.

A summary of test results is provided in Table 22 and Figure 34 through Figure36.

During Discharge #1 (Figure 34), the vehicle speed was increased on the dynamometer, and pedal position was increased until discharge power reached approximately 70kW. This discharge power level was maintained: the saw tooth pattern visible in the data is the result of iterative increases in the pedal position to increase current output from the RESS as the RESS voltage dropped. When RESS temperatures reached approximately 60°C, the output power from the RESS was limited, to approximately 25kW, a normal response. The output power continued to be limited and the RESS temperature did not exceed approximately 60°C. After approximately one hour at 25kW power output, when the RESS reached 5% SOC, discharge was manually terminated for experimental convenience (to avoid the low SOC charging regime that would limit charge current and delay the next stage of testing).

During Charge #1 (Figure 35), while the RESS remained at approximately 60°C, a Level 3 charger was connected to the vehicle. The RESS temperature remained at approximately 60°C, charge current was limited to a maximum of approximately 70A (charge power maximum of 25kW), a normal response. Charging terminated normally when the RESS reached 100% SOC.

At the beginning of Discharge #2 (Figure 36), the RESS temperature was slightly below 60°C. The vehicle speed was increased on the dynamometer, and pedal position was increased until discharge power reached approximately 70kW. When RESS temperatures reached approximately 60°C, the output power from the RESS was limited, to approximately 25kW, a normal response. The output power continued to be limited and the RESS temperature did not exceed approximately 60°C. When the RESS reached 5% SOC, discharge was manually terminated for experimental convenience (to avoid the low SOC charging regime that would limit charge current and delay the next stage of testing).

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 22 - Summary of Charge and Discharge During High Temperature Test Results.

Operation	Discharge #1	Charge #1	Discharge #2
Time (hours)	1.8	5.7	2.8
Initial SOC	100%	5%	100%
Final SOC	5%	100%	5%
SOC change	95%	95%	95%
Maximum RESS Temperature (C)	60°C	60°C	60°C
Evidence of Smoke	No	No	No
Compromised Cabin Tenability	No	No	No
Evidence of Fire	No	No	No

Evidence of Explosion	No	No	No

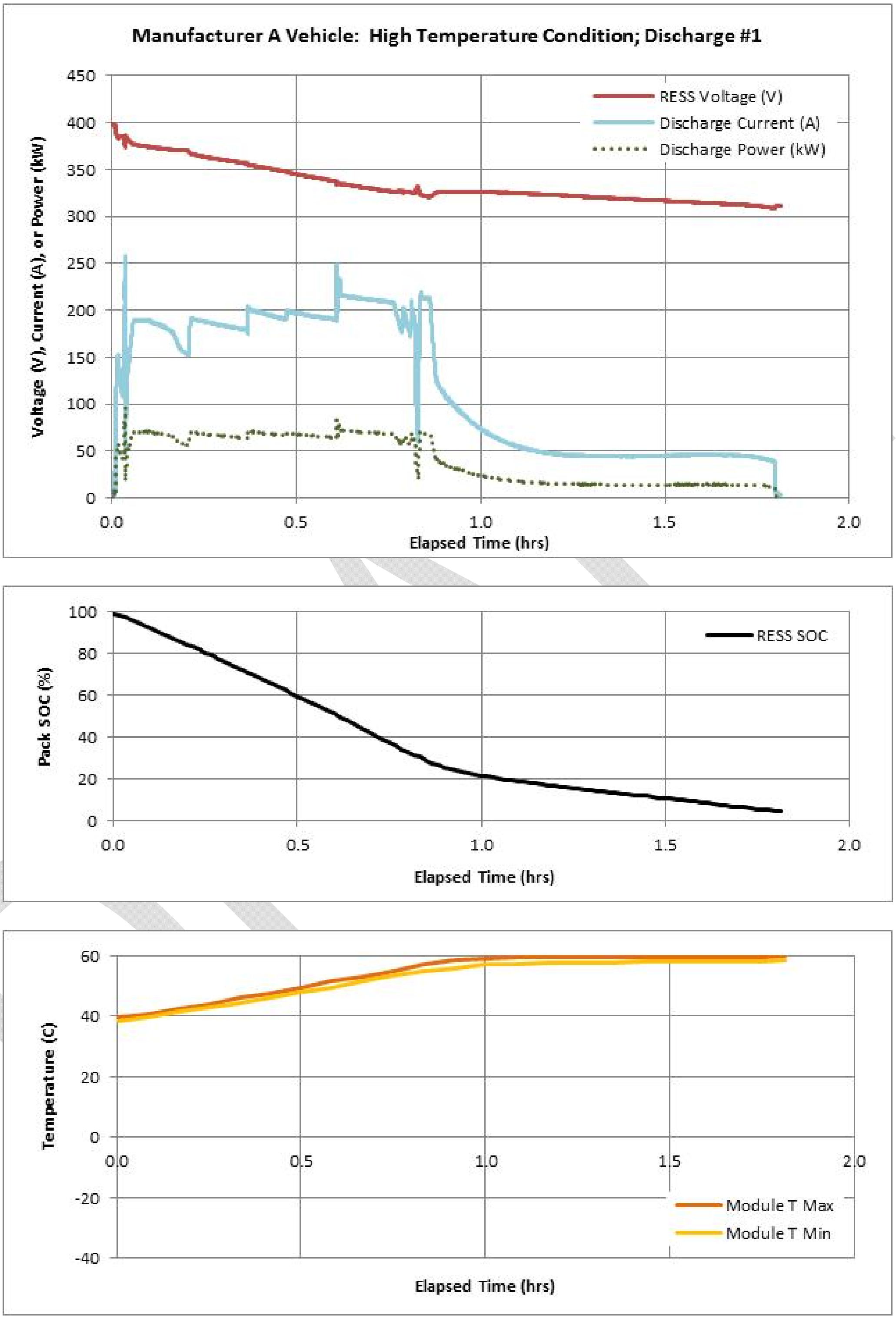

Figure 34 - Measured voltage, current, SOC, and temperature during Discharge #1 at 40°C.

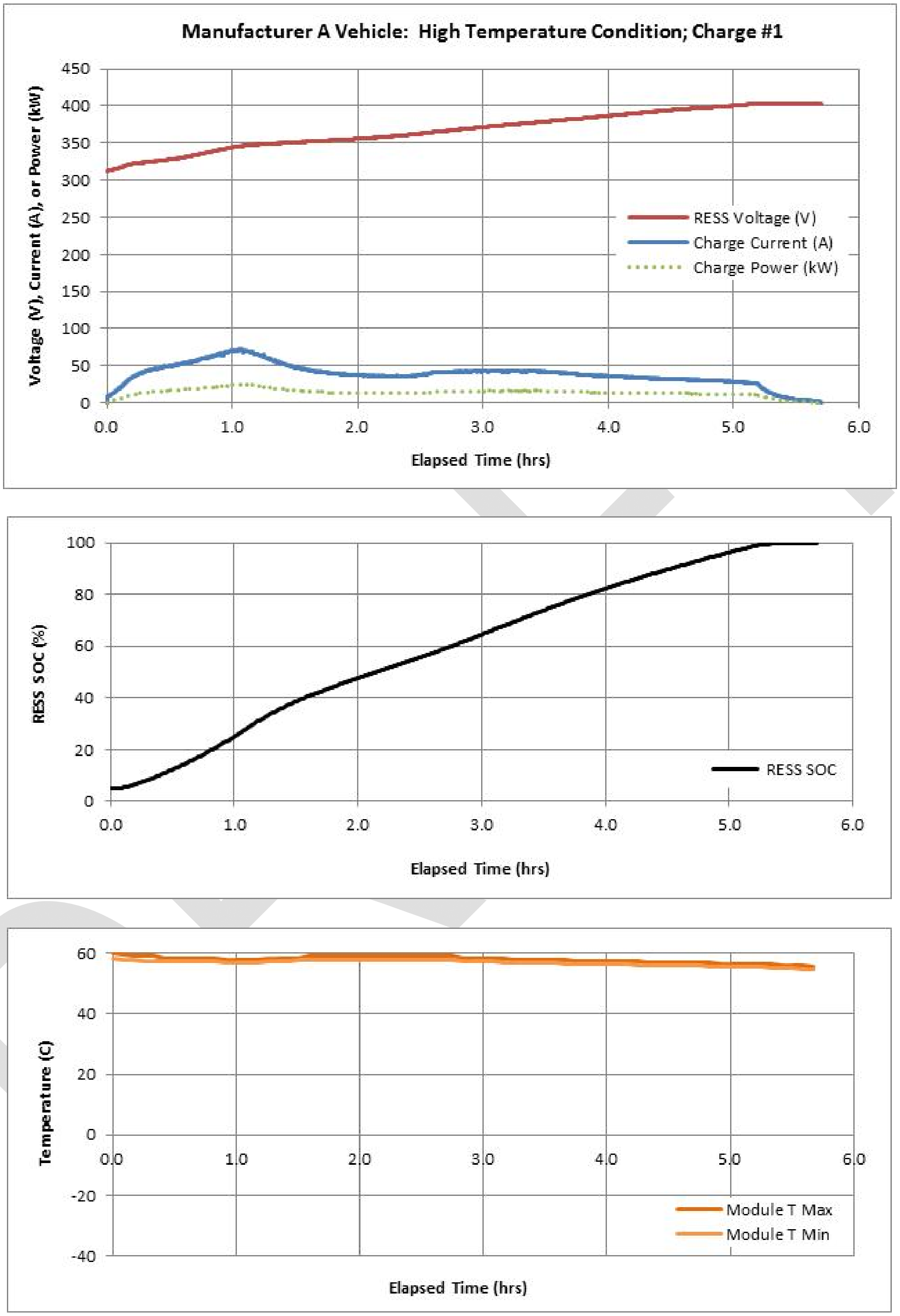

Figure 35 - Measured voltage, current, SOC, and temperature during Charge #1 at 40°C.

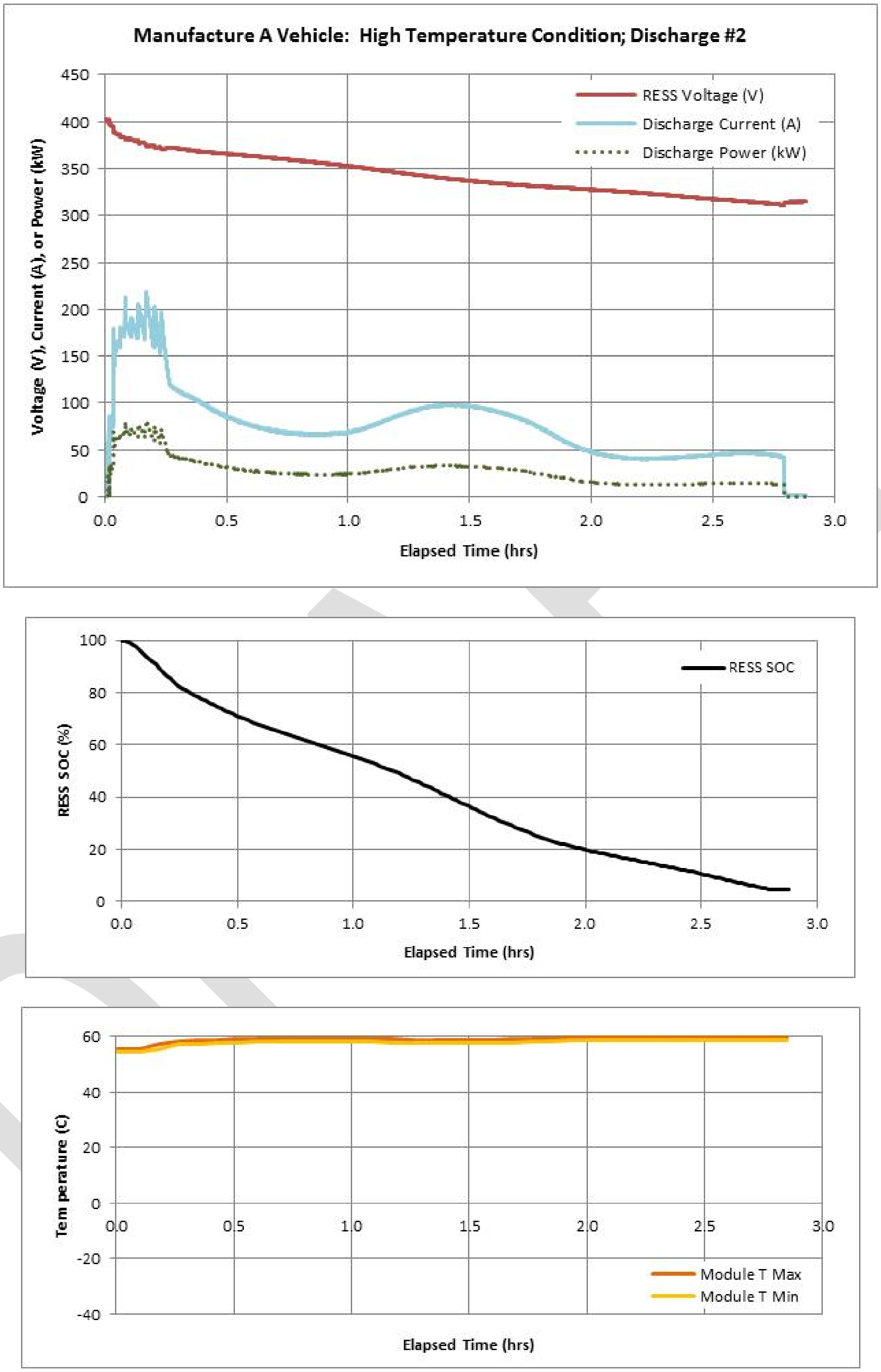

Figure 36 - Measured voltage, current, SOC, and temperature achieved during Discharge #2 at 40°C.

8.2.5 Manufacturer A Vehicle RESS Over-Discharge

Connections to the DC link on the Test Vehicle were made as per Sections 7.3 and 8.1. The RESS was isolated from the vehicle by removing the first responder loop which prevents the RESS from closing contactors, and by opening the vehicle "High Voltage Interlock" system circuit (HVIL), which prevents the vehicle from delivering 12V power to keep contactors closed. The rear seats were removed to expose the high voltage junction box. DC Link cables were installed as shown in Figure 15 and Figure 37. Once the DC Link cables were installed, the HVIL circuit was closed and the first responder loop was re-installed. The over-discharge resistor used in the DC Link had a measured resistance of 199 Ω and was rated for a power discharge of up to 3 kW. A flow of cold air over the resistor was maintained to assure that resistance was constant throughout the test.

The Test Vehicle RESS was brought to approximately 10% SOC. A summary of test results is provided in Table 23 and Figure 38 and Figure 39.

Testing began with the RESS at approximately 12% SOC. The Test Vehicle was placed into Drive Mode, but the accelerator was not depressed (the vehicle remained stationary). The DC Link discharge resistor was placed into the circuit and allowed to discharge the RESS with a current draw of approximately 2A, resulting in a discharge power of less than 1kW (Figure 38). After approximately 4 hours, when RESS SOC approached 8% SOC, the RESS terminated discharge, a normal response. After discharge terminated, the DC Link discharge resistor was removed from the circuit.

The Test Vehicle was placed into Charge Mode and connected to a Level 1 charger. The Test Vehicle was allowed to charge to the point where drive mode would engage if the charger was unplugged.

The Test Vehicle was placed into a mode where charging was expected, and the charging cable was connected. The AC supply side of the charge cable was left detached. The DC Link discharge resistor was placed into the circuit and allowed to discharge the RESS with a current draw of approximately 2A, resulting in a discharge power of less than 1kW (Figure 39). After approximately 1 hour, when RESS SOC approached 7% SOC, the RESS terminated discharge, a normal response. After discharge terminated, the DC Link discharge resistor was removed from the circuit.

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 23 - Summary of Over-Discharge Test Results.

Operation	Drive Mode	Charge Mode
Time (hours)	4.2	
Initial SOC	12%	8%
Final SOC	8%	7%
SOC change	4%	1%
Maximum RESS Temperature (C)	22°C	16°C
Evidence of Smoke	No	No
Compromised Cabin Tenability	No	No
Evidence of Fire	No	No
Evidence of Explosion	No	No

Figure 37 - The location of the exposed DC junction box in the Manufacturer A vehicle. The light orange leads connect to the DC Link. Note that the vehicle rear seats have been removed. The junction box cover can be seen at the lower left of the image.

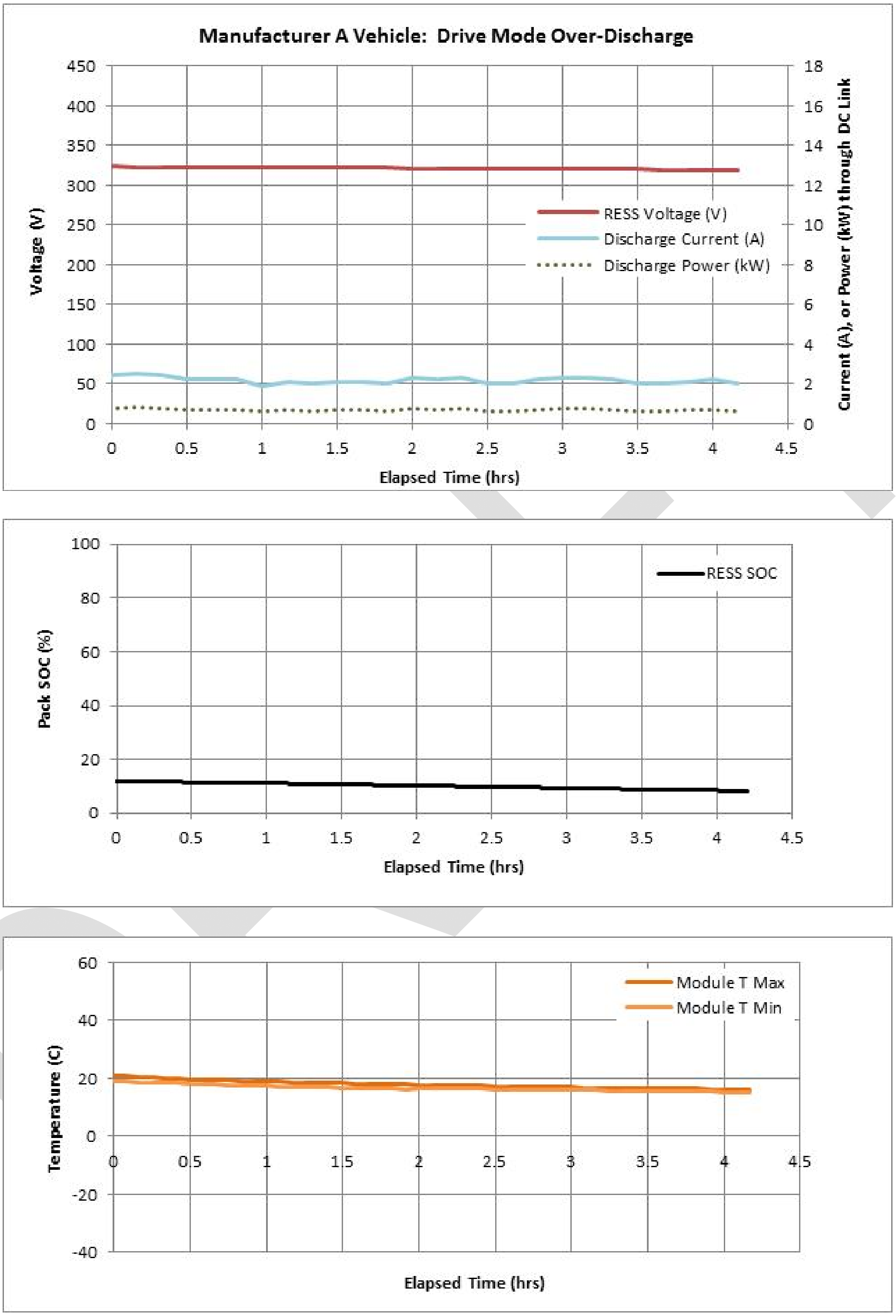

Figure 38 - Measured voltage, current, SOC, and temperature during drive mode over-discharge.

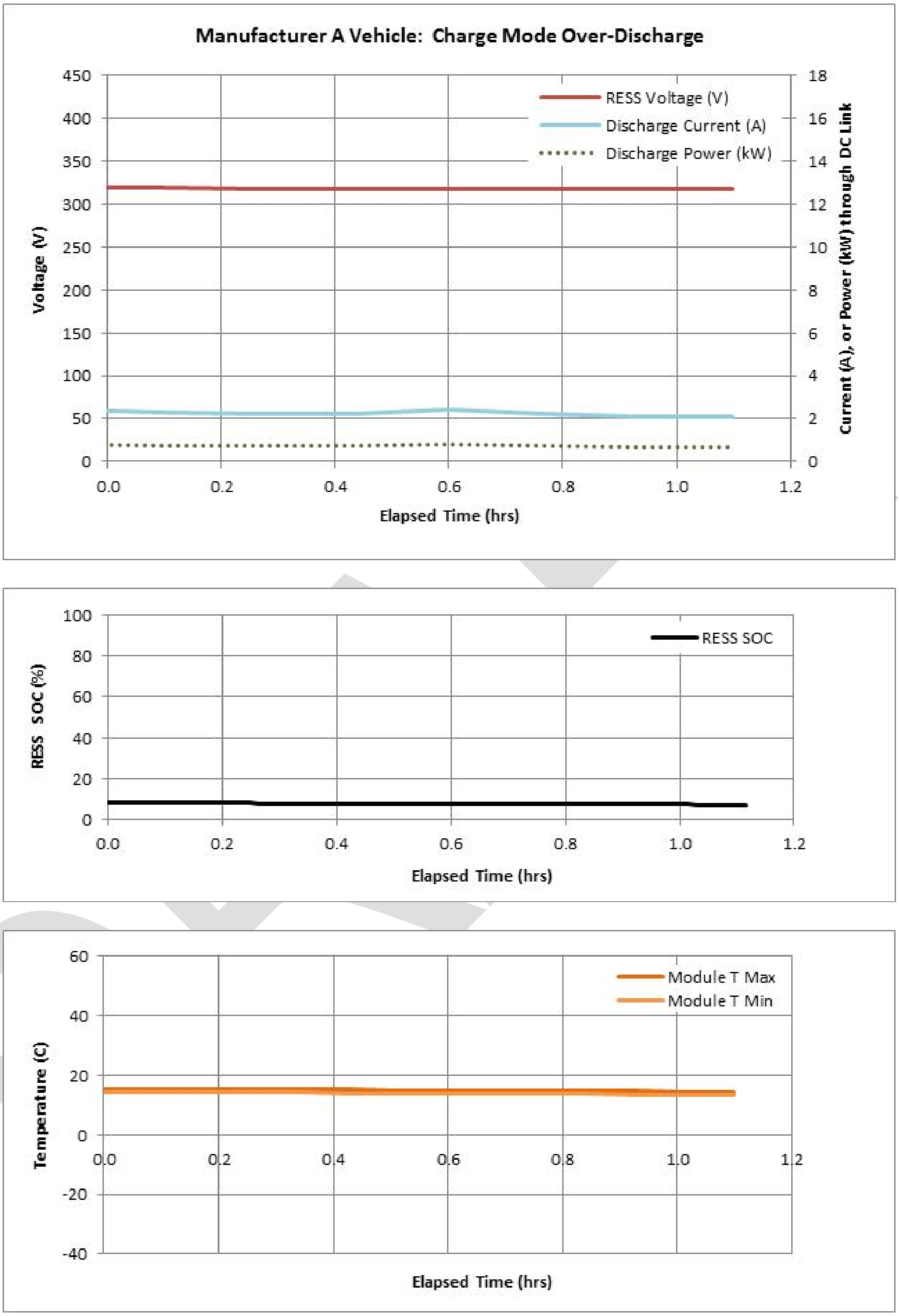

Figure 39 - Measured voltage, current, SOC, and temperature during charge mode over-discharge.

8.2.6 Manufacturer A Vehicle Over-Current Overcharge

The Test Vehicle RESS was brought to 95% SOC by charging the vehicle normally to 100% SOC and then using the vehicle cabin heater to discharge the RESS to 95% SOC.

Connections to the DC Link were verified. A Sorenson DCR-600 DC power supply (Figure 40) was selected to be an Over-Current Source for this test because its power limit (16A at 600 V or 9.6kW) exceeded the overcurrent shutdown limits of the Manufacturer A RESS (based on Manufacturer A provided information). The Sorenson was connected to the DC Link.

The test was conducted outdoors in ambient temperatures.

A summary of test results can be found in Table 24 and Figure 41. The vehicle was connected to a Level 1 charger capable of delivering 1.4kW of power to the RESS. Level 1 charging was allowed to occur for approximately 30 minutes, during which time, the RESS charge current stabilized at approximately 2A at 395 V (0.8kW). Approximately 30 minutes into the test, the Over-Current Source was activated and the current limit was ramped linearly through time. The vehicle RESS isolated itself from the power supply approximately 2 minutes into the overcurrent supply ramp, the current had reached approximately 11.5 A at 396 V (4.6 kW). Following isolation of the RESS, the Overcurrent Supply remained powered and connected to the DC Link for 2 hours. Further charging of the RESS did not occur. The RESS temperature remained constant throughout the test.

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 24 - Summary of Over-Current Overcharge Test Results.

Operation	Over-current overcharge
Time (hrs)	2.5
Initial SOC	95%
Final SOC	95.6%
SOC change	0.6%
Maximum RESS Temperature (C)	18°C
Evidence of Smoke	No
Compromised Cabin Tenability	No
Evidence of Fire	No
Evidence of Explosion	No

Figure 40 - The Sorenson DCR-600 DC power supply used for both over voltage and over current overcharge testing. It is rated for 600 V / 16 A (9.6kW).

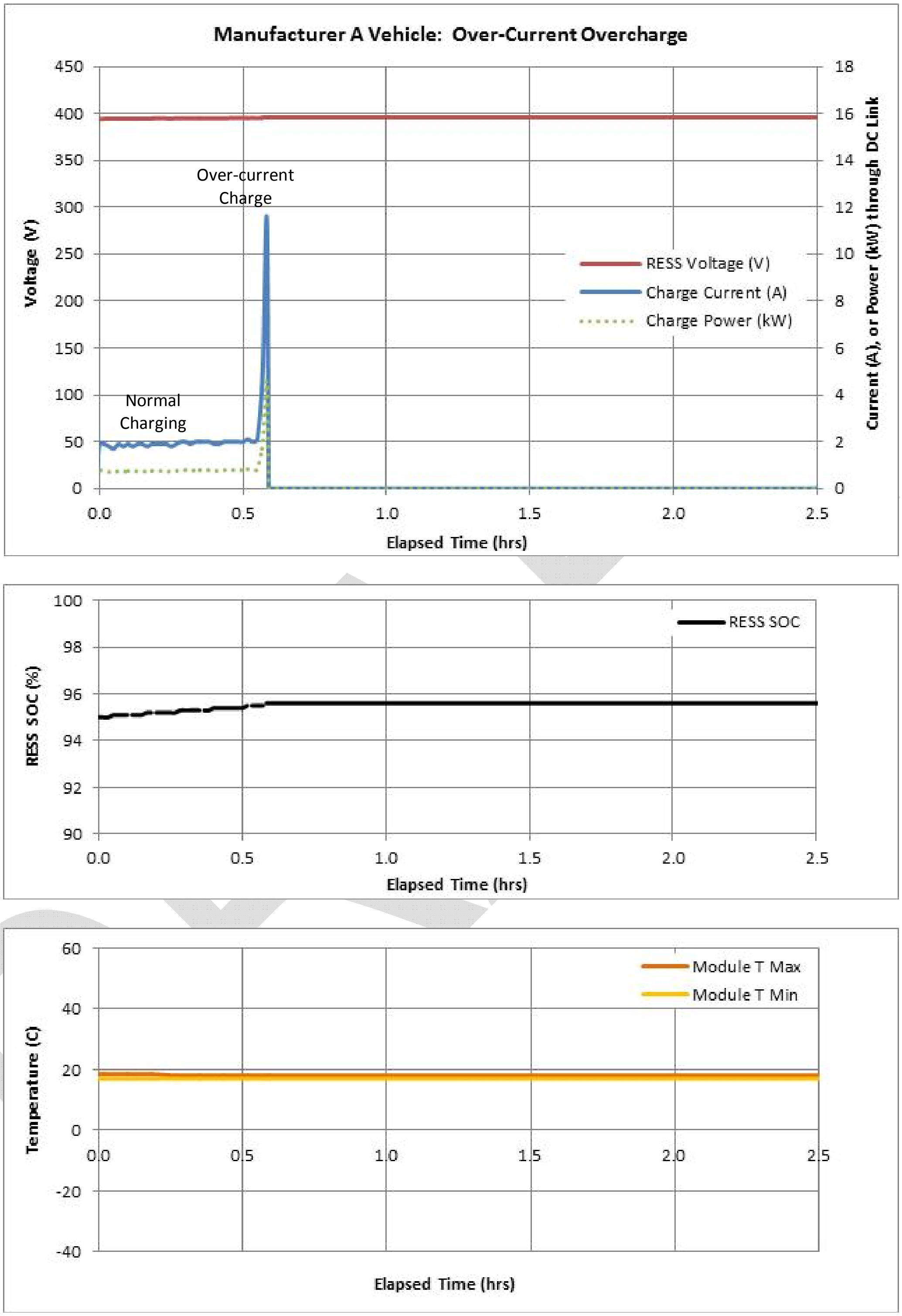

Figure 41 - Measured voltage, current, SOC, and temperature during over-current overcharge.

8.2.7 Manufacturer A Vehicle Over-Voltage Overcharge

The Test Vehicle RESS was at 96% SOC at the conclusion of the previous test (Over-current Overcharge), and was capable of accepting charge. Thus, the SOC of the RESS did not require adjustment.

Connections to the DC Link were verified. A Sorenson DCR-600 DC power supply (Figure 40) was selected to be an Overvoltage Source for this test. The voltage limit of the Overvoltage Source was set to 600 V (although 440 V would have been sufficient to meet the test requirements). The current limit was set to approximately 3A in order to achieve 1.4kW maximum charge rate. The Sorenson was connected to the DC Link.

The test was conducted outdoors in ambient temperatures.

A summary of test results can be found in Table 25 and Figure 42. The vehicle was connected to a Level 1 charger capable of delivering 1.4kW of power to the RESS. Level 1 charging was allowed to occur for approximately 10 minutes, during which time, the RESS charge current stabilized at approximately 1.8A at 395 V (0.7kW). Approximately 10 minutes into the test, the Overvoltage Source was activated. Charge current increased to approximately 3A (1.2kW applied power). Charge current remained approximately constant until the RESS reached 100% SOC and charging was terminated by the RESS, a normal response. RESS temperature remained stable throughout the overvoltage overcharge test.

Following the isolation of the RESS the DC power supply remained powered and connected to the system for 2 hours. The RESS remained isolated at all times, preventing further charging.

Because the Overvoltage Source was set to 600V rather than 440 V, the vehicle suffered minor damage to electronics external to the RESS when the RESS isolated itself from the external voltage supply. 600V was significantly higher than the maximum voltage that could be reasonably expected from a faulting charging system. This damage would have prevented future normal charge or discharge operations with the RESS. Thus, minor repairs to the electronics in the vehicle were completed with guidance from Manufacturer A before moving to the next stage of testing. The RESS did not require repair.

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 25 - Summary of Overvoltage Overcharge Test Results.

Operation	Overvoltage Overcharge
Time (hrs)	3.5
Initial SOC	96%
Final SOC	100%
SOC change	4%
Maximum RESS Temperature (C)	16°C
Evidence of Smoke	No
Compromised Cabin Tenability	No
Evidence of Fire	No
Evidence of Explosion	No

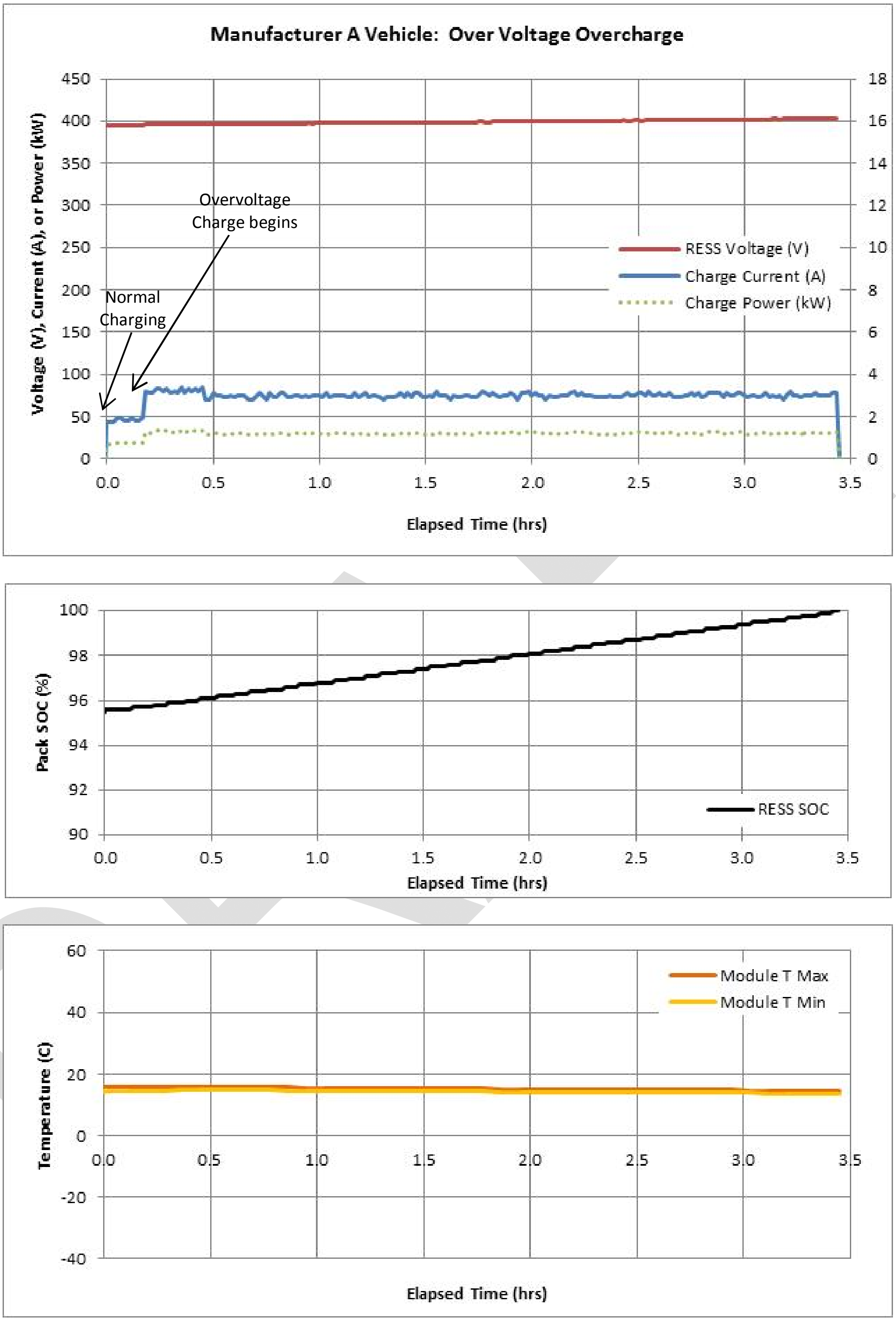

Figure 42 - Measured voltage, current, SOC, and temperature during overvoltage overcharge.

8.2.8 Manufacturer A Vehicle External Short Circuit

Connections to the DC Link were verified. The short circuit device was connected to the DC link. It contained two parallel fuses rated to 630A to protect itself from damage should the vehicle and/or RESS continue to source current.

The Test Vehicle RESS was brought to 95% SOC by discharging the RESS by using the vehicle cabin heater to 95% SOC (previous testing had raised SOC to 100%). The vehicle was allowed to equilibrate to ambient temperature, approximately 20°C.

The Test Vehicle was placed into Drive Mode. The short circuit device switch connected to the DC link was closed and the RESS was short circuited.

A summary of test results can be found in Table 26. The RESS interrupted the current flow almost immediately upon short circuit. The vehicle was monitored in place for one hour subsequent to short circuiting. RESS temperature did not change during the test. The short circuit device switch was then opened and disconnected from the DC Link. The fuses in the short circuit device were inspected and found to be unfused, verifying that the current interruption occurred upstream of the DC Link connection.

The RESS performed as expected during this test. There was no evidence of smoke or fire.

Table 26 - Summary of SOC Change and RESS Maximum Temperature During Short Circuit Testing.

Operation	Drive Mode
Time (hours)	1
Initial SOC	95%
Final SOC	95%
SOC change	0%
Maximum RESS Temperature (C)	22°C
Evidence of Smoke	No
Compromised Cabin Tenability	No
Evidence of Fire	No
Evidence of Explosion	No

8.2.9 Manufacturer A RESS Destructive Discharge

Destructive discharges were conducted on Manufacturer A cells and modules. The result of testing with single cells is discussed in Section 7.11.

Manufacturer A modules were subjected to salt bath destructive discharge. Two separate modules were placed in an approximately 30 gallon plastic trash can filled with salt water. After 1-3 days of submersion, the modules were fully discharged: all cell cases had been breached by the corrosion reaction (Figure 43). The modules were removed and sent for recycling. The liquid was also removed and sent for proper disposal.

The full Manufacturer A RESS was assessed for destructive discharge by salt bath. The assessment raised the following concerns:

- Although full RESS have been successfully subjected to this method in the past, they have generally contained a fraction of the energy contained in this particular RESS (28kWh vs 85 kWh).

- Flow around modules within the RESS, even with the RESS cover removed, was difficult to achieve due to RESS mechanical design. There would be a high risk of module overheating and cell thermal runaway reaction. Submerging individual modules would ensure better flow of water around each module.

- The large, flat design of the RESS would require a very large containment pool. Filling the pool to a sufficient height to prevent ejection of sparks and flames above the liquid would require a significant volume of water. If modules were separated and submerged individually or in pairs in smaller salt bath tanks, significantly less water would be required to complete the destructive discharge and modules could be oriented such that cell thermal runaway vents were not directed toward the liquid surface.

The results of the assessment indicated that destructive discharge should be conducted at an individual module level, which had already been demonstrated.

Figure 43 - Example of a Manufacturer A module after salt bath destructive discharge.

All test data is available on hard drive labeled “SAE-3257 RESS ISS Tests:, folder “Section 1 – Sequential”

[END OF DOCUMENT]